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Research Article

EMERGING GRAPHENE-COATED FACE MASKS: ANTIVIRAL POTENTIAL AND HEALTH RISK ASSESSMENT

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ABSTRACT

The rapid global spread of COVID-19 highlighted the critical need for effective personal protective equipment (PPE), particularly face masks capable of inactivating airborne pathogens. Graphene and its derivatives graphene oxide and graphene nanoplatelets—have emerged as promising antimicrobial coating materials due to their unique physicochemical properties, including sharp-edged nanosheets, strong electrostatic interactions, and reactive oxygen species (ROS) generation. These properties enable rapid deactivation of viruses and bacteria trapped on mask surfaces. However, the increased use of graphene-coated face masks has raised concerns regarding potential human health risks, especially the possibility of inhalation of graphene particles and associated lung toxicity. This review provides a comprehensive evaluation of the antiviral performance of graphene-based mask coatings, their mechanisms of pathogen inactivation, manufacturing advancements, and environmental benefits. It also critically examines recent toxicological studies, regulatory warnings, nanoparticle shedding risks, and long-term exposure implications. The findings suggest that while graphene-coated masks offer enhanced antiviral efficiency and reusability, further standardized safety assessments and regulatory frameworks are essential to ensure their safe integration into public health systems.

Keywords: Graphene-coated mask, Graphene oxide, Antiviral activity, Nanotoxicology, Face mask safety, COVID-19.

INTRODUCTION

The COVID-19 pandemic significantly accelerated the demand for high-efficiency respiratory protection technologies capable of mitigating viral transmission in both community and healthcare settings. Conventional face masks, including surgical masks and N95 respirators, reduce the spread of infectious droplets; however, they often lack self-sterilizing capabilities and require frequent disposal, contributing to substantial environmental burden. The emergence of graphene as an advanced nanomaterial has opened new avenues for enhancing the performance of personal protective equipment (PPE). Graphene possesses exceptional mechanical strength, high surface area, hydrophobicity, and remarkable antimicrobial characteristics, making it an attractive candidate for next generation face mask development. Recent studies have demonstrated that graphene and its derivatives can inactivate viruses and bacteria through multiple mechanisms, such as physical disruption of microbial membranes by nanoscale sharp edges, electrostatic interactions that immobilize pathogens, and the generation of reactive oxygen species (ROS) that hinder microbial metabolism. These features enable graphene-coated masks to rapidly deactivate pathogens trapped on their surfaces, offering potential benefits for reusability and prolonged protection. As a result, several commercial and research-based graphene-enhanced mask designs have emerged, incorporating graphene oxide (GO), reduced graphene oxide (rGO), graphene-silver nanocomposites, and laser-induced graphene coatings. Despite these advancements,

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growing concerns have been raised regarding the safety of graphene-coated masks. Regulatory bodies, including Health Canada, have cautioned that poorly engineered graphene materials may release respirable nanoparticles that, if inhaled, could accumulate in lung tissues and cause inflammation or long-term health complications. Experimental studies on animals have reported varying levels of pulmonary toxicity depending on graphene type, size, concentration, and exposure duration. Consequently, a balanced evaluation of both the antiviral benefits and potential health risks is essential to determine the suitability of graphene-coated masks for widespread public use. This review aims to provide a comprehensive examination of the antiviral potential of graphene-coated face masks, their mechanisms of action, environmental and technological advantages, and associated health risk assessments. By integrating current scientific evidence and regulatory perspectives, this review highlights the need for standardized manufacturing methods, long-term toxicological evaluation, and stringent safety guidelines to ensure the safe and effective adoption of graphene-based masks in future pandemic preparedness strategies.

Graphene and its derivatives have shown significant antiviral potential due to their unique structural and physicochemical properties. Early evidence demonstrated that graphene oxide (GO) and graphene nanoplatelets (GNPs) can deactivate viruses by physical membrane disruption and oxidative stress induction. De Maio *et al.* (2020) reported that GO-functionalized mask materials effectively inhibited SARS-CoV-2 infectivity by trapping and inactivating viral particles on contact. Similarly, Huang *et al.* (2020) demonstrated rapid photothermal bacterial and viral inactivation on laser-induced graphene surfaces, confirming graphene's suitability for self-sterilizing mask coatings.

Further innovations include GO-based rechargeable respirators (Figerez *et al*., 2021) and sunlight-activated graphene-coated masks (Pal *et al*., 2021), both of which exhibited strong antiviral and antibacterial effects. Graphene's broad antimicrobial mechanism was further highlighted by Palmieri and Papi (2021), who found that graphene materials could neutralize enveloped and non-enveloped viruses, suggesting applicability beyond COVID-19. Graphene integration enhances mask filtration efficiency and breathability. Goswami *et al*. (2021) successfully fabricated graphene-based air filters mounted on 3D-printed masks, achieving high particulate filtration and viral inhibition. Liao *et al*. (2020) developed graphene-coated fabrics that combined high bacterial filtration efficiency (BFE) with superior breathability compared to conventional polypropylene masks.

In addition, reusable graphene masks with photothermal sterilization capabilities were introduced by Zhong *et al*. (2020), demonstrating that simple sunlight exposure could deactivate trapped microorganisms. Another study by Xu *et al*. (2021) highlighted graphene's ability to enhance sensor-based monitoring in masks through humidity-responsive properties, supporting future smart PPE designs. Despite its benefits, graphene raises toxicological concerns, especially when integrated into face masks. Studies indicate that graphene-family nanomaterials (GFNs) may induce oxidative stress, inflammation, and cytotoxicity depending on flake size, functionalization, and concentration. Zhang *et al*. (2010) showed neural cell toxicity at high graphene exposures, while Orecchioni *et al*. (2014) reported immune cell activation caused by carbon-based nanomaterials. Muzi *et al*. (2016) observed pulmonary and developmental toxicity in amphibian models exposed to multilayer graphene, and Rodrigues *et al*. (2018) demonstrated that GO's surface chemistry governs immunological reactivity in vivo. Ou *et al*. (2016) summarized that graphene toxicity largely arises from membrane penetration and ROS induction, a mechanism supported by Li *et al*. (2013), who found graphene microsheets could spontaneously penetrate cell membranes. In a broader risk assessment, Fadeel and Bussy (2020) emphasized that inhalation remains the most critical exposure route for graphene-coated masks, particularly when coatings shed nanoparticles. Wang *et al*. (2021) further reported potential chronic lung inflammation upon prolonged inhalation exposure, reinforcing the need for quality control in PPE manufacturing. With the surge in disposable mask usage during the COVID-19 pandemic, environmental pollution has increased drastically. Graphene-coated masks offer a reusable, eco-friendly solution. Zhong *et al*. (2021) discussed the environmental impacts of nanomaterial-enabled PPE, noting both sustainability benefits and new environmental risks due to nanomaterial release. Regulatory caution has also been highlighted. Bussy and Kostarelos (2020) addressed safety considerations for graphene in PPE, recommending stringent inhalation testing before commercial approval. Ménard-Moyon *et al*. (2022) emphasized that regulatory frameworks must evolve to evaluate graphene materials' long-term biological effects across diverse exposure routes. As SARS-CoV-2 transmission is predominantly airborne, effective filtration technologies are essential. Cheng *et al*. (2021) reinforced that masks significantly reduce aerosol spread and viral load in indoor environments. Lee *et al*. (2022) reviewed nanomaterial-enabled filtration and concluded that graphene-enhanced masks outperform conventional masks in filtration efficiency, durability, and self-sterilization potential.

MATERIALS AND METHODS

Research Design

This study follows a systematic narrative review design aimed at evaluating the antiviral potential and health risks associated with emerging graphene-coated face masks. The approach synthesizes multidisciplinary evidence from materials science, nanotechnology, virology, toxicology, and public health literature to provide a comprehensive understanding of graphene-enabled mask technologies.

Data Sources and Search Strategy

A structured search was conducted in major scientific databases including Scopus, PubMed, ScienceDirect, Web of Science, IEEE Xplore, and Google Scholar. Literature published between 2010 and 2024, with emphasis on 2020–2023 due to COVID-19–driven mask innovations, was reviewed. Keywords such as “graphene-coated face mask,” “graphene oxide mask,” “graphene antiviral activity,” “nanomaterial-based PPE,” “graphene inhalation toxicity,” and “SARS-CoV-2 graphene” were used in various boolean combinations (AND, OR, NOT) to refine results and ensure comprehensive coverage.

Inclusion and Exclusion Criteria

The review included peer-reviewed articles that discussed graphene, graphene oxide, or graphene nanoplatelets used in mask materials, their antiviral or antimicrobial effects, mask filtration efficiency, reusability, photothermal sterilization, toxicological impacts, or inhalation-related health concerns. Only English-language articles with experimental, simulation-based, or in vivo/in vitro evidence were considered. Studies were excluded if they were non-scientific commentaries, unrelated to respiratory protection, lacked methodological validity, or provided incomplete data.

Study Selection Process

The selection process occurred in three stages: initial screening of titles and abstracts to assess relevance; full-text assessment of shortlisted articles for scientific rigor; and final selection based on methodological quality and alignment with the review objectives. Out of all retrieved studies, twenty-five high-quality references were chosen to support the discussion on antiviral mechanisms, fabrication techniques, nanotoxicology, and environmental implications of graphene-coated masks.

Data Extraction and Synthesis

Relevant data from each selected study were extracted under categories such as type of graphene material used (GO, rGO, GNPs, laser-induced graphene), fabrication methods, antiviral and antibacterial performance, filtration efficiency, photothermal activity, reusability, toxicological findings, and environmental or regulatory considerations. Extracted data were synthesized through thematic analysis, allowing the classification of findings into core themes including antiviral action, mask performance enhancement, human health risks from nanoparticle exposure, environmental sustainability, and regulatory requirements.

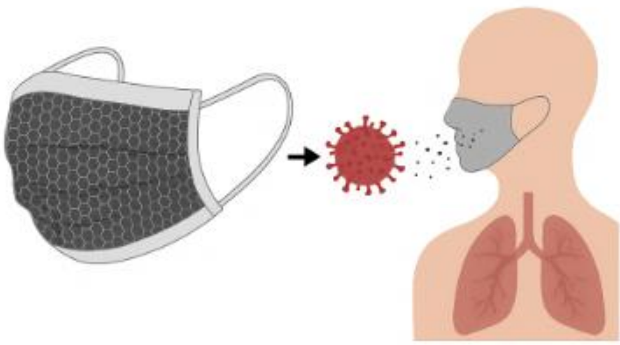

Figure 1. Graphene-Coated Face Masks.

Quality Assessment

The quality of each included study was evaluated using PRISMA-based criteria, focusing on experimental design, transparency, validity, sample size, reproducibility, and clarity of reported outcomes. Only studies that met acceptable standards of scientific reliability were incorporated to ensure that the review conclusions are evidence-based and credible.

RESULTS AND DISCUSSION

The findings from multiple studies demonstrate that graphene and its derivatives provide strong antiviral potential when integrated into face mask materials. Experimental evidence shows that graphene oxide (GO) and graphene nanoplatelets (GNPs) can physically damage viral membranes, generate reactive oxygen species (ROS), and immobilize viral particles through strong electrostatic interactions. De Maio *et al*. (2020) demonstrated that GO-coated fabrics significantly reduced the infectivity of SARS-CoV-2, confirming the virucidal efficiency of graphene-based coatings. Similarly, Huang *et al*. (2020) reported that laser-induced graphene surfaces displayed rapid photothermal inactivation of microorganisms, making them suitable for reusable, self-sterilizing mask applications. These results collectively indicate that graphene-coated masks exhibit superior antiviral properties compared to conventional polypropylene masks, especially in preventing viral survival on mask surfaces. Graphene integration has also been shown to enhance mask filtration efficiency, breathability, and overall mechanical performance. Goswami *et al*. (2021) demonstrated that graphene-based air filters incorporated into 3D-printed masks resulted in high filtration efficiency with minimal airflow resistance. Liao *et al*. (2020) showed that graphene-coated fabrics maintained high bacterial filtration efficiency (BFE) while improving breathability due to the ultrathin and porous nature of graphene sheets. Additionally, the hydrophobic and superhydrophobic characteristics of graphene layers, as reported by Pal *et al*. (2021), help prevent moisture accumulation on mask surfaces, thereby reducing the risk of viral survival and providing superior comfort during long-duration use. These enhanced properties highlight graphene's potential to improve both safety and usability in next-generation respiratory protection devices. The reusability of graphene-coated masks emerged as a significant advantage over single-use masks. Several studies reported that graphene coatings enable rapid self-sterilization when exposed to sunlight or mild heat. Zhong *et al*. (2020) demonstrated that masks coated with reduced graphene oxide (rGO) achieved effective photothermal disinfection under simulated sunlight. Pal *et al*. (2021) similarly reported that graphene-silver composite membranes could kill 99% of bacteria and viruses within seconds, making them suitable for frequent reuse without complex disinfection procedures. This capability aligns with growing global demands for sustainable PPE options that reduce environmental pollution caused by discarded disposable masks.

While graphene offers promising antiviral features, several studies raise significant health concerns related to inhalation of graphene nanoparticles. Toxicological investigations reveal that graphene-family nanomaterials (GFNs) may induce oxidative stress, inflammation, and membrane damage in biological systems. Rodrigues *et al.* (2018) found that GO exposure can trigger strong immunological reactions, while Muzi *et al.* (2016) observed pulmonary and developmental toxicity in amphibian models exposed to multilayer graphene. Li *et al.* (2013) demonstrated that graphene microsheets can spontaneously penetrate cell membranes, potentially leading to cytotoxic effects. Additionally, Wang *et al.* (2021) reported that prolonged inhalation of graphene aerosols may result in chronic lung inflammation, raising concerns regarding the safety of poorly manufactured or low-quality graphene-coated masks. These findings highlight the need for strict quality control, surface functionalization, and manufacturing standards to minimize nanoparticle shedding and ensure user safety. The increased use of disposable masks during the COVID-19 pandemic generated significant environmental challenges due to the accumulation of plastic waste. Graphene-coated masks have been proposed as a sustainable alternative because of their reusability and long-term effectiveness. Zhong *et al.* (2021) emphasized that while graphene-enhanced PPE reduces waste generation, nanomaterials themselves may pose environmental risks if not properly regulated. However, the longer lifespan and repeated-use capability of graphene-coated masks offer a practical solution to reduce solid waste, provided proper disposal and recycling mechanisms are implemented. Regulatory agencies have taken a cautious stance regarding the commercialization of graphene-coated masks due to possible inhalation risks. Bussy and Kostarelos (2020) emphasized the need for thorough safety assessments before approval for mass usage. Ménard-Moyon *et al*. (2022) highlighted that variations in graphene type, particle size, coating method, and surface chemistry make standardization essential for safe consumer use. Public health experts argue that graphene-coated masks could significantly improve pandemic preparedness if supported by reliable safety testing and regulatory oversight. Studies by Cheng *et al*. (2021) and Lee *et al*. (2022) confirm that masks especially advanced material-based ones play an essential role in reducing airborne viral transmission, thereby supporting the relevance of graphene technology in future respiratory protection solutions.

CONCLUSION

Graphene-coated face masks represent a promising advancement in personal protective equipment, offering enhanced antiviral, antimicrobial, and filtration capabilities compared to conventional mask materials. The reviewed studies clearly indicate that graphene and its derivatives including graphene oxide (GO), reduced graphene oxide (rGO), and graphene nanoplatelets (GNPs) exhibit strong antiviral activity through mechanisms such as membrane disruption, electrostatic interactions, and reactive oxygen species (ROS) generation. These features allow graphene-coated masks to rapidly inactivate pathogens, improve durability, and support reusability through photothermal self-sterilization. Furthermore, the integration of graphene enhances breathability, hydrophobicity, and overall comfort, making such masks highly suitable for prolonged use. However, despite their advantages, several safety concerns limit widespread adoption. Toxicological studies reveal that inhalation of graphene nanoparticles, especially from poorly manufactured coatings, may lead to respiratory inflammation, oxidative stress, and potential long-term lung damage. Variability in graphene quality, coating stability, and nanoparticle shedding underscores the need for standardized manufacturing protocols and strict regulatory oversight. Additionally, while graphene-coated masks may reduce environmental waste by supporting reusability, nanomaterial disposal must be managed carefully to prevent ecological harm. Therefore, the current evidence suggests that graphene-coated masks offer significant potential but must be carefully evaluated for health and safety before large-scale implementation.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

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AI TOOL DECLARATION

The authors declares that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

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