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REVIEW ARTICLE

Nanotechnology-enabled face masks: Balancing protection and pollution in aquatic environments

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Abstract: Face masks are widely regarded as essential tools for preventing respiratory infectious diseases, with the incorporation of nanofibers and nanoparticles significantly enhancing their antimicrobial performance. However, the same nanotechnology that strengthens their protective function also introduces complex risks. The extensive use and improper disposal of single-use masks have led to substantial environmental pollution. Discarded masks act as inadvertent conduits, releasing engineered nanomaterials and nanoplastics into wastewater systems through weathering processes. This represents a new and growing source of nanoscale pollution, which may exert cumulative effects on marine organisms and pose potential ecological threats. In light of these concerns, this review systematically assesses the balance between human health benefits and environmental risks associated with nanotechnology-enabled masks in aquatic environments. Furthermore, we explore feasible strategies to address the safety issue, including the development of biodegradable nanomaterials, improved mask designs to reduce emissions, and enhanced end-of-life management. It is crucial to align the application of such advanced masks with a sustainable and acceptable risk–return framework, ensuring that public health advancements do not come at the expense of environmental integrity.

Keywords: Face masks; Nanoplastics; Aquatic ecosystems; Environmental risk assessment; Waste mask management

1. Introduction

The widespread adoption of face masks has played an instrumental role in mitigating the transmission of respiratory infectious diseases, as strongly supported by epidemiological evidence.[1-3] In recent years, the recurrence of such diseases has posed severe threats to public health and socioeconomic stability, making the appropriate selection and use of masks a critical component of disease prevention strategies.[4-6] However, this essential protective measure carries a significant environmental cost. Approximately 194 billion disposable masks are used and discarded globally each month, with daily consumption reaching several billion at peak periods.[7] A substantial proportion of these used masks eventually enter aquatic environments, where improper disposal leads to the release of microplastics and nanoplastics, contributing to a growing ecological burden.[8-11]

Nanotechnology and nanoengineered functional textiles represent the frontier of garment technology, with nanomaterials integrated into masks to impart new functions (sterilization and disinfection) without compromising comfort.[12] In particular, metal and metal oxide nanoparticles are among the most commonly used nanomaterials in the textile industry due to their antibacterial properties.[13] Engineered nanomaterials are similar in size to viruses and exhibit distinct characteristics compared with bulk materials because of their large surface area.[14-17] To better control infectious diseases, nanotechnology has been widely applied to enhance the self-cleaning and antibacterial properties of materials. Textile enterprises are actively adopting this technology and specialized nanomaterials to explore innovative ways of improving the antiviral properties of textiles.[18,19] The incorporation of nanoparticles and nanofibers can endow masks with high antiviral performance. Nanomaterials embedded in textile products can improve filtration efficiency to a certain extent, while also influencing the survival of viruses upon contact with the mask surface.

With increasing reports of environmental pollution caused by disposable surgical masks, public concern regarding mask-related pollution has also grown.[20,21] A growing concern is whether the application of nanotechnology in the mask industry introduces new forms of pollution that have gradually entered public attention.[22,23] Once released into the environment, discarded masks are easily affected by solar radiation and heat, leading to the release of microplastic fibers from the mask matrix. These fibers are prone to fragmentation, resulting in the generation of large quantities of secondary microplastic fibers.[24-26]

Evidence has shown that engineered nanoparticles released from commercial products into aquatic environments can persist as potential pollutants and pose significant risks to aquatic organisms.[27-30] Consequently, these new antiviral masks may release microfibers or nanofibers containing nanomaterials into water bodies when improperly discarded. In addition, the indiscriminate use of commercial disinfection products containing nanomaterials may further exacerbate the negative effects of microplastic and nanoplastic pollution on certain species.

Nanomaterials, due to their small size and large specific surface area, have the potential to efficiently adsorb pollutants and play a role in pollution control. However, their extremely small size makes them difficult to contain, increasing the likelihood of environmental release. Once nanomaterials enter water bodies or soils, they may be ingested by low-trophic-level organisms, such as plankton and benthic organisms, subsequently accumulating through the food chain. Nanomaterials may also exert direct toxic effects on aquatic organisms. For instance, silver (Ag) nanoparticles can release Ag ions, causing oxidative stress in the antioxidant systems of fish livers and leading to tissue damage.[31-33] Moreover, exposure to nano-Ag can significantly alter the community structure of plankton, reducing the density of cladoceran zooplankton while increasing the diversity of phytoplankton and bacteria, thereby disturbing the balance of the food web.[34,35]

In addition, nanomaterials may interfere with key processes in aquatic ecosystems. Studies have shown that nano-Ag can inhibit soil denitrification rates in the short term and promote the emission of greenhouse gases (such as carbon dioxide [CO_2, methane [CH_4, and nitrous oxide [N_2O]). However, aquatic plants (such as *Schoenoplectus tabernaemontani*) can mitigate these negative effects by absorbing Ag^+ ions and regulating soil microbial communities. In the long term, nano-Ag may also affect ecosystem carbon budgets by altering plankton-mediated carbon cycle and reducing CO_2 release at the water–air interface.[36]

However, the integration of nanotechnology into masks raises several unresolved concerns. Key issues, such as the durability of nanoparticle coatings during washing, the environmental degradation of discarded masks, and the associated release of microplastics and nanoparticles remain inadequately studied. If these nanomaterials are easily separated, they may be released after daily use or disposal, posing potential ecological risks. Therefore, this review aims to examine the production of nanotechnology-enhanced masks and to highlight the nanosafety considerations frequently overlooked in the industry. In addition, we discuss the necessary shifts in public awareness and potential regulatory frameworks required to mitigate the environmental impact of these essential protective items in aquatic environments.

2. Application of nanotechnology in masks

In the biomedical field, nanomaterials have wide-ranging applications in the diagnosis and treatment of many diseases. Over the past few decades, research on the use of nanomaterials in various biomedical fields has steadily progressed. Nanomaterials significantly enhance detection sensitivity through their optical, magnetic, and other unique properties. Gold nanoparticles combined with antibodies can identify extremely low concentrations of cancer proteins or viral antigens via observable color changes. Fluorescent quantum dots can label cellular molecules and track disease progression in real time.[37] Carbon nanodots and graphene quantum dots have been used to develop SARS-CoV-2 antibody test strips, while gold and Ag nanoparticles enable high-precision pathogen detection through surface-enhanced Raman scattering technology.[38-40] Nanocarriers can precisely deliver drugs to lesion sites. Liposome nanocarriers encapsulating chemotherapy drugs can bypass normal tissues, directly reach tumor areas, and trigger controlled release in the microenvironment.[41-43] Clinical studies have confirmed that this approach can significantly reduce side effects.[44] Nanomaterials can simulate the cellular microenvironment to promote tissue regeneration. Bone repair materials containing hydroxyapatite nanoparticles can guide the directional growth of bone cells, and conductive nanopolymers can accelerate the regeneration of nerve axons.[45-47] Nanotechnology is driving medical development toward miniaturization, functionalization, and the creation of intelligent systems. In the future, it is expected to enable organ-targeted drug delivery and cell-level precise intervention. With the deep integration of materials science and biotechnology, nanomedicine will bring further breakthroughs in the prevention and treatment of major diseases. Therefore, in the present public health situation, it is not surprising that nanotechnology is being applied in the prevention and treatment of infectious diseases. For the prevention and treatment of respiratory infectious diseases, various nanotechnology-based products have been applied in different fields, including: (i) Integrating nanofibers, nanocomposites, and nanoparticles into masks to provide antiviral and antibacterial properties; high breathability and filtration efficiency, and washing capacity; (ii) using nanomaterials and nanofibers in air purification devices; (iii) developing nanotechnology-based disinfectants and detergents, such as soaps and washing powders synthesized with nano-Ag; and (iv) producing medical products based on nano-Ag technology, such as masks, gloves, wipes, and bandages.[48]

While nanomaterials are embedded in masks, they can functionalize the fibers and enhance performance. At the same time, nanomaterials can influence the viability of bacteria and viruses after contact with masks. At present, existing masks incorporating nanomaterials include graphene, copper, copper dioxide, zinc (Zn), nano-Ag, and titanium dioxide (TiO_2).[48,49] When bacteria and viruses pass through the mask, nanomaterials can inactivate them, thereby providing self-disinfecting properties.[50] Interestingly, semiconductors, such as TiO_2 can kill bacteria and viruses through photodynamic therapy.[49] When nanoparticles are exposed to sunlight, they can produce free radicals that destroy bacterial proteins, membranes, and nucleic acids.[51] Nanofibers and TiO_2 have been used to produce antibacterial filters, both independently and in combination with graphene[52] and Ag.[53]

In addition, as effective drug delivery carriers, metal–organic frameworks (MOFs) have attracted widespread attention for their combination with fibers (masks) due to their biodegradability and antibacterial activity. The metal centers of MOFs are typically metal ions with antibacterial potential, such as Ag^+, Cu^{2+}, cobalt ions, and Zn^{2+}. These metal ions can be gradually released into the environment as the MOF matrix degrades, thereby achieving an antibacterial effect. A study carried out by Yang *et al*.[54] reported that zeolitic imidazolate framework-8 (ZIF-8) was grown on cotton fiber using an *in situ* growth method to produce durable, superhydrophobic, antibacterial cotton fabric. The findings showed that the material not only had strong oil–water separation ability but also exhibited more than 99% antibacterial efficacy against *Escherichia coli* and *Staphylococcus aureus*. Kumar *et al*.[55] developed a nanowire antibacterial mask with high hydrophobicity, high sterilization efficiency, and reusability by impregnating a Cu@ZIF-8 composite antibacterial agent onto the mask's filter layer. In addition, Li *et al*.[56] constructed a polypropylene (PP)/polyvinyl alcohol (PVA)/ZIF-8 graded fiber membrane by combining the PP melt-blown method with PVA/ZIF-8 electrospinning technology. The composite membrane exhibited a low pressure drop, high filtration efficiency, and good mechanical strength, and was expected to be used as a filter layer for recyclable antibacterial masks. Moreover, some MOFs also possess semiconductor-like properties, enabling charge separation to occur upon illumination to initiate photocatalytic processes.[57] Reactive oxygen species produced during this process can oxidize and destroy the cell membranes or genetic material of bacteria, as well as oxidize debris and secretions into CO_2 and water, thereby achieving a clean and efficient bactericidal effect.[58]

3. Human and environmental safety versus nanotechnology

As respiratory infectious diseases continue to occur in many parts of the world, disposable nanomasks have been widely used. However, discarded masks have gradually become a problem threatening the environment and the survival of living organisms. The production and use of new nanotechnology-based masks may further exacerbate this environmental crisis. The environmental fate of nanomaterials integrated into masks remains uncertain. Most research on the health risks of nanoparticle exposure comes from *in vitro* and *in vivo* experiments or computer simulations, with limited epidemiological data available for humans.

Copper and Ag nanoparticles can be released from textiles and induce severe environmental and health effects, such as immunotoxicity in pregnant mice and their offspring,[59] as well as toxic effects on marine species.[60] Nanotechnology-based products, such as nanomasks, which come into direct contact with the skin, should therefore be extensively tested, especially when worn for prolonged periods.[61] TiO_2 nanoparticles cannot penetrate the deeper skin layers and can thus be regarded as dermally safe nanomaterials.[62] Graphene materials, such as graphene, graphene oxide, or multilayer graphene, do not cause skin irritation alone; however, when prepared with irritant surfactants, such as sodium dodecylbenzene sulfonate or sodium dodecyl sulfate, they may induce skin irritation.[63]

Respiratory infectious diseases pose severe challenges, and nanotechnology offers clear advantages. Nevertheless, as nanoproducts rapidly gain popularity, the knowledge gap continues to widen, and the imbalance between the pace of nanosafety testing and technological research and development has become evident. As a result, this knowledge gap in the field is likely to deepen further.

In addition, new nanotechnology masks are fabricated using nano-sized polytetrafluoroethylene plastic fibers with diameters <1 μm.[64] Once released into the environment, these masks may generate more microplastics and nanoplastics, and at a faster rate than plastic bags and bottles. Figure 1 illustrates the potential environmental risks associated with the large-scale application of new nanotechnology masks. The negative effects of nanoplastic pollution on various species may be exacerbated by the release of nanofibers containing nanomaterials into the environment and by the indiscriminate use of commercial disinfectants and cleaning agents containing nanomaterials.

The molecular interactions among nanomaterials, microplastics, and nanoplastics, as well as their combined toxicity to aquatic organisms, have recently been investigated.[65,66] Research conducted by Li *et al*.[67] revealed that Ag nanoparticles can become trapped on the surface of microplastics, suggesting that microplastics may serve as important carriers of nanoparticles in aquatic environments. Dong *et al*.[68] investigated the combined effects of TiO_2 nanoparticles and nanoplastics on the nematode *Caenorhabditis elegans*, finding that co-exposure altered the molecular basis of oxidative stress and that the presence of nanoplastics further enhanced the toxicity of TiO_2 nanoparticles by inducing the production of intestinal reactive oxygen species. Moreover, Oliveira *et al*.[69] examined the formation of nanoparticles (TiO_2 and iron) and river dynamics, as well as their association with potentially hazardous elements (lead, chromium, cadmium, and mercury) in suspended sediments. The results demonstrated that these nanoparticles may adsorb and concentrate hazardous elements, altering their geochemical distribution and ecotoxicity in river sediments.

Microplastics and nanoplastics originate from similar sources containing nanoparticles, including nanomasks and personal care products.[70] Therefore, it is necessary to invest in technological innovations and waste management infrastructure to prevent new nanotechnology masks from entering the environment, as well as to study and monitor nanoplastic and nanoparticle pollution in different aquatic environments. Furthermore, the development of nanotechnology should prioritize renewable and biodegradable materials to reduce the environmental impact of these products.

4. Addressing nanotechnology safety

In the field of nanotoxicology, the toxicological mechanisms of many nanomaterials remain unclear, and broadly generalizable knowledge is limited. Compared with traditional toxicology, nanotoxicology has distinct features. Although present research has identified a series of complex toxicological phenomena, the underlying mechanisms remain obscure. Numerous studies emphasize high-dose, acute exposure—suitable for accidental release—but less applicable to everyday products containing low nanomaterial loads. Moreover, the lack of research in real-world workplaces limits conclusions about occupational safety. Research data in nanotoxicology have often been characterized by numerous contradictions and poor comparability. Although analytical methods have matured, broadly applicable conclusions remain limited.

To enable rigorous, objective evaluations of the biological safety of nanomaterials, more in-depth and systematic research on nanotoxicology is still needed, especially *in vivo* experimental verification and studies

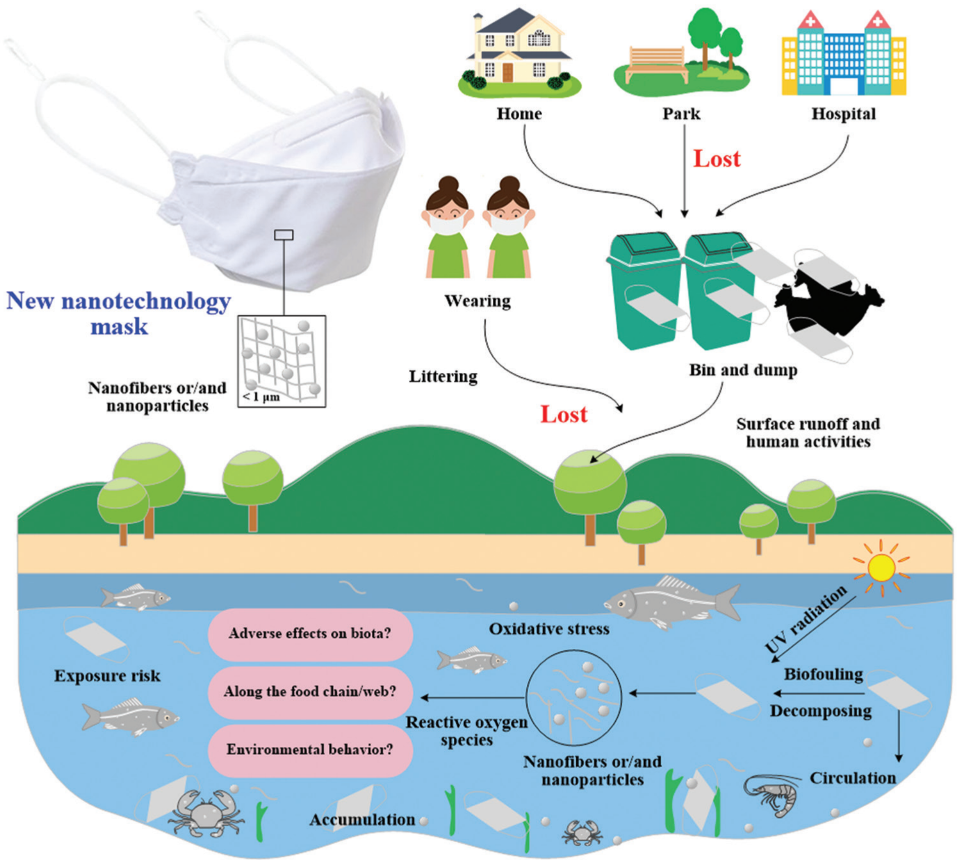

Figure 1. Potential environmental risks associated with the large-scale application of new nanotechnology masks in aquatic environments. Figure created by the authors.

on toxicological mechanisms. In safety evaluations, in addition to considering the traditional dose–effect relationship, the size and structural effects of nanomaterials should also be fully taken into account. Accordingly, more comprehensive nanotoxicology research is required to support fair, accurate safety assessments.

Due to the increased reactivity of nanoparticles, additional large-scale testing of chemicals is necessary alongside standard tests. Without such testing, the risk of unexpected negative health and environmental consequences arising from improper use of nanotechnology may increase significantly in the coming years. Consequently, nanomaterials should not be deployed at scale without concurrent safety testing and risk assessment. Figure 2 depicts a multistage process for addressing the environmental and health risks associated with nanotechnology products, with details for each level—from the central government and scientific community to local governments and citizens.

4.1. Government decision-making

Government agencies need to develop guidelines for the production of nanotechnology-based products. The main regulatory issues include establishing a unified nanoparticle nomenclature and developing control frameworks specific to nanomaterials, both of which pose additional difficulties for regulators. The government should commit to implementing the principle of extended producer responsibility. As more nanoparticles are released into aquatic environments, new strategies for detecting and removing nanowaste are required. Whether naturally occurring or artificially synthesized, nanoparticles are widely present in environmental media, making human exposure to these particles inevitable and continuous. Given the potential acute and chronic adverse effects of nanoparticles on human health, national health systems must inform consumers of the risks associated with nanowaste exposure. Governments should actively publicize the potential environmental risks of improper disposal of nanotechnology-based masks. In addition,

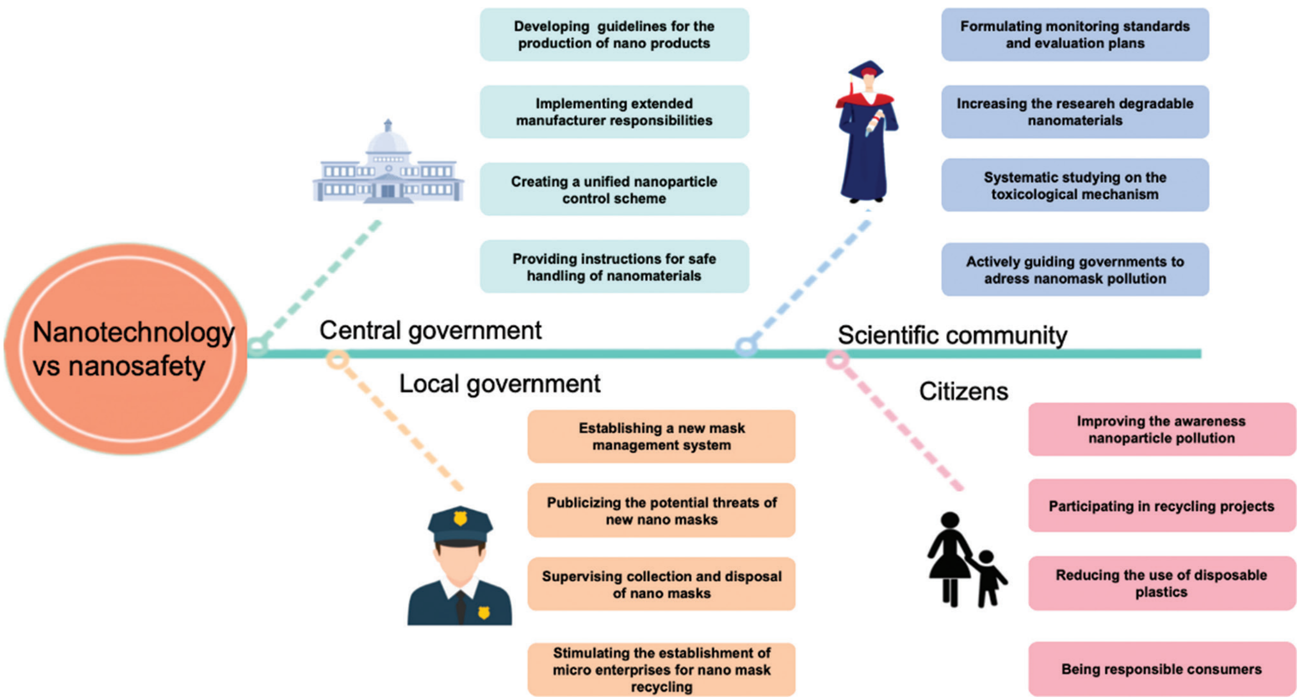

Figure 2. Multistage processes for addressing the environmental and health risks of nanotechnology products. Figure created by the authors.

consumers should be provided with clear information regarding the controlled release of nanomaterials from nanotechnology products, as well as instructions for safe handling and cleaning.

4.2. Local implementation

Local governments should establish new mask management systems, raise awareness about the environmental threats posed by new nanotechnology-based masks, and collaborate with the media to increase public understanding of nanoparticles and nanoplastics. They should also strictly supervise the collection and disposal of nanotechnology masks in communities, upgrade nanoparticle and nanoplastic removal equipment in wastewater treatment plants, and strengthen ecological remediation measures addressing nanoparticle, microplastic, and nanoplastic pollution in key areas. Local governments should encourage the public to follow health department guidance and enhance the recycling of discarded masks.[71] A recent study showed that all masks could release microparticles, nanoparticles, and heavy metals into water, and that these particles detach even without agitation, indicating mechanical instability and a high detachment potential.[72] A recognizable mark should be clearly indicated on the outer packaging of masks to distinguish traditional masks from new nanotechnology-based ones. In addition, local authorities should promote economic incentives, support recycling projects for disposable items, and stimulate the establishment of small-scale recycling enterprises.

4.3. Science and technology support

There is a limited systematic understanding of the migration, distribution, and complex toxicological mechanisms of nanoparticles, nanoplastics, and their associated pollutants in marine organisms. The scientific community should formulate monitoring standards and evaluation plans for nanoparticles and nanoplastics to guide local responses to mask pollution in aquatic environments. Microplastics undergo long-range transport via ocean currents and gradually break down into nanoscale particles, enhancing their diffusion capacity in water bodies. It is necessary to combine long-term exposure experiments with field investigations to clarify the impact of nanoplastics on population dynamics and ecosystem functions. In the future, multi-disciplinary methods, such as environmental chemistry, toxicology, and ecology should be integrated to develop green alternative materials (such as degradable polymers) and optimize pollution control technologies. The scientific community should formulate monitoring standards and assessment plans for nanoparticles and nanoplastics to guide local governments in addressing mask pollution in aquatic environments. Migration and distribution of nanomaterials in marine organisms are jointly driven by physical, chemical, and biological processes, and toxicity involves physical damage, chemical synergies, and molecular-level interference. Further research on degradable nanomaterials, such as MOF-based nanomaterials, is needed to balance antiviral performance with lower environmental hazard.

4.4. Mass participation

It is necessary to enhance awareness of the pollution caused by nanotechnology-based masks, nanoparticles, nanoplastics, and microplastics, and actively promote it. As groups directly exposed to pollution from nanotechnology-enabled masks and microplastics, the public can help bridge communication gaps left by formal science outreach through word-of-mouth promotion in communities, workplaces, and other settings. By participating in activities, such as waste sorting and reducing the use of disposable plastic products, the public can transform awareness into actual environmental protection behaviors. Community-based outreach and education should be carried out to introduce knowledge of science, technology, and environmental protection into local communities. By leveraging new media platforms, such as the Internet and mobile communication, a science-communication system that combines online and offline approaches should be established. Activities, such as selecting "Science Popularization Model Families" can be organized to enhance residents' scientific literacy. In addition, the use of single-use plastics should be eliminated or reduced as much as possible, and social pressure should be exerted on policymakers and manufacturers to advocate for changes to help reduce mask pollution.

5. Conclusion

In summary, while nanotechnology-enhanced masks represent a significant advancement in combating respiratory pathogens, their deployment must be tempered by rigorous nanosafety protocols. To ensure their sustainable application, it is imperative to establish comprehensive safety testing standards and enforce strict regulatory compliance. The development of new nanoproducts should not proceed solely on the grounds of addressing infectious diseases when potential risks may outweigh benefits. Enhanced environmental monitoring and robust risk management strategies are essential. Furthermore, fostering public awareness and international collaboration will be crucial in identifying and mitigating potential hazards. Future research should prioritize elucidating the environmental risks of nanomaterials, advancing nanoparticle control technologies, and promoting collective responsibility for ecological stewardship.

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Conflict of interest

Wenjun Wang and Maocai Shen are Editorial Board Members of this journal but were not involved in any way in the editorial and peer-review process for this paper, directly or indirectly. The remaining authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Availability of data

Not applicable.

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