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A review of the role of graphene-based nanomaterials in tackling challenges posed by the COVID-19 pandemic

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Abstract

In 2020, the World Health Organization (WHO) declared a pandemic due to the emergence of the coronavirus disease (COVID-19) which was resulted by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). Significant efforts have been devoted by many countries to develop more advanced medicines and vaccines. However, along with these developments, it is also extremely essential to design effective systems by incorporating smart materials to battle the COVID-19. Therefore, several approaches have been implemented to combat against COVID-19. Recently, due to its superior physicochemical properties along with other fascinating properties, graphene-based materials have been explored for the current COVID-19 and future pandemics. Therefore, in this review article, we discuss the recent progress and the most promising strategies related to graphene and related materials and its applications for detection, decontamination, diagnosis, and protection against COVID-19. In addition, the key challenges and future directives are discussed in detail for fundamental design and development of technologies based on graphene and its related materials and lastly, our personal opinions on the appropriate approaches to improve these technologies respectively.

Keywords: COVID-19, Graphene, Graphene Oxide (GO), Anti-viral, SARS-CoV-2, Applications, electrochemical biosensors, face mask
1. Introduction

COVID-19 infection caused by novel SARS-CoV-2 virus was firstly reported in Wuhan city, China, [1-3]. In different ways, COVID-19 disease affected the human population globally [4-6]. Unfortunately, the spread of this virus occurs from one person to another or place to place through the respiratory droplets resulting from physical touch, sneezing, and coughing. These drops consist of different sizes and in general, these drops are sub-5µm in size. It is important to note that the drops with size larger than 5 µm do not have the ability to travel long distance, thus, resulting it to settle within 1 m to 2 m due to gravitational force [7] while smaller size remain floating in air for a long period of time, thus, resulting the spreading level of the virus to increase. Globally, the spread of COVID-19 resulted in increase in contagion and deaths, the infections are coming as waves [8]. Governments are facing great challenges to compete with the high demands to protect the economy and the healthcare systems respectively. Furthermore, significant efforts have been devoted by researchers around the world to develop suitable and effective strategies to diminish hospitalization, contain the pandemic and to develop a variety of vaccines [9]. At the initial stage, to provide a physical barrier, surgical masks have been employed to prevent the exposure to respiratory droplets. In addition, several safety measurements were taken to disinfect and decontaminate human and public places namely offices, shopping centres, airports, parks, and hospitals from COVID-19 and various types of sanitization solution and systems were developed and implemented accordingly.

In the past years, two-dimensional materials such as the graphene and its related materials have attracted significant attention due to their remarkable physical and chemical properties, which render them powerful components for various applications. Graphene related materials are made up of various carbon two-dimensional materials, each of them having a specific structure and nomenclature [10, 11]. As illustrated in Figure 1, graphene, GO, and rGO are the most promising materials among the different graphene related materials [10]. For instance, graphene consists of a honeycomb sp² carbon lattice structure which results this material to have superior strength and flexibility, excellent electrical conductivity, and high lipophilicity. Alternatively, GO is an oxidized form of graphene containing numerous oxygenated groups and some sp³ carbons lead this material to be highly hydrophilic and water dispersible, however, there is a decrease in the mechanical and electrical performances [11]. The GO can be further reduced to form reduced graphene oxide (rGO) to partially
restore the electrical conductivity but retaining the water dispersibility to a great extent. Interestingly, graphene-based materials exhibit both antiviral and antimicrobial efficiency. For instance, among all graphene derivatives, several studies have revealed that GO has the highest negative charge and also has high affinity for virus that are positively charged [7]. In other words, via hydrogen bonding and electrostatic interaction, the lipid bi-layer of feline COVID-19 can be adsorbed on the GO surface. Furthermore, the viral membrane that were destroyed by the binding of the GO confirmed the efficiency of GO against the viruses. In short, the versatility of the graphene related materials makes this material to be a promising candidate in a wide variety of applications including different device prototypes.

![Graphene Related Materials](image)

**Figure 1:** Schematic model illustrates the chemical structures and the fabrication of the antiviral graphene related materials [10].

Therefore, this review article critically discusses the importance of graphene-based materials for diagnosis, detection, decontamination, and protection against COVID-19 followed by the most relevant applications of graphene-based materials that can be foreseen to battle viral pandemics. The key challenges and future directives for fundamental design and development of technologies based on graphene and its related materials are discussed and lastly, our personal opinions on the appropriate approaches to improve these
technologies. In the near future, we strongly believe that the graphene-based materials along with their fascinating properties will pave the way to fight the fatal of SARS-CoV-2.

2. Interaction of graphene and its derivatives-based materials with contagious virus

The interaction of graphene and viruses constitutes a distinct addition to the potential successful applications of COVID-19, where Di et al. prepared graphene and antibody-coupled panels respectively that can rapidly detect target virus proteins and thus can be a very useful population screening group [12]. In 2012, the effect of graphene on viruses was reported, whereby it revealed that graphene had a good ability to inhibit viruses. In addition, rGO is a material with very thin sheets and a very large surface area with high conductivity. Akhavan et al. synthesized GO via the modified Hammer method, giving hydrothermal reduction of GO and rGO by exploiting thin particles of tungsten oxide with rGO for photo-activation of stamens under visible light irradiation [13]. Derivatives of graphene have been used in the pharmaceutical industry to obtain antiviral compounds such as graphene-conjugated reverse transcriptase inhibitors for the treatment of HIV and in the treatment against COVID-19 [14-16].

The two-dimensional graphene material has remarkable electronic properties and promising applications, including bacterial infection control or detection. Graphene also interacts with light: a single layer of graphene can absorb 2.3% of incident visible light [17]. This property is used to generate heat and sterilize materials, since GO contains oxygen groups, its surface is similar to rGO and graphene. Surface oxygen has the advantage of providing reaction sites for uptake or activation by proteins, enzymes, and nucleic acids, through selective chemical activation, due to the presence of surface oxygen, and GO can also participate in the fight against SARS-CoV-2.

Graphene-based technology can be used to treat the COVID-19 disease that works both outside and inside the cells of host cells. Mohamed et al. explored GO, the most widely used two-dimensional material in biomedical applications, as a nano-platform for interaction with SARS-CoV-2 [18]. The molecular docking analyses of GO sheets were performed upon interaction with three different structures: SARS-CoV-2 GO viral spike. Here, the results exhibited a high affinity for the surface of the three structures (6M0J, 6VYB and 6VXX), when comparing the binding affinities and the respective bonding types, GO interacts more strongly with spike or ACE2, compared to 6M0J. Infection experiments were conducted using four types of infectious virus particles for validation purposes. The results showed that
the thin GO sheets were able to significantly reduce the transcription of three different viral layers. On the other hand, the results showed the ability of GO leaves to interact with the surface components of SARS-CoV-2 and inactivate infection even in the presence of any mutations on the viral spike. In addition, the disruption of the SARS-CoV-2 pathway using graphene oxide (GO) was investigated by Masahiro et al. It is based on the antiviral effect of GO sheets by three strains of SARS-CoV-2. RT-PCR) as 50 and 98% of the virus in the supernatant can be removed after incubation with (100 μg/ml) GO for 1 and 60 min [16] [19].

Here, the results further confirmed the existence of a two-step virus inactivation method (1) spike adsorption of positively charged SARS-CoV-2 on the negatively charged GO surface and (2) inactivation of SARS-CoV-2 on the GO surface through viral proteolysis. This is due to the damage to S protein with GO since the interaction of S protein with human angiotensin-converting enzyme 2 (ACE2) is required for SARS-CoV-2 entry into human cells, making GO a potential candidate to be used in contributing to the inhibition of the global spread of SARS-CoV-2 and contribute significantly to prevent the spread of the virus.

Moreover, graphene and its derivatives are characterized by high antimicrobial activity, which leads to the presence of physical and chemical mechanisms for damage. They are ideal materials for dyeing fabrics such as personal protective equipment, face masks and gloves to control the transmission of SARS-CoV-2 more effectively. Amrit et al. fabricated biosensors using graphene can effectively detect the virus with high accuracy and sensitivity, providing rapid quantification [20]. In other words, accurate, highly sensitive and cost-effective diagnostic tools have been developed using graphene to efficiently monitor and control the spread of COVID-19 and other airborne viruses. The interaction of graphene materials with the viruses is schematically illustrated in Figure 2.
For the SARS-CoV-2 Spike S1 protein receptor binding domain interaction with heparin, Palmieri developed a therapeutic line by repurposing heparin and antiviral sulfur derivatives of GO. The light absorption property of graphene can be used to destroy viral particles. Sulfonated magnetic nanoparticles working with rGO have been successfully used to capture and eliminate herpes simplex virus type 1 (HSV-1) by photothermal use by near-infrared (NIR) light [8]. The results demonstrate how GO capture may be combined with NIR treatments for the lungs. In fact, the presence of highly absorbent materials such as graphene and GO on the window of transparency of the NIR tissue and allow deep penetration into the body of the incident light, this technique is used in the treatment of lung metastases.

Interestingly, graphene has unique properties such that its large surface provides the highest contact area for negatively charged sulfate adsorption bonds. Thus, negative charges can interact with positively charged virus residues and inhibit microorganisms such as coronavirus. Ziem et al., were able to synthesize heat-resistant rGO derivatives from rGO sulfate and the results showed antiviral activity against herpes virus, fever virus African pigs and orthopoxvirus [21]. In 2014, according to Sametband et al., it was discovered that the main factor affecting virus inhibition is the charge density and that due to the difference between GO and the sulfur derivative of rGO. This was not evident in the antiviral activity against HSV-1, as these materials had a negative charge density similar to the virus [22]. In 2016, Ziem et al. continued to combine rGO with vulcanized cleaved polyglycerol (dPG). These materials have the property of binding to dPGS as the heparin-binding domain of the
A27 surface protein on different orthopoxvirus strains [23]. It was possible to investigate what happened when the viruses came into contact with the surface of graphene, as the results showed the interaction of GO with viruses due to the presence of hydrogen bonds, electrostatic interactions and redox reactions, which in turn revealed a strong relationship between the toxicity of graphene compounds and the length of fatty amines. Song et al. confirmed the presence of the hydrophobic property, with this chain and the double lipid layer of the virus in this interaction [24].

3. Modelling of graphene based super-hydrophobic coating to prevent COVID-19 infections

In December 2019, it was revealed that there was another lethal infection known as SAR-CoV-2 that had begun circulating among the people and spreading via the respiratory beds [25, 26]. In addition, through the interaction with the debased exteriors, an individual could possibly get in contact with this infection which then will further result this infection to spread up to the mouth, nose, and eyes respectively. It was also reported that on different surfaces, the SAR-CoV-2 has a variable life span [27]. For instance, when compared to cardboard and copper, it was estimated that the adherence of the coronavirus was greater on the plastic and tempered steel surfaces respectively. Furthermore, in comparison with non-uniform surfaces such as wood, printing/tissue papers and materials, this infection was observed to be steadier on smooth surfaces. However, the discernible degree of the infection on the outside film of the surgical masks was an issue, whereby it could only last for approximately a week [28]. Also, the touch surfaces that contain these infected viruses can retain the virus for a longer time, thus, resulting the virus to spread at a faster rate. In the current epidemic crisis, where the coronavirus infections are drastically expanding around the world on a day to day basis, therefore there is a huge demand to enhance the effectiveness of the coronavirus protecting coatings/surfaces which could possibly be a promising solution to minimize the spread of the virus via any source [29]. On the other hand, graphene or graphene derivatives were noted to be potential alternatives due to their anti-bacterial properties [30]. For instance, Sametband et al. revealed the anti-viral attributes of GO and slightly reduced sulphuric acid treated with GO was further investigated against herpes simplex virus Type-1 by a specified unique mechanism. As illustrated in Figure 3, GO and its derivatives contained groups of negatively charged elements which were comparable to the receptor heparin sulfate cell surface, therefore, the two moieties were challenging one another in connection with the HSV-1 [28, 31].
Furthermore, to defend the Vero cell from the disease, the graphene-based materials are considered as the primary inhibitor. For instance, Ye et al. investigated the viral reduction effectiveness of GO, rGO, GO-polyvinylpyrrolidone (PVP) composite and GO-poly-diallyldimethyl-ammonium chloride (PDDA) composite [32]. This investigation resulted in the opening of a huge antiviral tendency of GO against the infections associated with Pseudorabies and porcine pestilence looseness of the bowels infection respectively. In addition, it was also concluded that the antiviral attributes of GO were due to its adversely charged and high pitch structure. In addition, an intense antiviral movement were exhibited by the GO formed with PVP (non-ionic polymer), whereas, the GO/PDDA composite displayed no infection hindrance, thus, further confirming the importance of the negative charge for antiviral attributes [32]. In another study to identify and sterilize natural infections, Song et al. investigated on the GO based label free method on Enterovirus 71 and endemic gastrointestinal infections derived from birds [24]. Here, it was revealed that the redox reactions between the GO layer and the viruses arising from the physico-chemical process acts as a vital parameter to destroy the viruses. Interestingly, the antiviral efficiency of the GO sheet was observed to enhance particularly under the influence of higher temperature surrounding. Moreover, Chen et al. proved in his research that GO sheets play a vital role to display the possibilities of critical antiviral restraint towards covered feline COVID-19 and the silver particles connected to the structure of GO expands its antiviral capability in the direction of non-enveloped infectious bursal disease virus [33]. On the other hand, Yang et al. fabricated curcumin stacked β-CD functionalized sulfonated graphene composite (GSCC) and further analysed its antiviral characteristics besides the negative sense respiratory syncytial infection (RSV) [34]. Here, it was revealed that GSCC could possibly prevent RSV

**Figure 3:** Schematic model illustrates (a) the structure of the COVID-19 virus and (b) the mechanism of breaking the long chain of the virus envelope [28, 31].
from infecting the host cells by blocking the association of the disease and deactivating the contamination clearly and in return, the GSCC does provide medicinal and prophylactic effects towards the contamination. In addition, due to the issues associated with porcine regenerative and respiratory related diseases, this led Du et al. to investigate on the antiviral effect of the composite synthesized from GO incorporated with silver nanoparticles [35]. Here, the results clearly proved that with an accuracy of 59.2%, the GO incorporated with silver nanoparticles successfully prevented the infection from entering into the host cell, thus, further resulting in the creation of interferon (IFN)-invigorating qualities and IFN-α which impedes the expansion of the infection respectively. Interestingly, extensive probability in the enhancement of antiviral coatings and surfaces have been exhibited by graphene based surfaces for protecting fouling from harmful and infectious infections and high possibility to control the transmission of the illness respectively [36]. For instance, for the COVID-19 virus, structures consisting higher carboxyl groups and less endurance of this infection on copper surfaces and GO/rGO-\(SO_3\) coatings incorporated with copper nanoparticles could be a promising material combination for the advancement of hostile to COVID surfaces. Illustrated in Figure 4 is the schematic model of the viral restriction process from graphene and its derivative based coatings in repelling numerous viruses including COVID [30]. In short, these materials discussed above play a vital role to limit the infection endurance time on different covered surfaces and to catch and destabilize the infection structures [37].
Alternatively, via a dual mode laser-induced forward transfer technique, Zhong et al. synthesized graphene layer based super-hydrophobic low melting temperature non-woven surgical masks which had superior photo-thermal and self-cleaning properties [38]. In addition, after sunlight sterilization, these functional masks are reusable due to the fact that the surface temperature can rapidly increase up to 80 °C under the influence of sunlight and the lifetime usage of these masks increased significantly as it showed the tendency of salt rejection. On the other hand, efficient protection against viruses have been revealed by the superhydrophobic surgical masks that are fabricated via the roll-to-roll method. As illustrated in Figure 5, the SEM representations of the pristine surgical mask revealed the smooth surface of the melt-blown fibers of 20 µm, thus, exhibiting non-super-hydrophobic properties [38]. Moreover, via a static contact angle (CA), the wetting tendency of this mask was observed to be approximately 110°, thus, confirming the surface hydrophobicity. However, the droplets being attached to the surface were one of the drawbacks observed with this mask. Interestingly, the presence of nanostructured flakes, size varied from 100 nm to few mm, was
observed on the mask surface specifically after employing the dual mode laser-induced forward transfer technique, thus, resulting the CA to increase up to 141° (Figure 5) [38].

Figure 5: Schematic model illustrates the CA measurement and SEM representations on (a) uncoated and (b) coated graphene non-woven fiber surgical mask respectively [38].

The use of graphene-based face masks is a promising approach to reduce the spread of respiratory diseases namely the COVID-19 in affected areas [39-44]. A part of a non-pharmaceutical intervention, the face mask is capable to reduce the transmission of respiratory pathogens by creating a specific barrier. Furthermore, a better respiration is ensured by graphene particularly when embedded in air-filtering membranes of the respirators due to the fact that graphene has a two-dimensional honeycomb lattice structure in which the $sp^2$-hybridized carbons are arranged in a hexagonal form [45, 46]. In addition, the large surface area of graphene is another key feature that makes it appropriate for interfacial interactions [10, 47, 48]. In short, the attributes of graphene such as large surface area, hydrophobic nature, high electrical conductivity, and photocatalytic activity have attracted remarkable attention among researchers globally in designing high-quality respirators [49]. Furthermore, due to graphene having an extreme hydrophobic nature and microporous structure, the water droplets, particles, pathogens, and aerosols are therefore restricted to enter hence, to remain in the outer layer of the respirators for long periods. Interestingly, compared to the virus size (0.05 – 0.14 µm), the pore size of the graphene membrane (5.7 –
25.2 Å) is much smaller, thus, resulting it to serve as a selectively permeable membrane to separate the pernicious SARS-CoV-2 [50, 51].

4. Relevance of graphene and its materials in battling the COVID-19 virus

4.1. Anti-viral surfaces and coatings

In the wake of the Covid-19 outbreak, many countries and individuals across the globe have joined hands to bring back the freedom of pre-Covid. In many attempts to stop or curb the spread of the disease such as social distancing, face masks and many others, many believe that by researching and developing anti-viral surfaces and coatings will help prevent the spread of the disease. This is mainly due to the way viruses spread, specifically the cells of its hosts for survival and replication. For many, this can be seen as a very effective method of preventing Covid and many other viruses which can survive for long durations even outside of hosts. For example, the Covid-19 virus is effectively blocked from an individual using surgical face masks but is able to stay alive for a whole day on the surface of N-95 face masks which is mainly used worldwide to combat Covid-19 [52, 53]. During this period, virus can latch on to other surfaces or even when touching the mask for disposal can transport the virus. For this reason, anti-viral surfaces and coatings have been researched with the idea of mass productions in mind.

Recently, graphene and its derivatives such as graphene oxide (GO), reduced graphene oxide (rGO), and graphene-based nanoparticles (GBNP), have come under the spotlight for their unique antimicrobial and antiviral characteristics. Graphene and its derivatives, mainly, have been highly focused due to its lack of toxicity towards humans and environment. For example, in GO, the nanowalls of GO form sharp edges, most effective at the least number of nanowall layers, which inhibits cell replication by physically disabling the viral function of the virus, its effectiveness at lesser layers of graphene oxide nanoparticles (GONP), combination of GONP and other metal nanoparticle which boost its antiviral activity, etc. [54]. Graphene oxide has shown promise in many key areas to fend viruses such as H9N2, Pseudorabies and enteric EV71 due to its ability to grab on to viruses and disable it [12]. An explanation to its catching capabilities, GBNPs have sharp edges at which viruses get caught in and is dismantled. Furthermore, it is also capable of shattering the cellular lipid bilayers of viruses and inhibit the protein-protein unfolding as well as conversion of α-helix segments into β-sheets, which causes the structure to become inactive fibrillar agglomerates [10].
Another form of graphene that can help in the battle against the SARS-CoV 2 is rGO which is obtained by reducing the oxygen content of GO by chemical reactions and thermal methods. It was demonstrated that rGO, when paired with carbon dots and polyphenol curcumin can effectively halt the spread of Covid-19 by adding the method into existing production lines of personal protection equipment (PPE) [55]. Prevention of the spread of SARS-CoV-2 virus should be top priority of governments and individuals across the globe, but another prime priority is early detection of the virus in individuals. With early detections, the authority can rightfully segregate and quarantine any close contacts. This is vital as those with close contacts can be contracted and quarantined before carrying the virus to another person. The implementation of rGO in Covid-19 detection is shown where three-dimensional (3D) printed gold coated on rGO was capable of catching and detecting CoV-2 spike S1 antigens, which gives the Covid-19 virus its viral properties [56]. When compared to two-dimensional (2D) printed gold coated rGO, there was a significant bump in detection levels, by 2.5 times. This is also vital in combating Covid-19 as freshly infected individuals will have far less CoV-2 Spike S1 antigens in their bodies when compared to already infected individuals. Existing products for detection may not be able to detect this level of antigen as it does not work in nanoscopic levels like rGO does.

These graphene derivatives can be used as coatings and surfaces in many places and products, like food packaging, which is passed down from the chef/baker to the food delivery person and/or then to the customer [57]. In this process chain alone, the virus can infect an entire state within a relatively short time when there are no safety precautions. Even with safety precautions, a sliver of the virus will somehow be able to break this free of this chain and start a local outbreak. An even more important application is PPE [58]. As humans are hugely affected by the Covid virus, PPE, when used properly, can help mitigate or even block the spread of the Covid virus from an already infected person to another non-infected person [59]. At the end of the virus pathway is always a host, specifically a human. To coat every contactable surface with antiviral material is an extremely difficult task and the specific thickness is virtually impossible. However, by targeting regularly used surfaces like handrails when climbing up a staircase or holding rails in trains or busses, a huge percentage of surfaces in which the virus can survive on can be eliminated. This can be done by using GO or rGO coated with copper nanoparticles [60]. As illustrated in Figure 6, the implementation of this graphene design can destroy the virus by its Van der Waals interactions with the virus membrane as well as electrostatic interactions [61].
Figure 6: Schematic diagram of likely interactions between SARS-CoV-2 and graphene and graphene nano-hybrids comprising graphene-metal ion, leading to virus inactivation on the coated surfaces [61].

In short, graphene as a material used for antiviral coatings and surfaces has, relatively, just been researched recently, but the advancements in applications and capabilities of graphene against not only SARS-CoV-2, but various other viruses and diseases have been explored. Many studies have been able to demonstrate the potential of graphene against the SARS-CoV-2 virus without the side effects, like toxicity towards humans and with the passage of time, the effectiveness of graphene against the SARS-CoV-2 virus is only expected to increase. Illustrated in Table 1 are the numerous types of graphene and its derivatives for anti-viral surfaces and coatings.

Table 1: Summary of numerous types of graphene and its derivatives for anti-viral surfaces and coatings [103-105, 108-109].

| Materials | Mechanism | Targeted virus | Remarks | Ref. |
|-----------|------------|---------------|---------|-----|
| GO        | The GO-Infection physiochemical associations resulted in the infection catching and RNA spillage from the infection. | EV71 (RNA capsid Infection, Capsid Infection, extremely normal among kids) H9N2 (RNA wrapped infection, liable for human flu alongside bird influenza). | • The GO upholds outright destruction, rejection, and sterilization, approximately a 6-log decrease in infectivity. • The GO nanoparticles were reported to be progressive approach to anticipate infection transmission in the climate and bringing down the danger of disease via | [24] |
| GO/Ag nanoparticles | The inhibitor restricted the infection from entering the host cell and by advancing ISGs and IFN-α. | Procine reproductive and respiratory syndrome virus (PRRSV) typically contaminated the young pigs. | GO/Ag based nanocomposites inhibited the PRRSV towards the inside in the host cell and its replication. [62] |
|---------------------|-------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|
| GO, r-GO, Graphite, Graphite oxide, GO-PVP, GO-PDDA | The antiviral component is ascribed to the negative charge of GO and its nanosheet structure. | PRV (DNA infection, contaminated the greater part of the vertebrates, causing fundamental injuries in CNS, respiratory framework and regenerative framework) PEDV (RNA infection, having a place with emphatically charged α Covid, which was responsible for high death rate in Pigs). | • PRV and PEDV by underlying obliteration before the viral passage into the cell. At even low concentration, the best anti-viral effect was exhibited by GO, GO-PDDA, and GO-PVP. • Polylaminate GO was observed to exhibit a much more fragile inhibitory impact compared to mono-layered GO and rGO, though graphite having the non-nanosheet structure showed no antiviral movement, thus, revealing that the nanosheet structure is basic for the antiviral activity. [32] |
| GO and rGO/SO₃ | Competitive Inhibition Mechanism | Herpes simplex virus type-1 (HSV-1) (DNA infection, contaminating 70 to 90% mortal populace) | • A good inhibition of the viral infection at low concentration was exhibited by the GO and r-GO/SO₃ and the plaque development was reduced significantly. • Both graphene and SO₃ based reduced graphene showed non-toxic attribute to the Vero cell culture. [22] |
| Curcumin decorated with β-CD functionalized sulfonated graphene (GSCC) | Via a competitive inhibitory mechanism | RSV (wrapped RNA infection can taint the respiratory lobes and regularly causing respiratory sickness in recently conceived new-born youngsters, youths, mature individuals, and Immune compromised people groups). | The powerful grouping of GSCC was revealed to be non-harmful to the host cells. The viral titer showed four sets of decreases utilizing GSCC. [34] |

### 4.2. Graphene cytotoxicity

Cytotoxicity of a material plays a crucial role when it is utilized in medical-based sectors as it indicated the toxicity level of the material towards living cells concurrently understanding its biological reaction. In context of carbon-based materials particularly
graphene, their cytotoxicity level is low together it exhibits antiviral activities allowing the incorporation of graphene for specific antiviral treatments [55]. For instance, Xiao et al. functionalized graphene oxide into β-cyclodextrin to inhibit the respiratory syncytial virus (RSV) and confirmed that the graphene oxide has the ability to efficiently inhibit RSV from infecting the host cell together providing excellent biocompatibility to the host cells [34]. On the other hand, Ting Du and co-workers investigated on the antiviral activity of graphene oxide-silver nanocomposite in prevention of the virus entry using porcine reproductive and respiratory syndrome virus (PRRSV) as the infection pattern and perceived that the number of viruses significantly dropped upon introduction of the nanocomposite indicating the graphene oxide-silver nanocomposite prevents the entry of the virus in the host cell by inactivating it. Simultaneously the presence of this nanocomposite activates the innate immune system of the host to secret more interferon-based genes and protein to suppress the virus infection by inhibiting the proliferation of the virus [35]. In the context of SARS CoV-2 virus, Tahereh and Ali et al. respectively stated that graphene-based materials can efficiently inhibit the invasion of the virus into host cell due to splendid binding efficiency of the graphene-based material with the spike protein of SARS CoV-2 [63]. This was further confirmed by Ievgen et al.’s research on investigating the interaction of SARS CoV-2 with precise dual sulfate/alkyl functionalities and reported that graphene inhibits the SARS CoV-2 invasion via virtue disruption of the viral envelope with significantly low toxicity towards human cells [64]. Generally, materials with more than nine carbon atoms (long aliphatic chains) is highly destructive for eukaryotic cells due to increase in their toxicity however from the above research it was perceived that long aliphatic graphene-polyglycerol sulfate (contains 11 carbon atoms) is efficient in combating strong viruses such as FCoV and SARS CoV-2 without exhibiting significant cytotoxicity towards eukaryotic cells [64]. Cytotoxicity of graphene-based material is often investigated with the cell viability as the structure and physiochemical properties of the graphene-based materials such as graphene oxide, reduced graphene oxide, and functionalized graphene have great influence on the cell viability and biocompatibility. For instance, Qianqian et al. incorporated 9 µg/mL of graphene oxide (GO) nanosheets of diameter more than 1µm into a dendritic cell (DC) vaccine for SARS CoV-2 and reported that the DC vaccine treated with GO provides better contact area between DC and the T-cells which boost the T cell secretion in fighting covid-19 with splendid cell viability more than 90% indicating it is not toxic for eukaryotic cells [65]. According to Angel et al., concentration of these materials, oxidation degree, cell type, lateral size, and the exposure should also take into account besides the structural difference during cytotoxicity
analysis of graphene-based material as the cytotoxicity of the materials differ accordingly [66]. In terms of concentration, rise in the concentration of the material in the treatment increases its cytotoxicity where non-cytotoxic concentration of graphene is efficient in combating mild viruses such as porcine epidemic diarrhea virus (PEDV) and PRRSV which is lesser than 6 µg/mL and 4 µg/mL respectively, meanwhile higher concentration window is required in combating strong viruses like SARS CoV-2 (50 µg/mL) and FCoV (10 µg/mL) [66]. In short, even though higher graphene concentration is used for SARS CoV-2 treatment, yet the toxicity level is still low to cause significant drop in the cell viability making it safe for humans. Howbeit, it is worth to note that the above factors of graphene and graphene-based materials should be taken in account when preparing for the drugs or treatment for SARS CoV-2 because it is closely related to the cytotoxicity of the material and how it reacts with human body.

4.3. Sensors

With the advent of the Coronavirus, major smart materials and their integration with sensor platforms and applications have been used as tools that can be used in the scope of COVID-19 diagnosis. Graphene-based bio-sensing systems have been developed due to the advantages of various sensing mechanisms for it, such as field effect (FET), optical, electrochemical, etc. Chauhan et al. was able to modify its surfaces using chemical methods, such as amino silane, carboxy, and diazonium, as well as plasma chemistry that causes the immobilization of the biological recognition element leading to the identification of different types of pathogens [14]. Graphene provides strong and flexible mechanical, electrical and thermal properties as well as bio-tolerance and other antiviral properties [16, 67].

Graphene is used with nanoparticles to detect viruses. A multilayer (sandwich) immunoassay was developed by Anik et al. for detection of avian influenza virus H7 (AIV H7) composed of graphene coated with silver nanoparticles with a minimum detection (LOD) of 1.6 pg/ml [68]. We were able to develop an electrochemical influenza A biosensor consisting of a graphene-golden (Au) hybrid electrode. By measuring the activity of neuraminidase (N), the biosensor was tested to examine the analytical properties of influenza A, the results showed a linear range between 10-8 U/mL-1 and 10-1 U/mL-1 with a relative standard deviation value of 3.23% (for 10 -5 U mL-1 of N, n: 3) with a maximum detection value of 10-8 U mL-1 N. In addition, it was further used to detect true influenza A (H9N2) virus with successful results [68]. Moreover, Akanksha et al. developed a super sensitive graphene biosensor to detect Japanese encephalitis virus (JEV) [69]. The sensors were tested
in the range of 1 fM to 1 μM for both JEV and AIV antigens and showed a limit of detection (LOD) of 1 fM and 10 fM for JEV and AIV, respectively. The GFET biosensor structure was then modified with a sugar chain by Matsumoto et al. and this was used to detect both human and avian influenza virus [70]. On the other hand, as illustrated in Figure 7, Joydip et al. successfully utilized graphene field-effect transistor-type biosensor for the rapid detection of SARS-CoV-2 [71]. In other words, graphene field-effect transistor biosensors are considered for virus detection and graphene-based transistors are unique in their ability to detect sensitivity and low noise respectively. By coating a graphene sheet of FET with a specific antibody against the SARS-CoV-2 spike protein, Seo et al. reported a field-effect transistor (FET)-based biosensor used to detect SARS-CoV-2 in clinical samples [72]. The sensor was examined using cultured antigen and virus protein samples as well as oropharyngeal swab samples from COVID-19 patients. The sensor was able to detect SARS-CoV-2 spike protein at concentrations of 1 fg/mL in phosphate-buffered saline and 100 fg/mL so it is considered as a promising FET biosensor for SARS-CoV-2; The device is a good way to diagnose hypersensitive immunity to COVID-19.

![Figure 7: Schematic model illustrates the SARS-CoV-2 detection mechanism via the GFET Error](image)

4.3.1. **Electrochemical biosensors**

Biosensors are analytical devices consisting of a biological identification system and a physicochemical transducer [73]. Biosensors are used in the diagnosis of many clinical diseases, such as biomarkers of cancer or tumours, bacteria, and viruses. Electrochemical biosensors are distinguished by their robustness, excellent limits of detection, ease of miniaturization, as well as the ability to be used in turbid bio-fluids with optically luminous
and absorbent compounds [74, 75]. Yugender et al. investigated on the electrochemical diagnosis of twelve life-threatening viruses such as COVID-19, and mechanistic aspects of sensor systems for such viruses [76]. Whereas, electrochemical sensing systems consisting of antibody, aptamers, or direct/intermediate electron transfer through the recognition matrix were explicitly separated by Fauci et al. into separate subsections for critical comparison [77].

**Figure 8** illustrated the labelled and label-free approaches proposed for the development of a fiber-optic biosensor based point-of-care device for SARS-CoV 2 detection from saliva samples [77]. Fabrication of a biosensor used for the selective detection of COVID-19/SARS-CoV-2 virus; Based on RT PCR serological assays, antibodies, and an enzyme-linked immunosorbent assay (ELISA) have shown results for detecting viral infection as sensors can monitor biochemical signs of disease through body fluids, such as saliva, blood, or urine.

**Figure 8**: Schematic model of the labelled and label-free approaches proposed for the development of a fiber-optic biosensor based point-of-care device for SARS-CoV-2 detection from saliva samples [77].

Biosensors have distinctive properties due to the ability to adapt the specific reaction of compounds by immobilizing biological recognition elements on the sensor, whereby the basic components of biosensors are namely bio-receptors, signal transducer, and amplifier respectively [78]. POC biosensors based on carbon and graphene were developed. Graphene is expected to play a distinctive role in the treatment of COVID-19, given the low cost of this
material, it can be used to detect viruses and improve their sensitivity and selection by modifying their hybrid structure, allowing their optical and electrical properties to be tuned [79]. For instance, graphene sensors that can be used to detect SARS-CoV-2 are photoluminescence, colorimetric sensors, and SPR biosensors. In 2020, Siu et al. was able to encapsulate graphene sheets of FET with a specific antibody against the protein as the spike of the physical virus contributed to the development of a field-effect (FET)-based biosensor to detect SARS-CoV-2 at concentration of 1 fg/ml in phosphate-buffered saline medium [80]. It is used in detecting the virus in clinical samples, as it showed a LOD of $2.42 \times 10^2$ copies/ml, and as a result, this device is considered as a promising alternative for immunological diagnosis of diseases [81]. The available approaches to battle the COVID-19 virus via the utilization of graphene-based sensors are illustrated in Figure 9.

Figure 9: Different ways of using graphene-based nano-sensors to battle the COVID-19 virus.

Interestingly, different materials are frequently utilized to amplify the sensitivity and signal of electrochemical biosensors. For instance, in electrochemical biosensors, any
significant electrochemical change at the interface between an electrolyte and electrodes, based on a conformational change produced by biometric recognition between antigen and antibody, is measured. In addition, due to its stable electrochemical and optical attribute, superior mechanical and thermal properties and high electrocatalytic activity, graphene has been widely explored to design highly efficient biosensors [82]. For instance, to create biosensors, graphene-based platforms have been employed to immobilize biomolecules. Here, J. Pena-Bahamonde et al. demonstrated the approach to immobilize the biomolecules onto the surface of the graphene via surface chemical engineering such as the covalent bonding which involved the coupling of the biomolecules via 1-ethyl-3-(3-dimethylamino propyl) carbodiimide hydrochloride and N-hydroxysuccinimide reactions and physisorption respectively. Alternatively, Afsahi et al. demonstrated the detection of zika virus using graphene-enabled portable biosensor [83]. Moreover, Joshi et al. reported the use of GO-based biosensor in detecting the influenza virus [84]. In addition, in phosphate-buffered saline (PBS) and saliva samples, the detection limit for the targeted virus was measured to be approximately 26 and 33 PFU/mL. For instance, based on chitosan/Ag nanoparticle-graphene composite materials, Huang et al. reported a highly sensitive electrochemical biosensor to detect the avian influenza virus H7 (AIV H7) [85]. Here, it was observed that the developed biosensor exhibited an efficacy with a low detention limit of 1.6 pg/mL. In other words, the graphene-based electrochemical biosensors have proven to be significantly effective to detect biomolecules, specifically for the viruses, hence, suggesting that these types of biosensors have the highest potential to effectively detect the SAR-CoV-2. However, a significant amount of high-end research and testing are still required to develop reliable diagnostic devices. Illustrated in Table 2 is the summary of graphene and its related materials-based electrochemical biosensors to detect a variety of viruses.

Table 2: Summary of the previously reported graphene and its related materials-based electrochemical biosensor in detecting a variety of viruses.

| Materials | Type of sensor | Sensing performance | Others (Biomarkers) | Ref. |
|-----------|----------------|---------------------|---------------------|------|
| Gold nanoparticles on piezoelectric quartz crystal microbalance (QCM) | QCM | 0 - 1 log CFU/mL | Viable bacterial cells | [86] |
| Piezoelectric Crystal | Piezoelectric immunosensor | 0.6 - 4 mg/mL | SARS-CoV-2 | [87] |
| BSA precoated Crystal | Piezoelectric immunosensor | 50 pg/L | protein antigen/IgG | [88] |
| Device/Method                                                                 | Sensing Technique | Detection Threshold | Target Pathogen                          | Reference |
|------------------------------------------------------------------------------|-------------------|---------------------|------------------------------------------|-----------|
| Oligonucleotide functionalized gold nanoparticles on piezoelectric crystal   | QCM               | 2 – 2 × 10⁶ PFU/mL  | Dengue virus                             | [89]      |
| Graphene interdigitated gold electrode piezoelectric sensors                 | Piezoelectric     | 41 cfu/mL           | Staphylococcus aureus                     | [90]      |
| Array of gold nanoparticle modified carbon electrodes                        | Square wave       | 0.4 and 1.0 pg/mL   | Proteins namely Influenza                 | [91]      |
| Gold surfaces on piezoelectric quartz                                        | Piezoelectric     | 0.8 - 38.8 mM       | Hepatitis B virus                         | [92]      |
| Gold nanoparticle-graphene nanocomposites                                     | Amperometric      | 1.6 pg/mL           | Monoclonal antibodies                     | [85]      |
| Graphene-gold hybrid nanocomposite                                           | Amperometric      | 10 - 8 U/mL         | PNA lectin                               | [68]      |
| Ag nanoparticles/graphene quantum dots                                        | Electrochemical    | 3 fg/mL             | Antibody                                 | [93]      |
| Graphene                                                                     | FET               | -                   | Human-type 2.6 sialoglycan                | [94]      |
| Graphene                                                                     | FET               | Detection at concentrations of 1 fg/mL in PBS and 100 fg/LmL clinical transport medium | SARS-Cov-2 spike protein | [95]      |
| Graphene                                                                     | FET               | 47.8aM - 10.5 nM    | HIV-1 and MLV                             | [96]      |
| GO                                                                           | Electrochemical    | 8.3 fM              | Immunodeficiency Virus Type 1 (HIV-1)     | [97]      |
| GO surface by APTES                                                          | Impedimetric      | 1 fM                | DNA target                               | [98]      |
| rGO                                                                          | Electrochemical    | 26 and 33 plaque-forming units | Plaque                                     | [84]      |
| rGO                                                                          | Electrochemical    | 0.5 PFU/mL          | Monoclonal antibodies                     | [99]      |
| Functionalized graphene with amino groups                                    | Electrochemical    | 0.1 ng/mL           | Antibodies (anti-p2)                      | [100]     |
Interestingly, besides the fabrication of electrochemical biosensors for the recognition of the SARS-CoV-2 virus, graphene and graphene-based materials are also widely utilized in electrochemical biosensing applications such as reliable point of care (POC) test etc. Moreover, due to their highly conducting nature, many other graphene and its derivatives-based biosensors are highlighted in Table 3.

**Table 3**: Various other graphene and its derivatives-based biosensors.

| Materials                                    | Types of biosensors | Biomarkers                                  | Limit of detection | Ref. |
|----------------------------------------------|---------------------|---------------------------------------------|--------------------|------|
| Silver/graphene quantum dots (GQDs)          | Microbalance        | Antibody                                    | 3 fg/mL            | [93] |
| Gold/graphene nanocomposites                 | Amperometric        | Monoclonal antibodies                       | 1.6 pg/mL          | [85] |
| Graphene interlinked with gold electrode/piezoelectric sensors | Piezoelectric Quartz Crystal | Bacterial cell of Staphylococcus aureus | 41 cfu/mL          | [90] |
| GO                                           | Electrochemical     | Human immune-deficiency Virus Type 1        | 8.3 fM             | [105]|
| rGO                                          | Electrochemical     | Plaque                                      | 26 and 33 plaque-forming units | [84] |
| rGO                                          | FET                 | Ebola virus glycoprotein                    | 2.4 pg/mL          | [101]|

5. **Graphene-based gene-editing technology**

Due to the emergence of viruses of different types such as SARS-CoV-1 (2003), MERS-CoV (2012) and SARS-CoV-2 (2019), there is an urgent need for diagnostic tools capable of identifying infected people. Graphene is rarely used for rapid virus diagnosis. A
graphene-based field-effect biosensor (GFET) used for the quantitative detection of viral RNA and viral skeletal protein has been developed. The sensor was fabricated for the purpose of identifying the COVID-19 spike protein FET as it relies on the fusion of an anti-SARS-CoV-2 antibody with graphene, while the GFET sensor is used to identify viral RNA using bio-CRISPR/Cas technology.

Recently, graphene-based technology has been used to diagnose viral diseases, as the unusual properties of graphene have been relied upon to diagnose COVID-19. Graphene-based field-effect transistor (GFET) biosensors have been developed for the quantitative detection of viral RNA and viral spike protein. The COVID-19 FET sensor for spike protein recognition relies on integrating a graphene-based SARS-CoV-2 spike antibody, while the GFET sensor is used for viral RNA recognition via bio-CRISPR/Cas technology.

6. Current advancements on the potential approaches to protect against COVID-19

A person who gets COVID-19 is unlikely to be treated as there are no standard treatments for COVID-19. Thus, it is important to adopt effective prevention approaches to avoid virus infection and transmission [106]. The COVID-19 protection approaches are:

1. PPE Kits and Masks
2. Disinfectants and Sanitizers
3. Air filtration and purification
4. Vaccination

In the following sections, the current advancements in the potential approaches are discussed in detail.

6.1 PPE Kits and Masks

Considering the diverse modes of COVID-19 transmission, one of the effective prevention strategies is by applying personal protective equipment (PPE). PPE is usually used by healthcare frontliners [107]. Different types of PPEs such as aprons, gloves, eye protection, surgical face masks, gowns, nonpowered filtering facepiece respirators (FFRs), and powered air-purifying respirators act as physical protection from the infectious particles present in human fluids [108, 109]. The objective of the application of PPE is to provide complete protection for frontliners (doctors, nurses, other healthcare workers) from the deadly spread of this virus [108].

The size of the COVID-19 virus is between 70-90 nm in diameter. Nevertheless, coughing and sneezing usually produce Flügge droplets that are below 5 μm in size, and the virus can
move up to 4.5 m. WHO has suggested that when handling any aerosol-generating procedures (AGP) on an identified COVID-19-positive patient, workers are recommended to use an American standard N95 or European standard FFP2 mask [110, 111]. Both of the masks work well as PPE [6]. Public health England (PHE), on the other hand also suggested on using an FFP3 mask a the similar case [110]. Surgical masks are good in preventing spray and inhalation of droplets in the 5 m range, but their ability to filter submicron-sized droplets is restricted [111]. N95/FFP2 masks are at 95% minimum efficiency for particles with a size of 0.1 to 0.3μm, and 99.5% or higher efficiency for 750 nm or bigger size particles [110].

**Table 4 and Table 5** respectively illustrates the comparison between two types of masks which are the surgical mask and N95 respirator and the latest graphene and graphene-based fabrics for smart and PPE cloth fabrication utility that exhibit efficient properties.

**Table 4.** Comparison between a surgical mask and N95 respirator [112, 113]

| Structure                  | Surgical Mask                                                                 | N95 Respirator                                                                 |
|----------------------------|-------------------------------------------------------------------------------|-------------------------------------------------------------------------------|
| Structure                  | -Consist of very fine middle layers with additional fine glass fibers covering| -Consist of hydrophobic nonwoven PP outer layer construction to avoid moisture |
|                            | both sides by acrylic bonded parallel-laid or wet-laid nonwoven material      | -Comprise of a melt-blown nonwoven PP filter layer to trap oil and non-oil-based particles |
|                            |                                                                               | -Possess a support layer and an inner layer                                  |
| Ability                    | -Resistant to fluids                                                         | -More protection against airborne particles than surgical masks               |
|                            | -Protection against large droplets, sprays, and splashes                      | -Filter large and small particles including aerosols                        |
|                            | -Trap the user’s respiratory droplets and avoid contamination to the patient  |                                                                                |
| Testing and Approval       | Cleared for use in medical settings by the Food and Drug Administration (FDA)| National Institute of Occupational Safety and Health (NIOSH) has evaluated, tested, and approved to ensure that the filtering facepiece can remove at least 95% of airborne particles |

**Table 5:** The fabrication of smart and PPE cloths derived from graphene and graphene-based modified fabrics with efficient properties.

| Materials                        | Techniques                          | Improved material properties                  | Applications    | Ref.  |
|----------------------------------|-------------------------------------|-----------------------------------------------|-----------------|------|
| Para-aramid/graphene/Polyurethane| Para-aramid was enfolded by graphene/waterborne polyurethane via immersion and drying method. Then, under distinct temperatures, the prepared composites were hot pressed. | Cleaning durability                           | Protective wear | [114] |
| PET/Graphene                     | Compression molding and melt compounding (Brabender mixer).                   | The electrical conductivity was enhanced remarkably. | Smart PPE       | [115] |
| Nylon-12/GO                      | Soften compounding and compression molding                                     | Tensile strength, improved bearing             | Protective wear | [116] |
| Method | Preparation Method                                                                 | Properties                                                                 |
|--------|------------------------------------------------------------------------------------|----------------------------------------------------------------------------|
| Fe, N-doped-Cotton/GO/TiO₂ | Dispersed, hydrothermal method, by immersion and coating method, the TiO₂/Fe/N/GO was dried and smeared over to the textiles | Self-compatible, biologically compatible and great antimicrobial activity Fighting uniform, medical apron and sporting garments. |
| Polyester/rGO | With the assistance of plasma treatment and bovine serum albumin as a bonding agent | Boost Conductivity Smart fabrics |
| Silk/rGO | The silk material was bound by GO via dip and dry method. Then, treated fabrics were chemically reduced by sodium hydrosulfite. | Superior electrical conductivity, water repulsive and antiultraviolet nature Medical cloth and E-textile |
| Silk/rGO/bovine serum albumin (BSA) or re-modelling and spacing factor 1 (RSF) Protein | Silk fabric was wrapped with GO Suspension using the dipping approach. BSA and RSF protein was used as a bonding agent. It was further condensed by thermal treatment. | Excellent electrical conductivity Smart fabrics |
| PET/rGO/polypyrrole | Polypyrrole was coated on PET/r-GO fabric via in-situ synthesis. The chemical reduction method along with dip and dry method was employed to combine the PET with GO. Finally, the composite was hot pressed to make a film. | Surface chemistry and extraordinary soaking ability Shielding clothing |
| Wool/rGO/TiO₂ | GO/TiO₂ was immersed with wool, where the hydrolysis of titanium isopropoxide and the chemical conversion with the assistance of sodium hydrosulfite took place to form graphene/TiO₂ nanocomposite. The composite dried out and condensed by chemical route. | Excellent antimicrobial activity and self-cleaning ability Smart fabric and medical care cloths |

During the pandemic, new technologies and innovations were demonstrated. Graphene technology has the potential to produce new creations of personal protection equipment and new medical solutions [122]. Graphene and its derivatives are utilized to create and evolve multifunctional materials to prevent and control coronavirus [107]. However, this review focuses on graphene technology to improve existing COVID-19 protection kits. Recent developments in the manufacture of two-dimensional graphene and graphene oxide (GO) can produce highly useful PPE and masks to protect from SARS-CoV-2 infection [123]. Applying antiviral graphene coating to PPE can improve its protective
qualities [107]. Thus, advanced technology in graphene and GO has become promising for highly functional PPE [123, 124]. Graphene is commonly employed as a coating material for woven and non-woven PPEs due to its fire-resistant and UV-resistant, lightweight, and conductive properties. These features are particularly useful in developing PPE materials [124]. The ability of GO to interact with microorganisms has also led to the designation and development of PPE textiles used to restrict COVID-19 spreading as well as inactivate the virus [123]. The oxygen groups in GO enhanced surface hydrophilicity and initiated interactions with organic molecules. The application of hydrophobic graphene into PPE against SARS-CoV-2 can be seen in Figure 10. The graphene derivatives can also destruct the SARS-CoV-2 membrane by the adsorption of charged lipids [125]. The researchers believed that under the Scanning Electron Microscopy (SEM) visualization of the graphene and GO functionalization on both cotton and polyurethane materials, these materials are highly applicable PPE materials.

![Figure 10: Configuration of hydrophobic graphene materials against SARS-CoV-2 [123].](image)

The integration of graphene and GO in masks with cotton and non-woven, polyurethane (PU), and polypropylene [124] non-woven materials, have resulted in virus filtrations and an almost complete elimination of SARS-CoV-2 infectivity. The graphene functionalized masks have also shown antibacterial effects [123]. There is also a development for potential virucidal composite ink, which is graphene-based, that is utilized in fabrics such as N95 face masks and other PPE. The graphene ink was started by the UK-based Graphene Composites Ltd (GC) to fight COVID-19 to increase the protection for fabrics used in N95 face masks and PPE. This is also believed to provide safety for frontline workers and hospital
Ramaiah et al. presented implementing graphene-based materials to create unique masks and germ trap technologies. For example, Nanene and Polygreen are graphene-integrated face masks that supply useful antiviral and antibacterial characteristics. These four layers (graphene outer protective layer, polypropylene non-woven fabric, melt-blown (MB) fabric, outer shell, cotton filtering layer) fabric masks could reach 95% of filtration efficiency and can provide the wearer, protection against viral particles and air-borne bacterial [124].

The development in mask technology also includes 3D printing in mask fabrication. An example of a 3D-printed distinctive film known as ‘Maya sticker’ is attached to a face mask to improve their protective capabilities. Maya stickers possess nanoscale fibers coated with disinfectants which enlarge the nanoscale particles neutralization and trap as can be seen in Figure 11 [111]. There are also studies on applying 3D printing to customize face masks, such as the Copper 3D NanoHack mask [7, 126]. In the future, studies and research on graphene can be made to produce graphene-based 3D-printed add-ons for face masks.

![A SIMPLE SURGICAL MASK WITH ADD ON PROTECTIVE LAYER AGAINST COVID-19](figure11.png)

**Figure 11:** Surgical mask with add on 3D protective layer [111].

Furthermore, Goswami et al. fabricated a functionalized graphene (fG) filter-based 3D-printed facial protective equipment. The functionalized graphene was coated on the masks with air filters and was installed in a 3D-printed facial mask replica. Functionalized graphene is applied over a polypropylene (PP) cloth to intensify its antimicrobial and antiviral properties. The fG-coated filter's efficiency was evaluated against SARS-CoV-2 viral particles, and it has been shown that viral transmission is completely stopped at the fG-coated layer. Figure 12 shows the four layers of a stacked air filter. The multiple layers stacking improved the stopping of droplets penetration. The fG-coated filter in the middle is used in
the prevention against micro-organisms and small particulates by holding it within the mask [46]. The graphene interacts with viruses directly, primarily through hydrogen bonds, electrostatic interactions, and redox reactions. Illustrated in Figure 13 are different types of masks namely surgical mask, N95 respirators, FFP2 respirators and 3D printed mask respectively. Moreover, depicted in Figure 14 are the filtering efficiency of graphene-based face masks in terms of electrostatic influence, electrothermal effect, nano-porous membrane and photothermal activity [127]. Lastly, illustrated in Table 6 are the commercially available graphene and graphene-based facemask along with its superior properties.

Table 6: The commercially available graphene and graphene-based facemask respectively.

| Product Name                | Fabricated by                                             | Antibacterial agents                         | Product efficiency                           | Observations                                                                 | Ref. |
|-----------------------------|------------------------------------------------------------|-----------------------------------------------|----------------------------------------------|-------------------------------------------------------------------------------|------|
| Maya sticker                | National Emergency crew of Israel and Israel Institute of Technology | Nanofibers glazed with disinfectants          | Blocks and diminish the effect of viral Debris. | This label can be involved in ordinary surgical face guises for utilization. | 96   |
| Graphene enhanced face mask | Planar TECH & IDEATT's 2 a.m. (UK) and Thailand            | Graphene and other carbonaceous-based materials | Within 24 hours, it was observed to be 99.95% effective against S. aureus. | Reusable up to 10 cycles, repels the PM 2.5 dust. A pack of three masks is available at US $ 24.95 | 94   |
| Nsafe+                      | Nanoscale solutions and Indian Institute of Technology Delhi (India) | -                                             | -                                            | Antimicrobial layer on the mask with Triple-layer filtration. The best filtration efficiency was observed to be approximately 99.2%, as much as 50 times recyclable affinity. | 97   |
| Leaf                        | Redcliffe Medical Devices Inc. (US)                        | Ultraviolet C (UVC)                           | Discount of influenza A Virus approximately 99.99% | FDA cleared UVC N99 to face mask, HEPA and vigorous carbon filters, 99.9997% filtration ability of 0.3 mm size | 95   |
| Guardian G-Volt             | LIGC Applications (US)                                     | Graphene and electrical Charge                | -                                            | Deposited particles were repelled by electric charge. It was found to be 99% effective towards the 0.3 mm particles. | 93   |
**Figure 12:** PP cloth stacking order for fG-coated mask fabrication [128].

**Figure 13:** Schematic model illustrates (a) Surgical mask (b) N95 respirators (c) FFP2 respirators (d) 3D printed mask respectively.
**Figure 14:** Schematic model of the filtering efficiency of graphene-based face masks: (A) the microorganisms are trapped by the graphene materials via the electrostatic force, (B) the electrothermally active graphene face masks effectively restricts the entry of inactive harmful viruses, (C) graphene membrane destroys the protein envelope of the virus in presence of IR radiation and (D) the average diameter of graphene nanopores is smaller compared to the size of SARS-CoV-2 virus respectively [127].

### 6.2. Sanitizers and Disinfectants

Disinfectants are used widely in sterilizing areas and surfaces. The tendency of a disinfectant to kill microbes is determined by the chemical’s mode of action, the pathogen’s surface molecular structure and intracellular vulnerability [129]. The SARS-CoV-2 virus can live on different types of surfaces for periods ranging from a few hours to a few days, and contaminated surfaces have been discovered to be the virus’s second most common mode of transmission. Disinfectants and sanitizers are important protective alternatives to coronavirus [130].

The U.S. Environmental Protection Agency (EPA) is the agency that updated the disinfectants used for COVID-19 prevention. The hypochlorite-based products involve the sodium hypochlorite liquid, and calcium hypochlorite solid or powder formulations. The
synthesis of this formulation in water will form a dilute aqueous chlorine solution and hypochlorous acid (HOCl) which is undissociated, active as the antimicrobial compound. At various concentrations, hypochlorite shows wide antimicrobial activity and is efficient against a variety of pathogens. The suggestion of 0.1% (1000 ppm) conservative hypochlorite concentrations are required for the COVID-19 context to stop many other pathogens in the healthcare setting. COVID-19 disinfectants are more encouraged to use and effective with fabric or wipes which have been immersed in disinfectant compared to spraying or fogging. Spraying disinfectants can even be harmful to human health [131].

The common surface disinfectant only gives a temporary result and is not advised for long-term use due to their irritation, toxicity, and also quickly evaporates [107, 131]. However, in the current pandemic situation, developing effective anti-SARS-CoV-2 coatings/surface disinfectants play an important role in controlling the viral spread of COVID-19 [54, 131]. For example, disinfectant sprays such as virucidal chemicals give unfavorable effects and have toxicity properties. Sodium hypochlorite and hypochlorous acid, on the other hand, leave residue and are corrosive to certain metallic surfaces.

The SARS-CoV-2 virus has a structure that is rich with -COOH functionalities and a short lifetime on copper surfaces. The surfaces of copper are reported to have anti-pathogenic performance [54, 132]. No living COVID-19 could be observed on copper alloy surfaces after four hours of exposure [63]. Thus, GO/rGO-SO$_3$ coatings refined with copper nanoparticles/copper ions can be promising to develop anti-SARS-CoV-2 surfaces and inactivate the SARS-CoV-2 viruses [37, 129]. Other nanohybrids of GO/rGO-SO$_3$ based doped with Ti, Ag, and Au can also be suggested for the fabrication of antiviral coatings. Such materials ideally capture and disrupt the viral particles and reduce their chance to survive when found on the antiviral coatings [132].

Recently, nano-graphene oxide (nanoGO) is one of the graphene derivatives which has gotten a great interest in this field. Chung et al. have studied the antiviral properties of GO towards coronaviruses (Alphacoronavirus and Betacoronavirus) in a high organic materials presence (5% FBS). This study has shown the nanoGO’s antiviral activity in a partially mimicked biological fluid setting [133]. There is also a study on disinfecting the masks for reusing purposes to overcome the global shortage of PPE masks. The exposure of hydrogen peroxide vapor was used as a technique to disinfect N95 masks and powered-air purifying respirators (PAPRs) masks. The study found that the N95 respirators retained their filtering effectiveness
even after 50 disinfection sessions [111]. A similar approach from Smart tech hygiene company, Cleanbox Technology, with its product, Clean Defense was used for the thorough decontamination of N95, cloth, and other layered masks. The patented technology utilized UVC lights to decontaminate the masks Clean Defense has been studied on Sars-CoV-2, removing the COVID-19 virus at 99.999% on all three layers of the mask in seconds [111, 134].

6.3. Air filtration and purification

Air filters have the ability in removing air pollutants and enhancing indoor air quality. In filters, normally fiber, super fine glass fiber, film compound, and electret materials are utilized for high-efficiency filter materials, while glass fiber and activated carbon fiber are utilized as the primary and mid-efficiency materials for filters [135]. On the other hand, air purifiers normally contain multiple filters and a fan. The fan is responsible in drawing in ambient air and sends it through the filters, and then circulates the clean air back into the room [136]. Other than being useful in removing air pollutants, a specified air purifier can also be useful in preventing COVID-19 virus transmission. For a virus that can be transmitted through airborne droplets and aerosols [137], the centers for disease control and prevention (CDC) mask and testing has suggested for a good room ventilation by applying air purifiers. This can produce a reduction in the quantity of infectious particles in the air as well as good protection from SARS-CoV-2 indoor transmission between persons. One of the air purifiers which can prevent COVID-19 transmission is by applying the high-efficiency particulate air (HEPA) filter/purifier [137, 138]. In addition, in terms of HEPA air filter/purifier, common HEPA filters are constructed by folding microfiber glass or other fibrous media which made from several layers of randomly oriented fibers with their diameter size from 2 nm to 500 nm [47] [139].

HEPA media is normally under 0.508 mm thick and made up of few hundred fibers layers to restrict the penetration of particles [140]. They are utilized to filter air particulate, pollen, dust, mold and bacteria [141]. Van der Waals forces, electrostatic attraction, and capillary action can all contribute to filter fibers adhesion. Figure 15 illustrates HEPA capturing and filtering airborne particles (from 0.01 micron to 10 microns) [140]. The different processes which occur are depending on their sizes. Large particles will be incapable to penetrate through the fibers openings and will directly trapped. The smaller size particles will get captured in one of the three methods: impaction, interception and diffusion [141]. A high-
quality HEPA-based air purifier could remove 99.97% of contaminants from the air, including the coronavirus-spreading respiratory droplets (particles larger or smaller than 0.15 microns). The particle size of SARS-CoV-2 which reported to be 0.06 to 0.14 microns falls within the HEPA filters capturing efficiency. Even though not yet fully tested, the CDC has suggested in using HEPA filters in powered air purifying respirators for a highly efficient filtration of the SARS-CoV-2, abased on SARS-CoV-1 studies [139].

HEPA filters are well known for their application in medical and industrial buildings. They are utilized to filter air particulate, trap air-borne pathogens and are believed to have the capability in filtering the SARS-CoV-2. The particle size of SARS-CoV-2 falls within the HEPA filters capturing efficiency, which is 0.01 micron and more. A high-quality HEPA-based air purifier could remove 99% of contaminants from the air, including the coronavirus-spreading respiratory droplets. They can trap the virus, by using a high voltage to produce and release negative ions charge into the air. The negative ions will work by sticking to the virus and kill them [136].

Figure 15: HEPA capturing and filtering via diffusion, interception, and inertial impaction process [141].

Interestingly, carbon-based materials such as GO has been employed broadly in the fabrication of air filters due to its extraordinary features namely unique construction, superior anti-microbial performance, and excellent mechanical and chemical stability respectively.
Illustrated in Table 7 are the roles of GO for the fabrication of effective air filters [52-54, 56-57].

Table 7: Summary of the significance of GO for the fabrication of effective air filters.

| Materials                          | Microorganism/Pollutant       | Results                                                                                      | Ref.  |
|------------------------------------|-------------------------------|----------------------------------------------------------------------------------------------|-------|
| Functionalized graphene            | SARS-CoV-2                    | The filtration efficiency was observed to be at 98.2%                                         | [142] |
| Polyacrylonitrile and GO           | Particulate matter 2.5        | After exposing the polyacrylonitrile/GO filter in a medium with approximately 460 μg/m³ of particulate matter 2.5, the removal efficiency was reported to be 99.6%. Moreover, after 100 hrs, the removal efficiency was maintained 99.1%, thus, revealing exceptional sorption ability and long-term stability. | [143] |
| Polyacrylonitrile/GO/polyimide     | Particulate matter 2.5        | An exceptional mechanical strength, high thermal stability of 300 °C, high filtration efficacy of 99.5 %, and low pressure drop of 92 Pa were exhibited by the prepared air filter membrane. | [142] |
| GO/Silver nanoparticles/polyacrylonitrile | S. aureus and E. coli       | The bactericidal properties, adsorptive and mechanical stability was observed to remarkably enhanced with the presence of silver nanoparticles and GO fillers. | [144] |
| Ultra-thin GO/polydopamine hybrid on the surface of polypropylene | Airborne pathogens       | The resultant filter significantly improved the protection and antimicrobial performance. | [49]   |

7. Challenges and future perspectives

Globally, the outbreak of the current pandemic crisis has urged scientists to think out of the box in order to develop novel strategies and to have a strong collaboration between laboratories with different background mainly to battle against the spread of COVID-19. Furthermore, since unexpected issues require unexpected solutions, the current best weapon to combat the COVID-19 is via the development in research and technology. Therefore, in this review article, we propose that graphene-based nanomaterials is a promising candidate since it offers innovative solutions from antiviral activities up to biomedical research due to their fascinating physical and chemical properties respectively. In other words, graphene-based tools should be employed for decontamination, diagnosis, detection and prevention from this disease. As discussed above, to fight against this virus, numerous graphene-based products have been developed. For instance, graphene can be fabricated as a decontaminating agent either in the form of lotion or gel to kill these viruses. Alternatively, graphene coated
wipes can also be potentially used to disinfect the objects surfaces. Additionally, the mist spray that is generally utilized to sanitize human body can also be used to clean any surfaces. Interestingly, the conjugation between graphene based nanodrugs and antivirals can be a successful formulation and effective.

On the other hand, in order to restrict the aerosol transmission into various infected areas including the hospitals, graphene coated PPE is essentially required. Also, to efficiently filter clean the SARS-CoV2 and various other respire gems that present in air, it is vital to prepare air-conditioning and air-purification machines which have built in multi-layered graphene-based layers with modified positive charge filters. Furthermore, by tuning their interlayer spacing and microstructural properties, it is possible to separate COVID-19 virus from water by utilizing graphene-based filter membranes. Moreover, graphene based photocatalyst can also be fabricated to degrade and inactivate COVID-19 virus in water directly. With regards to this statement, several investigations related to the photocatalytic inactivation of microorganisms have been reported, for instance, it has been revealed that the photocatalyst is a suitable candidate as a good disinfectant against pathogens, which not only destroy them but also the photocatalyst can be utilized as sterilization respectively [7].

In addition, the significant results exhibited by graphene-based nanomaterials as sensors to detect COVID-19 point towards a promising future. However, it is essential to exploit the approaches involved in the development of graphene with other two-dimensional materials, which will offer a wider choice of physical and chemical properties towards designing new sensors. Previously, various of the strategies proposed involved the usage of noncovalent chemistry to immobilize large biomolecules on the flat surface of the two-dimensional materials. At the same time, before introducing these sensors to the market industry, the reproducibility during production at a large scale and the stability of the devices over a period of time are some of the key components that needs to be evaluated accordingly. Moreover, it is vital to ensure the versatility of the sensing platforms so that it will have the capability to adapt to the possible mutations of these viruses. On the other hand, in the drug delivery system, it is important to consider long term perspective of the applications of graphene-based nanomaterials and other common hard nanomaterials respectively. Therefore, there is need for a deeper understanding on the antiviral efficacy and multifunctional strategies. Furthermore, there are many thoughts related to the biocompatibility and long term toxicity of two-dimensional materials, for instance, despite various studies being reported previously, there still lies an unclear picture on the toxicological risks of graphene related materials [10].
Up to date, several types of hard nanomaterials have been clinically approved to treat human, however, we are also hoping that in the future, some of the graphene related nanomaterials will also be used for human treatment [10]. Even though graphene-based nanomaterials have revealed excellent results, these materials have only marginally explored in viral infections and their other capability has been unleashed yet in terms of their potential in inhibiting viral replication, blocking cell uptake and alerting the immune system respectively. In short, a lot more work is required to address these specific requirements concerning several exciting and challenging applications in antiviral, drug delivery and biomedical sciences respectively.

Currently, despite knowing the fact that graphene-based nanomaterials are a promising candidate to combat against the COVID-19, in our opinion, it is equally vital to explore other types of two-dimensional materials namely covalent organic frameworks, metal organic frameworks, transitional metal dichalcogenides metal carbide (MXene), etc. In other words, due to their fascinating properties such as large surface area, mechanical robust, high affinity for guest materials, good conductivity, layered structure and flexibility, the versatile family of the two-dimensional materials could perhaps be an ideal platform against the SARS-CoV-2 virus. Last but not the least, in the process to battle against the current COVID-19 and future pandemics, we can foresee a bright future for graphene-based nanomaterials provided if more significant efforts are being devoted to theoretically and experimentally modulate such unique materials via controlled functionalization and to explore the most suitable material with graphene and other two-dimensional materials for ideal properties.

Despite their advantages, the nanotechnology-based systems also face various obstacles before they can be safely introduced to the market. Therefore, before being widely adopted in the healthcare system, it is vital to address some bottlenecks associated with the nanotechnology applications. For instance, it is essential to ensure the safety of the nanomaterial via in-vitro studies of their biocompatibility, whereby the due to the formation of protein corona, the fate of the nanomaterials can be changed into the body specifically when they travel through the blood stream [145]. Hence, in order to obtain a detailed understanding of the nanoparticles toxicity in the body, the in-vivo studies need to be executed very carefully [146]. Due to the limitations, at an early stage of research, generic protocols have been introduced and implemented for categorization and development which will result in minimizing the chances of failures associated with the clinical translation of nanotechnology based therapy [147]. On the other hand, it is essential that all regulatory agencies, toxicology, scientific experts in material science and pharmacology to have a closer
collaboration in order to overcome other related limitations. Furthermore, as far as toxicity of nanoparticles is concerned, it is related to their distribution in the lymph streams and bloodstream and their ability to penetrate through almost all tissues, organs and cells as well as to interact with different macromolecules respectively. The functioning and structure of the organs can be altered by the toxicity of the nanoparticles. Also, it is important to understand that the body defence system does not recognize specific types of nanoparticles, thus, resulting in the accumulation of nanoparticles in the tissues and organs which then leads to high lethality or toxicity respectively. In other words, rather than using the currently available traditional nanoparticles, the appropriate solution is to design nanoparticles with a lower toxicity. Therefore, there is a need to develop more advanced approaches and research to investigate the toxicity of nanoparticles and also to analyse different pathways and mechanism of toxicity at molecular level [148]. To support this statement, the design of nanoparticles was investigated by Campos et al. which had very small or no negative effects. Here, it was revealed that it was significantly impossible to investigate such nanoparticles unless all quantitative and qualitative physical and chemical properties of nanoparticles were systematically taken into consideration and a relevant experimental model to estimate their influence on biological systems is available [149].

From the future perspective point of view, the nanoparticle-based medicine is a promising candidate to potentially reduce the burden of illness. Due to their distinctive properties namely lower cost, size, simple preparation, effortless modification, etc., the significantly smaller nanoparticles (< µm) have received remarkable attention in combating the COVID-19 disease. Currently, to battle against this virus, there are several nanotechnologies-based approaches which include the innovation of tools for sensitive, speedy and precise diagnosis of SARS-CoV2 infection, delivery of antiviral drugs into host, efficient delivery of mRNA-based vaccines into human cells and the development of efficient disinfectants respectively. On the other hand, even though there has been significant research work done on nanotechnology-based tools to combat COVID-19, there are still various challenges present which needs to be addressed. For instance, the combination therapy by using nanoparticles as a delivery system, nanomaterial based disinfectant agents to kill pathogens, potential use of nanomaterials to avoid the conventional restriction related with antiviral drugs and early, rapid, exceeding sensitive, portable and reasonable development of diagnosis kits as well as the development of nanoparticle-based vaccine to battle against the SARS-CoV-2 and other pathogens respectively. In addition, as mentioned above, cell toxicity, immunotoxicity,
genotoxicity fibrosis, oxidative stress and inflammation respectively are some of the drawbacks associated with nanoparticles which needs to be solved before it is being implemented. Hence, in our opinion, via the utilization of nanotechnology-based strategies, we predict that many advances will be soon accomplished in terms of diagnosis, therapy and treatment of COVID-19 virus. For instance, nanotechnology-based tools can be used to treat this virus and the emerging pathogens, whereby via the utilization of nanotechnology based therapeutic antibodies (e.g., mRNA or protein-based vaccines), the active drugs are then specifically delivered to the host targeted organs, thus resulting in a rapid detection of the viruses present in a human body. Last but not the least, the ultimate challenge for the near future that requires a solution is to identify approaches to transfer nanomaterial technology to actual clinical applications as well as the feasibility of production on a large scale.

8. Demand aspects of graphene-based products

Globally, with the outbreak of the SARS-CoV-2 virus, this has resulted in the opening of a vast gateway for research and leading to the inventions of new materials and techniques along with the advancement in technology to battle against the pandemic. Interestingly, the mother of all carbon allotropes, graphene, and its derivatives, have emerged as a wonder material to battle against the virus. Due to their unique features such as excellent properties, small size and high anti-microbial efficacy, graphene and its derivatives have gained much spotlight to be explored for the detection, prevention, and treatment of SARS-CoV-2 virus [155] [150]. Furthermore, the commercialization of graphene advancements in the field of semiconductors, electronics, aeronautics, etc, have been widely reported in various studies, whereby more than 50% of the advancement involves graphene and graphene-based materials. In addition, with the outbreak of the SARS-CoV-2 virus, this has resulted the demand of graphene to increase drastically in the healthcare sector, whereby it has been estimated that by 2027, a 39% annual growth rate will be experienced by the graphene market and a market size of USD$ 2864 million will be achieved [150]. In short, by using graphene-based materials, a variety of facemasks, biosensors, prophylactic, SARS-CoV-2 diagnosing kits, etc., have been developed by many top-tier companies globally, however, a significant amount of research is still required to be conducted for mature market handling. On the other hand, besides the urgent demand for vaccines to battle against the COVID-19, the market monitoring of graphene-based materials should be carefully proceeded. For instance, before being released into the market, the limitations such as the instability or the quick aggregation properties of graphene needs to be properly addressed first. Since the graphene market is
expected to increase due to this COVID-19 outbreak, therefore, it is mandatory that the cooperates frequently check and consider the risks and opportunities of graphene in the market [150]. Moreover, it is important to understand that the finance system can be affected by the impact of SARS-CoV-2 on prices, commodity, supply chains, etc., hence, various alternatives and backup strategies should be planned and prepared by the corporates to address future issues. In addition, in the fields of electronics, a loss of market was observed as the COVID-19 affected the transportation and demand of graphene [151]. However, globally, the sales and the demands will eventually increase rapidly with the increase in the productivity of graphene-based materials, thus, resulting the overall import and export of graphene and its derivatives to significantly increase. Finally, in the pandemic era, the increase in graphene and graphene-based materials stocks will benefit the economy of a country.

9. Conclusion and Outlooks

Worldwide, the COVID-19 pandemic has resulted to an unprecedented loss of human lives and economy. Therefore, there is urgent need of collaboration from the medical industry, engineers, scientists, and physicians to battle this global threat of SARS-CoV-2 virus and to custom a strong response to tackle and overcome such phenomena in the future. Moreover, global commitments from all countries, interdisciplinary collaborations, government organizations, WHO, etc. are essential to support, raise sufficient funds and to strengthen the research and development in science and technology respectively. Interestingly, for future advancements, graphene-based technology has proven to be a promising tool to diagnose, prevent and treat numerous emerging and remerging diseases. As mentioned previously, despite the extremity of treatment and vaccines needed for COVID-19 combined with the shortage of a complete toxicity characterization make an in vivo use farther off that what we expected, there are still other opportunities to exploit graphene and its related materials to fight against the COVID-19. Moreover, GO has showed antiviral properties towards coronaviruses in a high organic materials presence (5% FBS) in a partially mimicked biological fluid. The lipid bi-layer of feline COVID-19 can be adsorbed on the GO surface via hydrogen bonding and electrostatic interaction and the viral membrane destroyed by the binding of the GO confirmed the efficiency of GO against the viruses. Graphene sensors that can be used to detect SARS-CoV-2 are photoluminescence, colorimetric sensors, and SPR biosensors. Moreover, WHO continuously highlighted the importance of PPE supplies for frontline health workers, thus, strongly recommending the utilization of graphene
coatings facemasks to reduce the risk of transmission. GO have been employed broadly in the fabrication of air filters due to its extraordinary features namely unique construction, superior anti-microbial performance, and excellent mechanical and chemical stability. In short, this review article summarizes the current state of knowledge of graphene and its related materials, and the importance of the research and development associated with technology to battle the COVID-19 pandemic respectively.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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