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Potential of graphene based photocatalyst for antiviral activity with emphasis on COVID-19: A review

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ABSTRACT

Coronavirus disease-2019 caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has been one of the most challenging worldwide epidemics of recent times. Semiconducting materials (photocatalysts) could prove effectual solar-light-driven technology on account of variant reactive oxidative species (ROS), including superoxide (\(\text{O}_2^\cdot\)) and hydroxyl (\(\text{OH}\)) radicals either by degradation of proteins, DNA, RNA, or preventing cell development by terminating cellular membrane. Graphene-based materials have been exquisitely explored for antiviral applications due to their extraordinary physicochemical features including large specific surface area, robust mechanical strength, tunable structural features, and high electrical conductivity. Considering that, the present study highlights a perspective on the potentials of graphene based materials for photocatalytic antiviral activity. The interaction of virus with the surface of graphene based nanomaterials and the consequent physical, as well as ROS induced inactivation process, has been highlighted and discussed. It is highly anticipated that the present review article emphasizing mechanistic antiviral insights could accelerate further research in this field.

1. Introduction

The new strain of coronavirus disease 2019 (COVID-19), caused by novel severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) was recognized in Wuhan, Hubei Province, China [1]. The new SARS-CoV-2 are more contagious than SARS-CoV and middle east respiratory syndrome (MERS-CoV) viruses [2]. Mainly, the virus is transmitted either through respiratory droplets from cough and sneezes that enter the air in the form of an aerosol or when comes in contact with the contaminated surfaces [3,4]. However, keeping any one of these underlying co-morbidities (hypertension/cardiovascular disease and diabetes) or immunocompromised persons, are more prone to underlying co-morbidities (hypertension/cardiovascular disease and diabetes) or immunocompromised persons, are more prone to underlying co-morbidities. In January 2020, the complete genome sequence of SARS-CoV-2 was determined [8]. The SARS-CoV-2 is accompanied by four viral proteins with different functions such as spike protein (S protein) (link the virus to the host cell), membrane protein (M protein) (regulates the shape and size of the cell), nucleocapsid protein (N protein) (gives a response to the host cell and engages in the replication cycle), and envelop protein (E protein) (hydrophobic viroporins) (Fig. 1) [9–11]. The viroporins outermost layer is a lipid (a constituent of hydrophobic phospholipids) which enabled the interaction with the host cells [12]. Knowing the possible interaction of the S protein with other materials is beneficial to get an idea of how SARS-CoV-2 transmission takes place and which material could be used as an efficient protective barrier [13]. Recently, nanomaterials with antimicrobial features (nano-antimicrobials) exhibit an imperative role in the protection against these be connected with herbal medications [6,7].
pathogenic viruses. In recent studies, two-dimensional (2D) materials particularly graphene-based materials, including, graphene oxide (GO), nanoporous graphene, reduced GO (r-GO) have attained great interest in desalination, water sterilization, photocatalytic disinfection, ultra-and nano-filtration, and many biomedical applications [14–18]. Interestingly, graphene and its derivative with antiviral characteristics display potential in the inactivation of viruses due to their high electrical conductivity and movement, specific surface area, outstanding electrochemical, piezoelectric, and mechanical characteristics [19–23].

In the mechanistic action of graphene-based materials against viruses, three mechanisms, including oxidative stress, phospholipids, and generation of reactive oxidative species (ROS) (such as superoxide radicals \( O_2^- \)) are widely reported [24]. In addition, other mechanism includes mechanical wrapping, photothermal ablation, and the surface interaction of the graphene’s sharp edges with cell membranes, resulting in cell lysis [25,26]. These antiviral actions occur at three steps (i) binding of a virus on the graphene surface (ii) membrane stress when in contact with sharp edges nanosheets, and (iii) superoxide anion-independent oxidative [27]. Furthermore, the oxidative stress mechanism produces ROS, which further invades the nucleic acids (RNA and DNA), lipids, proteins, and other essential components in the virus. Initially, the damage of enveloped virus induces from the interaction of GO with the outer wall, leading to efficient ROS production and virus inactivation [25].

A recent study by Palmieri and Papi, recognized graphene filters and textiles as the best candidates in monitoring the rapid spread of COVID-19 and for the development of environmental filters and sensors along with huge population screening, owing to its cost-effectiveness [28]. However, the preparation procedure of graphene is relatively expensive and complex. Thus, the preparation of biomass-derived graphene has proved a more effective alternative over other methods which involve the utilization of toxic precursors and solutions and are employed in the fight against COVID-19 [29–31]. Also, GO-based materials have been reported as an optical biosensor in textile applications and virus detection [32,33]. Cordaro et al. reported the contribution of graphene materials in COVID-19 virus diagnosis and discussed the detection strategies in virus and liquid biopsy [34]. Till date, most of the studies are emphasized on the potential of graphene-based materials in virus diagnosis, prevention, and usage of personal protective equipment [35]. Considering that, the present review article aims to deliver all-inclusive information on potentials of graphene based materials to combat COVID-19. Starting from the structural complexities of SARS-CoV-2, a perspective on photocatalytic viral inactivation via graphene based materials are presented. The fundamental mechanism of photocatalytic viral inactivation with an emphasis on significant features of graphene based materials as antiviral agents are also discussed. Moreover, the possible surface interaction between graphene materials with viruses and the inactivation phenomenon from generated ROS has been elaborated. Lastly, a summary highlighting major challenges accompanying viral inactivation phenomenon are mentioned.

2. Potential of graphene based materials in photocatalytic virus disinfection

The semiconducting materials have been used in the inactivation of various pathogens including viruses, and harmful bacteria. Sametband and co-workers in 2014 studied the antiviral activities of graphene oxide (GO) and moderately condensed sulfonated GO in addition to its inhibition mechanism to fight with Herpes Simplex Virus Type-1 (HSV-1) [36]. The sulfonated reduced-GO (rGO) and GO are accompanied by negatively charged species as like in receptor heparan sulfate cell, resulting in a competition of both moieties in binding mechanism with HSV-1. The results demonstrated that graphene nanomaterials blocked the binding sites by acting as an inhibitory agent to defense Vero cells from infection. Normally, the cell inactivation by photocatalyst proceeds through sterilization, growth inhibition, endotoxins degradation in the cytoplasm, and inactivation of secondary metabolites or genetic materials like amino acids, proteins, lipids, nucleotides, polysaccharides, lipopolysaccharides, and ribonucleic acid (RNA), and deoxyribonucleic acid (DNA) [24,25,37].

Notably, the microorganisms are composed of the outer cell membrane, peptidoglycan, and cytoplasmic membranes which maintain the integrity and retention of cell structure [38]. The internal liquid-based cytoplasmic matrix comprising genetic materials and biochemical mechanisms is enclosed by membranes. Therefore, based on the complexity in cell structure possessing different constituents, the exact photocatalytic inactivation is still partially unknown [39]. The typical photocatalytic viral disinfection process, as shown in Fig. 2, involves the irradiation of semiconducting material by light, leading to the generation of photoinduced electrons and holes which further generate ROS like \( \cdot OH \), \( \cdot O_2^- \), and \( H_2O_2 \) by reacting with \( H_2O \) and \( O_2 \) [40]. The resulting species participate in the photo-inactivation of viruses by attacking the cell membrane and triggering the rupture of protein capsid resulting in efflux of viral RNA surrounded by the protein layers. Consequently, the coenzyme A in the cell membrane is damaged causing the inhibition in the respiration followed by deactivation of the cell. For effective virus inactivation, the prerequisite is to acquire deep knowledge about the means by which the virus can invade host cells through the major steps involving (i) cellular connection and entry, (ii) viral genome replication along with viral proteins expression, and (iii) assembly, maturation, and exocytosis. Thus, based on this mechanism, an efficient antiviral material should have the ability to inhibit the virus replication process. Considering that, various advantages and potential features of graphene and its derivatives for the photocatalysis process are as follows:

So far, various photocatalytic materials undergo considerably low quantum yield, visible light harnessing, and stability which have severely hindered the designing and construction of semiconductor photocatalysts for practical application [41]. However, integrating graphene with other semiconductors represents a fascinating approach to amend the activities and stabilities of photocatalytic materials [42]. Considering the high potential and usability of graphene in different applications, environmentally friendly and cost-effective production of graphene is crucial. Therefore, based on the available life cycle
assessment studies on graphene, it is observed that the bulk production of graphene via chemical reduction and thermal exfoliation are major routes [43]. Typically, in the chemical reduction process, the reduction step along with the generation of reducing agents (hydrazine) is of considerably high impact [44]. On the other hand, the required heating energy to induce thermal exfoliation is the major concern. On contrary, the ultrasonic assisted exfoliation is a considerably facile approach with lower impact due to the reusability of the solvents [44]. Moreover, in the case of chemical vapor deposition (CVD) route, by reducing/reusing the feedstock (hydrocarbon gas) the impact can be substantially lowered [45].

Compared with zero dimensional (fullerenes) and one dimensional (carbon nanotubes; CNTs) carbon based materials, graphene and its derivatives exhibit superior physicochemical properties depending upon the synthesis route for constructing firm crystal-structured as well as defect induced graphene [46–50]. By virtue of various synthesis methods, the modulated intrinsic features involving number of layers, lateral size, morphology, and dispersibility significantly impact the antiviral activity [47]. For instance, an increased number of graphene layers has been reported to cause an increment in aggregation, decreased dispersibility, and more thickness resulting in reduced interaction between virus and graphene [51]. Similarly, the creation of defects like introduction of oxygen containing functional groups and alteration in basal planes promotes effective interaction between graphene based materials and viruses [52,53]. The interaction of various graphene based nanomaterials coated surfaces with SARS-CoV-2 is represented in Fig. 3 [24].

Notably, the presence of functional groups with negatively charged elements on GO and rGO substantially affects the antiviral properties of these materials [54]. The main functional groups involving hydroxyl, carbonyl, and carboxyl promote the redox reactions between the GO layer (possessing negative charge) and the viruses via considerably important physicochemical process and lead to the destruction of the viral membrane. Moreover, the intrinsic capability of GO and rGO for adsorbing charged lipids to destroy the cell membrane after interaction with the aromatic planes further boost their antiviral activity [55].
A variety of graphene materials were introduced in the studies of pathogenic inhibition and binding [56] . The nanomaterial graphene and its derivatives with a two-dimensional (2D) structure can be applied as antiviral materials owing to its ability to invade enveloped or non-enveloped viruses [57] . The strong negatively charged surface [69] . For COVID-19, the lipid envelope along with physical protection from the deadly virus as evident in Fig. 4 [35] .

Due to hydrophobic nature of S protein, the positively charged surfactant along with physical protection from the deadly virus as evident in Fig. 4 [35] .

Fig. 4. Diagrammatic illustration of multifunctional features of graphene modified personal protective equipments (PPEs).

Table 1
A summary of the antiviral activities of graphene-based materials against a variety of viruses.

| Graphene-based materials          | Target virus name | Genome     | Virus family                  | Viral envelope | Antiviral activity                                      | Ref. |
|----------------------------------|-------------------|------------|-------------------------------|----------------|--------------------------------------------------------|------|
| Graphene oxide (GO) and GO-Ag NPs | FCoV; IBDV        | RNA        | Coronaviridae; Birnaviridae   | Enveloped      | GO: 16.3% and 0.4% against FCoV and IBDV; GO-Ag NPs: 24.8% and 22.7% against FCoV and IBDV | [58] |
| GO-Ag NPs                        | PRRSV             | RNA        | Arteriviridae                 | Enveloped      | Inhibition the virus entry over 59.2%                   | [59] |
| Cu NPs-GO                        | Influenza A       | RNA        | Orthomyxoviridae              | Enveloped      | ~50% reduction                                         | [60] |
| CTAB functionalized reduced graphene oxide (rGO)/FeO₄ GO | PEDV; PRV         | RNA        | Coronavirus                   | Enveloped      | Reduction from 5 × 10⁷ to 2.5 × 10⁹ pfu/mL             | [61] |
| Sulfonated magnetic NPs functionalized rGO | HSV-1            | DNA        | Herpesviridae                 | Enveloped      | 99.99% inhibition (within 7 min) under NIR light illumination | [62] |
| GO nanosheets                    | SARS-CoV-2        | RNA        | Coronaviridae                 | Enveloped      | IC₅₀ (30 µg mL⁻¹)                                       | [63] |
| Graphene derivatives with polyglycerol sulfate coverage (GPGS-C12) | FCoV             | RNA        | Coronaviridae                 | Enveloped      | IC₅₀ (85.2 ± 50.9 µg mL⁻¹)                               | [64] |

Where; FCoV = feline coronavirus, IBDV = infectious bursal disease virus, PRRSV = porcine reproductive and respiratory syndrome virus, CTAB = cetyltrimethylammonium bromide, RNA = ribonucleic acid, DNA = deoxyribonucleic acid, PRV = pseudorabies virus, PEDV = porcine epidemic diarrhea virus, HSV-1 = herpes simplex virus, IC₅₀ = half maximum inhibitory concentration.

The graphene derivates such as GO contained an excessive amount of oxygen atoms with stronger hydrophilicity, water attachability, and dispersibility, whereas, GO with lower oxygen atoms and lost hydrophilic features resulted in the formation of rGO. The reason behind the antiviral characteristics of graphene-based materials is usually because of their electronic dynamic to a bacterial pathogen or virus [67]. This electronic movement destroyed the lipid membrane, generated highly reactive species, and reduction in metabolism, which finally degrade the glutathione and virus. For instance, a computational study demonstrated an efficient binding mechanism between mechanically exfoliated multilayered graphene and the S-protein receptor binding site of SARS-CoV-2 [68].

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surface could effectively interact with the lipid molecules present in enveloped viruses. However, the metal nanoparticles functionalized GO further exhibit superior binding between metal nanoparticles and \(-\text{SH}\) groups of viral proteins present in both enveloped and non-enveloped viruses [58]. Consequently, such effective interactions between graphene derivatives (GO/rGO) and oppositely charge lipid moieties facilitate superior adsorption and finally, destruction of liposome [69, 71].

In another study, Benkova et al. discussed the structural changes that occurred for spike glycoprotein trimer after adsorption onto the graphene sheet validated from molecular dynamics (MD) simulations [13]. The initial and final conformation of the S-protein interaction with graphene before and after 40 ns simulation run was delineated in Fig. 5a, b. In the initial phase of the adsorption (first 20 ns), the increased root mean square \((R_{gy} = (R_{gx}^2 + R_{gy}^2/2)^{1/2})\) of lateral components \((R_{gx}\) and \(R_{gy}\)) induced the reduction in perpendicular constituent \((R_{gz})\) of the radius of gyration. Also, the S-protein structural deformation was caused by adsorption on the graphene, but the decreased perpendicular component was attributed due to the S-protein re-orientation. In the adsorption process, the intramolecular-hydrogen bonding was appeared by replacing the S-protein-hydrogen bonds during the relaxation time of free S-protein in water. Hence, the study confirmed that lateral extension of S-protein was influenced after adsorption on the graphene sheet.

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Fig. 5. (a) Initial and (b) final conformation of S-protein during interaction with graphene layer, Reproduced with permission from ref. [13], Copyright Elsevier 2020, 2021 with license number [5146650139525].

Fig. 6. Molecular docking analysis of graphene oxide (GO) with (a) spike (6VYB) in an open state with the binding affinity of \(-10.4\) kcal mol\(^{-1}\), (b) spike (6VXX) in closed state with binding affinity of \(-8.7\) and \(-8.4\) kcal mol\(^{-1}\) (represented in green color), (c) docking results for ACE (1R42) and GO, and (d) viral inactivation by graphene-based photocatalyst. Reproduced with permission from ref. [64,74], Copyright Wiley 2021, American Chemical Society 2012.
3. Perspective of graphene based materials to combat COVID-19

Graphene derivatives have shown promising virus inactivation features in recent years. For instance, sulfated GO and GO nanosheets were revealed to be efficient in destroying HSV-1 virus, with two assumed inhibitory mechanisms i.e., viral wrapping and binding [62,72]. Moreover, thermally induced rGO nanosheets organized with hyperbranched polyglycerol (hPG) proceeded with the sulfonation process, generating graphene-linked heparin biomimetics. In this case, sulfated rGO-hPG nanosheets inhibited orthopoxviral and herpesviral strain, specifically in the initial stages of the viral infection, but were incapable of preventing cell-to-cell spread. In addition, the negatively charged surfaces and sharped edges of the single-layered sheets were responsible for the antiviral activities of graphene derivatives as a result of strong electrostatic attraction and high affinity towards the positively charged virus. These negatively charged sharp-edged surfaces enabled the binding of virus with individualized GO and rGO sheets and leading to the inactivation of porcine epidemic diarrhea virus (PEDV), pseudorabies infection, and influenza A virus (H9N2) viruses [60,62]. The mechanism suggested that graphene derivatives connected to the virus-definite antibodies also approved in antiviral platforms, because of antibody refereed sensing and binding mechanisms, applied to capture numerous viruses successfully, such as influenza virus (H1N1), avian influenza virus H7 (AIV H7), and H5 (AIV H5).

Due to the electroconductive feature, graphene derivatives can easily interact with various biomolecules or enter the plasma membrane, translocate inside of lysosome or endosome, and controls cytoskeleton, nucleus, and mitochondria [55]. More importantly, multi-layers graphene exhibits higher hydrophobicity in comparison to single-layer. Mostly, the stability and affinity of mono- and multilayer graphene derivative towards SARS-CoV-2 can be studied using computational based molecular docking analysis. Recently, molecular docking analysis for ascertaining the interactions between GO nanosheets with several SARS-CoV-2 structures involving viral spike (closed-6VXX or open state-6VYB), ACE2-bound spike (6M0J), and ACE2 (IR42) complex were reported [64]. Notably, receptor binding domains (RBD) of spike protein reflects as the main target for viral inhibition as it facilitated ACE2 and SARS-CoV-2 fusion. The 3-grounded glycoprotein 6VXX and 6VYB of SARS-CoV-2 was bounded to ACE2 with corresponding closed and open states of a viral spike, respectively. Fig. 6 a, b represents the interaction of GO with these glycoproteins with binding affinities ranging between $-9.0,$ $-8.3$ kcal mol$^{-1}$ (closed state) and $-10.5,$ $-9.4$ kcal mol$^{-1}$ (open state). These high binding affinities suggested stronger bond strength as GO served as hydrogen acceptor or donor for both types of glycoproteins within $2.214$–$3.326$ Å range. The docking results of GO and ACE2 spike displayed no overlap of their complex as shown in Fig. 6c. However, docking results evaluated the difference of 0.8 kcal mol$^{-1}$ binding energy between 1R42 and GO, mainly due to abundant and diverse bond formation, revealing stronger binding of GO with ACE2.

Notably, it has been found that the photo reduced rGO exhibits stronger electrical conductivity and ultra-high surface area which can be substantially beneficial for antiviral activity [73]. To achieve the visible-light-driven disinfection of viruses in water, Akhavan et al. integrated the GO layers with WO$_3$ films (graphene-WO$_3$) and decreased the MS2 titer of $2 \times 10^6$ plaque-forming units (PFU)/mL to $< 5$ PFU/mL under 400 nm light illumination for 180 min [74]. The photocatalytic degradation mechanism of MS2 virus including nucleic acids and...
proteins occurred where protein capsid was degraded initially and afterward release of RNA occurred. It was supposed that rGO produced after photo-reduction of GO by WO$_3$ was photodegraded under long-term visible-light exposure, but only 10% of the photocatalyst was degraded even after 20 consecutive cycles for 60 h, validating the strong stability of the graphene-WO$_3$ films for viral inactivation (Fig. 6d).

In addition to the chemical oxidation phenomenon, physical damage in virus disinfection mostly appears in graphene-based photocatalysts, where GO possessed a large number of sharp edges to disrupt protein shells membrane and finally inactivate the virus. The pristine GO displayed the same virucidal activity in the light as well as in the dark, indicating the mechanism of physical damage [75]. In the initial phase of photoreactions, the blunt edges of GO-aptamer caused low viral inactivation in comparison to pristine GO with sharp edges, indicating the importance of sharp edges in GO nanomaterials for the inactivation of viruses. Other than physical damage, the photoinduced redox reactions as shown in Fig. 7a-c, also promoted the formation of O$_2$•• radicals which fostered the breakage of protein capsid of the virus leading to efflux of enveloped nucleic acids. Additionally, the photocatalysis process further induced the oxidation and oxidative modulations of nucleic acids to generate protein carbonyls along with the reduction of GO into rGO.

Very recently, the inactivation of feline coronavirus and SARS-CoV-2 by graphene derivatives with dual functionalities (alkyl/sulfate) was investigated [65]. Graphene platforms with long alkyl groups (> C9) inhibited the coronavirus replication through degrading enveloped virus and confirmed from cryogenic electron microscopy and atomic force microscopy analysis. To study to study the inhibitory effects of graphene, a plaque reduction assay (expressed in plaque-forming units (PFU) mL$^{-1}$ to determine viral replication) displayed dose-dependent inhibition efficacy for the incubated components as evident in (Fig. 8a), where graphene with extended aliphatic chains showed
stronger viral inhibition than their counterparts. Moreover, graphene with polyglycerol sulfate coverage (G-PGS)-C11 was proved the most promising inhibitor, showing potential inhibition towards feline coronavirus with $6.3 \pm 1.2 \mu g \cdot mL^{-1}$ concentration. The result of the virucidal and plaque reduction assay suggested the significant role of longer aliphatic chains around the graphene surface was required for the viral membrane breakage (Fig. 8b). Similarly, the strong inhibition of SARS-CoV-2 (0.8 $\pm 0.3 \mu g \cdot mL^{-1}$ concentration) was observed using G-PGS-C11 with longer alkyl chains (>C9) from plaque reduction assay (Fig. 8c). However, cellular toxicity has occurred at higher concentrations, the effective SARS-CoV-2 inhibition under 50 $\mu g \cdot mL^{-1}$ concentration displayed no cellular toxicity. The G-PGS-C11 proved a virucidal system for SARS-CoV-2, while G-PGS, G-PGS-C6, G-PGS-C9 served as a virostatic system (Fig. 8d). Herein, the functionalized graphene platform confined virions through electrostatic interaction with the negative charged surface of PGS, which further disintegrated using alkyl side chains. Typically, the membrane breakage of feline enveloped virus takes place with an extension of aliphatic chains from G-PGS-C9 to G-PGS-C11 with strong inhibition and virucidal activity, indicating the potentiality of elongated alkyl chains for virus binding and disintegration. However, the electrostatic interaction occurred at the initial stage between the positive patches of spike virions and negative charges present at the PGS surface, afterward, the rupturing of viral membrane induced by aliphatic chains. This indicated that electrostatic interaction could predominantly disrupt the viral binding, while, graphene sheets with extended aliphatic chains (>C10) significantly penetrated cellular membrane to persuade cell death but also show cellular toxicity.

One important point worth discussing is the recyclability of graphene based materials. So far, the separation of carbon based nanomaterials from the reaction mixture is the biggest hurdle, especially after photocatalytic antiviral activity. The process becomes even riskier if the recovered photocatalyst has not gone through complete disinfection, and the surface of nanomaterials still has the adsorbed virus species [76]. Therefore, ensuring the complete disinfection and facilitating the recyclability of graphene based nanomaterials, loading with magnetic materials can offer significant benefits associated with magnetic features obtained. In this regard, Deokar et al. decorated rGO with sulfonated magnetic nanoparticles (SMRGO) which enabled effective capturing and destruction of HSV-1 by exhibiting ~99.99% efficiency [63]. The metal nanoparticles not just improve the recycling efficiency but simultaneously modify the electronic interactions between magnetic nanoparticles with viral species. As a whole, the abundant surface area, enhanced virus capturing performance, and excellent photothermal properties resulting from the integration of magnetic nanoparticles with graphene based materials rendered remarkable antiviral activity.

4. Conclusions

Considering the current scenario, the scientific community is actively working on finding sustainable solutions to combat COVID-19 pandemic. Current reports are emerging with substantial role of nanomaterials in fighting against SARS-CoV-2 virus but the research in this area is still in an infancy stage. Various studies have also reported the solar light-driven advanced oxidation-based photocatalytic inactivation of various harmful viruses (MS2, HSV-1 etc.) by utilizing semiconductor materials. Therefore, inspired by that, the present review article has presented an overview of photocatalytic viral inactivation by highlighting the potentials of graphene based nanomaterials. Starting from the basic insights of photocatalytic virus inactivation, the significant features of graphene based materials for their efficient utilization as an antiviral agent are explored. Afterward, a perspective of graphene based materials to combat COVID-19 has been presented. However, to extend the application of photocatalytic viral inactivation on large scale, major challenges such as (i) exact deactivation mechanism, (ii) identification and examination of metabolites produced during the process, (iii) the implementation of scaling-up and economic aspects, and (iv) criteria of biological safety associated with cytotoxicity and/or genotoxicity, must be given serious attention.

Despite encouraging studies on graphene based materials, the exact impact of each physicochemical property involving basal planes, number of layers, lateral size, and surface functionalization, on antiviral performance is still not clear. For this reason, the major objective of the follow-up study should be focused on the parallel research investigating the advance scientific understanding of mechanistic insights involving photocatalytic antiviral activity at the biochemical or molecular level. It is highly anticipated that the advances in photocatalytic antiviral properties of graphene based materials will prove fruitful in the near future. However, more systematic investigations exploring the critical challenges in this area are required to validate the performance of graphene based materials on large scale. Therefore, future work in this field should focus on both fundamental and applied research in photocatalytic viral inactivation with special emphasis on the role of graphene based materials and the response of viruses.

Credit Author Statement

All authors participate equally, otherwise mentioned in the manuscript.

Declaration of Competing Interest

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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