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Mind the gap: Sustainable management of the surging plastic waste in the post-COVID-19 pandemic

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The outbreak of COVID-19 inevitably boosted the global consumption of personal protective equipment (PPE), including face masks, gloves, and protective clothes. While wearing PPE could protect the public health from the transmission of infectious diseases, a concern draws attention on the environmental issues of plastic waste. This review examines the dual challenges of managing pandemic-associated plastic waste and mitigating the ecological and health risks posed by micro- and nanoplastics (MNPs). The results showed that the traditional technologies including landfilling and incineration accounted for around 40% and 25%, respectively. The incineration could reduce over 90% of the waste volume, but release MNPs or byproducts. Circular economy strategies—guided by reduce, reuse, and recycle principles—offer promising alternatives, particularly advanced thermochemical recycling that converts waste into value-added chemicals. For PPE, disinfection prior to reuse is of great necessity, including incineration (>800°C), chemical disinfection (ozone, H_2O_2), or physical methods (steam, microwaves). Although sorption and filtration strategies could remove the MNPs with over 99% efficiency, they are still in the lab-scale. Biological solutions—such as bacteria, enzyme, and worms—demonstrate potential for degrading synthetic polymers. This work underscores the urgency of integrating circular economy frameworks and tried to submit a comprehensive proposal to reduce the plastic waste, which could finally reduce the environmental burden brought by the COVID-19 pandemic.

KEYWORDS

post-pandemic period, plastic waste, personal protective equipment, health risks, management policy

1 Introduction

The outbreak of the COVID-19 pandemic has led to a significant increase in the usage of personal protective equipment (PPE). The widespread use of PPE, particularly face masks, gloves, sanitizer bottles, medical test kits, has played a critical role in blocking the transmission of the coronavirus (Wu et al., 2024a). The global plastic production increased from 370.7 million tonnes (Mt) in 2018 (pre-pandemic) to 413.8 Mt in 2023 (post-pandemic) (PlasticEurope, 2025). Even in the post-pandemic, the public perceptions and attitudes towards health and hygiene practices have changed, resulting in an annual growth rate of approximately 10% (Isobe et al., 2019). Wearing masks in public, which was once considered unusual outside of specific cultural contexts or health scenarios, has now become widely accepted and normalized. Therefore, the rapid escalation in PPE usage disrupted global supply chains and overwhelmed existing waste management systems (Zhao et al., 2024; Li et al., 2025).

Despite the concerted efforts made by the Basel Convention's Plastic Waste Partnership to advance global plastic waste management frameworks, about 79% is finally discarded in landfills or the natural environment (Geyer et al., 2017). Without appropriate treatment, the discharge of PPE would be particularly problematic since the pathogens or viruses found in the PPE could be the origins of the multiple outbreaks. PPE together with other plastic waste could also entangle the fauna and animals in the ecosystems, finally leading to injuries, impaired mobility, or even death, while contributing to long-term ecological disruption and threatening biodiversity in affected habitats. More than 267 species were reported to be influenced by plastic waste, especially 86% of turtles, 44% of birds, 43% of mammals, and various fish species (United States Environmental Protection Agency, 2022). Recent publications also revealed that the presence of plastic waste could also change the climate by disrupting carbon sequestration processes and altering the reflectivity of ice and terrestrial surfaces, thereby exacerbating global warming and climate instability (Sunil et al., 2024; Villarrubia-Gómez et al., 2024). On the other hand, climate change (e.g., higher temperature, stronger UV radiation, etc.) can further increase the degradation of plastic waste, releasing uncountable microplastics (MPs; <5 mm) or nanoplastics (NPs; <1 μm) into the environment (Wei et al., 2024).

Individuals are inevitably exposed to micro-(nano-)plastics (MNPs) through ingestion, inhalation, and dermal contact, contributing to health risks such as oxidative stress, chronic inflammation, and neurological impairments (Vethaak and Legler, 2021). For instance, exposure to MPs at environmentally relevant concentrations (e.g., 0.0125 mg mL^{-1}) induces mitochondrial dysfunction in human hepatic and lung cells, characterized by excessive mitochondrial reactive oxygen species (mtROS) production and suppressed mitochondrial respiration (Lin et al., 2022). Beyond cellular effects, MP accumulation in organs may trigger gut microbiota dysbiosis, exacerbate inflammatory responses, and impair neurobehavioral functions in model organisms (e.g., fish and mice), including altered locomotion and memory deficits (Guimaraes et al., 2021; Lee et al., 2022). The generation of MNPs could also release plasticizers, such as phthalates and bisphenol A, can interfere immune homeostasis and potentiate neurotoxicity, underscoring the systemic risks of plastic pollution through absorption, distribution, metabolism, and excretion (ADME) pathways (Wu et al., 2022).

The escalating global production of plastics, coupled with mounting evidence of the ecological toxicity of MNPs and plastic additives in ecosystems, has spurred interdisciplinary research efforts to develop targeted strategies for mitigating plastic pollution and its pervasive environmental impacts. Therefore, the study first summarized the traditional treatment of plastic waste and discussed the circular economic solution for common plastic waste. Second, the review evaluates the suitable treatments concerning the PPE generated by the pandemic. Finally, recent treatments of MNPs were also summarized and evaluated. Overall, this manuscript will be of vital importance to understand the treatments of plastic waste and MNPs, which can be conducive to reducing the overloaded pressure on the ecosystem, especially the possible risks brought by coronavirus disease prevention manners during (or even after) the pandemic.

2 Traditional treatment and circular economic solutions of plastic waste

Traditional approaches for plastics mainly include landfilling and incineration, accounting for around 40% and 25%, respectively (Vanapalli et al., 2021). Landfilling requires large space, along with releasing MNPs after gradual fragmentation under the influence of environmental processes (e.g., UV radiation and biological effects). The disposal strategy is unsustainable and contains the potential risks of contaminating soil and groundwater in the long term (Qi et al., 2020). Incineration reduces the waste volume by over 90% but with the release of MNPs and other hazardous substances (e.g., dioxins) into the atmosphere (Allen et al., 2019). Even before the pandemic, the International Solid Waste Association reported that the present waste disposal arrangements have been incapable of handling plastic waste properly (Jang et al., 2020). Coupled with the inevitably impending increase of plastic consumption during the pandemic, the situation will further overwhelm waste disposal systems worldwide (Patrício Silva et al., 2020). Thus, the search for circular economic solutions becomes more urgent than ever.

The circular economic solution requires plastic waste to be guided by the "3R" principles: reduce, reuse, and recycle (Figure 1). Governments have sought to minimize plastic use by raising public awareness of the negative consequences of MNPs pollution. Through outreach and advocacy, the public is encouraged to reduce plastic consumption through daily life decisions such as giving up plastic consumer products, applying reusable materials and recycling plastic wastes for multiple purposes. It should be noted that diminishing plastic consumption in lab work is also very critical as researchers (only accounting for 0.1% of the total population) disproportionately cause approximately 5.5 million tons (2%) of plastic waste worldwide (Urbina, M., Watts, A., Reardon, 2015). Some regulations were promulgated to ban plastic of low quality from entering the market and levy taxes on plastic consumption (Clancy et al., 2023). Meanwhile, some plastic products free of hazardous materials, such as plastic packaging (daily) and pipette-tip boxes (laboratory), could be reused after cleaning and disinfection (Wu et al., 2024b).

Recycling has emerged as a promising technology to reduce the impact of plastic wastes (Qi et al., 2020). According to plastic types and applications, different approaches including primary, secondary, tertiary and quaternary recycling can be adopted (Liu et al., 2024). Primary recycling is defined as closed-loop recycling, whereas secondary recycling referred to downgrading. These two recycling methods belong to mechanical recycling, which is the key approach employed to recycle plastic wastes (Liu et al., 2024). Mechanical recycling has several limitations, including difficulties in sorting out and high levels of contamination (Bezeraj et al., 2024). Tertiary recycling refers to completely depolymerizing the plastics into chemical constituents, which are then converted into value-added products, while quaternary recycling refers to recovering energy from waste or valorization (Wu et al., 2024b). Current studies focus on tertiary and quaternary recycling with three main directions: improving the recycling efficiency, reducing the need for sorting and expanding recycling plastic types. Two main

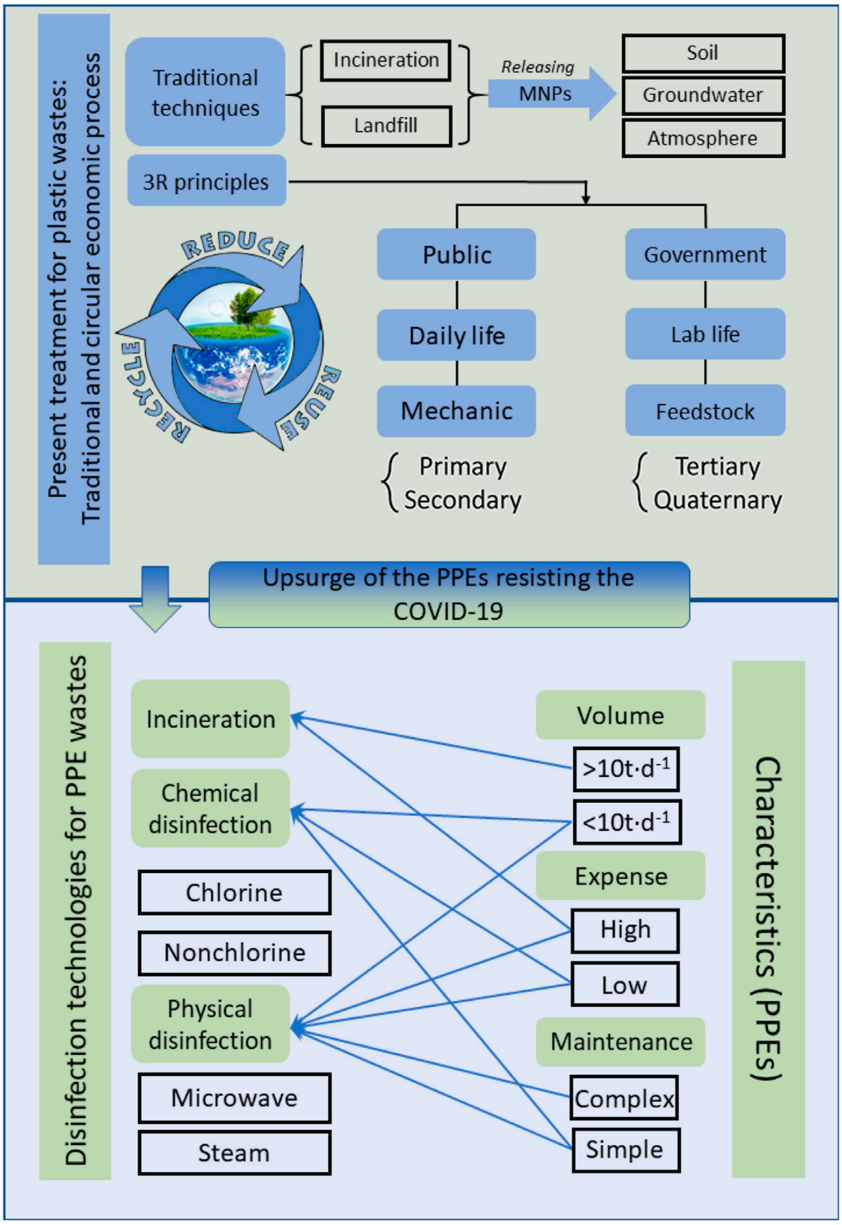

FIGURE 1
Present and advanced management for plastic wastes and the disinfection process for PPE wastes generating from resisting the COVID-19.

thermochemical routes were further proposed, namely, pyrolysis and gasification. Through pyrolysis, the single-type or mixed plastics wastes were converted into a mixture of value-added products such as hydrocarbons, hydrogen, carbon nanotubes, carbon monoxide and liquid fuels (Wu et al., 2024b). Gasification theoretically offers feedstock flexibility regarding the plastic type that can engender various types of useful gases (Choi et al., 2024). Yao et al. (2018) demonstrated a two-step process, including decomposition and catalyzation, that can reform plastic wastes to hydrogen-rich gases. Great improvement on a one-step technique was proposed by deconstructing plastics into hydrogen and carbons simultaneously (Jie et al., 2020). With the catalyzation of aluminum ferrite spinel, a yield of over 97 wt% of the hydrogen (55.6 $mmol{\cdot}g^{-1}$ plastic) was produced from the depolymerized plastic (Jie et al., 2020). Another one-step technique developed by Zhang et al. (2020) converts PE of various grades directly to liquid alkylaromatics at low temperatures (280°C ± 5°C), and the yield rate was kept above 80 wt% simultaneously. Although these techniques are still in the lab-scale, the prospects for treating the plastic wastes as a valuable sourced feedstock for generating value-added products seem attractive and promising.

3 Treatment for PPEs related to the COVID-19 pandemic

Eliminating the pathogens or virus is a critical procedure in the safe handling and disposal of abandoned PPE before any further treatment can be conducted. This is particularly crucial in the context of highly infectious diseases such as COVID-19, where improper disposal could lead to secondary transmission. In the COVID-19 pandemic, around 247 tons·day^{-1} of medical wastes were generated in Wuhan, approximately 5 times higher than before the outbreak (40–50 tons·day^{-1}) (You et al., 2020). A similar increase in medical waste was also found in many other cities that were affected by the pandemic. These massive discarded PPEs are far beyond the treatment capacity of hazardous wastes. Therefore, some countries try to utilize the municipal solid waste management system. According to the regulations on the administration of medical wastes, these wastes can be further handled after being decontaminated adequately through incineration, chemical and physical disinfection (Janik-Karpinska et al., 2023). Incineration treatments refer to the process of eliminating pathogens or viruses completely under a high temperature. As most of PPEs are made by PP and polyester, the incineration processes are relatively harmless, straightforward and efficient in which up to 90% organic matters could be burned up at over 800°C, thereby eliminating the hazardous components after the complete combustion. However, the remaining ash and gaseous byproducts must be carefully managed to prevent secondary pollution. The process is widely adopted when dealing with waste of large volume (>10 t·d^{-1}) with sufficient financial support (Figure 1). Despite it contained high effectiveness, incineration still requires substantial financial and infrastructural support, making it less feasible for regions with limited waste volumes (<10 tons per day) or inadequate funding. When the waste volume is smaller than 10 t·d^{-1} with limited financial resources, both chemical and physical disinfection would be preferred. Chemical disinfection is the process of killing pathogens or viruses with some typical disinfectants, including chlorine- (e.g., sodium hypochlorite) and nonchlorine-disinfectants (e.g., hydrogen peroxide, ozone, UV, etc.) (He et al., 2020). Chlorine disinfectants effectively inactivating pathogens by oxidizing the peptide bonds and inactivate the proteins. However, this process would release harmful byproducts such as dioxins and aromatic chemicals, which pose environmental and health risks. Common nonchlorine-disinfectants, like ozone, hydrogen peroxide and ultraviolet irradiation, offer safer disinfection with minimal harmful residues. They are often utilized to denature the proteins, resulting in the inactivation of the viruses. Physical disinfection means the destruction or removal of the pathogens by physical methods, including microwave and steam disinfection. Microwave with wavelengths between 915 ± 25 and 2450 ± 50 MHz can be absorbed by the substances and then generate the heat via molecules vibrating and rubbing (Wang et al., 2020).With the accumulation of the heat, the temperature would rise to the range from 177°C to 540°C and exhibit high-temperature disinfection under the inert atmosphere. This method has been confirmed to be much effective in on-site inactivate coronavirus by the Chinese Ministry of Ecology and Environment. Another common technique is steam disinfection, referring to the wet heat treatment that inactivates the proteins and kills the microorganisms under the saturated water vapor (93°C–177°C) (Ilyas et al., 2020). Under this temperature, the time needs for disinfection often around 20 min. This technique has been proved to contain low investment and operation cost (Pereira et al., 2025). Consequently, the amount of trash, available funds, and infrastructure all influence the decontamination method selection. For large-scale treatment, incineration is still the best option, but for smaller operations, chemical and physical disinfection offer good substitutes. In order to ensure sustainable medical waste management during future pandemics, future research should concentrate on increasing disinfection efficiency while reducing environmental effects.

4 Removal of MNPs using sorption and filtration methods

The ecotoxicity of MNPs calls for the development of further removal techniques, including sorption and filtration methods. These small particles are prone to being adhered onto the surface of marine algae, such as *Fucus vesiculosus, Pseudokirchneriella subcapitata*. The results found that the microalgae capabilities could be relatively high for the MNPs with positive charges as the electric attraction effects generated from the anionic polycarbohydrates (Wang et al., 2025). Through adsorption, microplastics could be captured and then removed by the filtration process. Among filtration technologies, membrane-based technologies have been identified as highly efficient filtration method that can successfully remove MNPs from aquatic environments. For instance, membrane bioreactors achieved a remarkable removal rate of 99.9%, reducing the turbidity from 195 NTU to <1 NTU within just 20 min, regardless of MNPs' shape or size, even microfibers as small as 10–100 μm in both influents and effluents (Talvitie et al., 2017). When integrated with the activated sludge technique, the removal technique could be successfully scaled up to the pilot-scale, achieving a 99.4% removal efficiency (Lares et al., 2018). However, practical challenges limit its applicability for on-site MNP removal in natural water bodies. Consequently, researchers have shifted focus toward biological interaction as a sustainable alternative to degrade the natural or synthetic plastics. Several outstanding work demonstrated that the MNPs in the environment can be degraded by a series of microorganisms in laboratory trials, such as bacteria (Yoshida et al., 2016), enzymes (Austin et al., 2018; Tournier et al., 2020), and worms (Yang et al., 2015b; 2015a). In detail, *Ideonella sakaiensis*, a bacterium discovered by Yoshida et al. (2016) broke down polyethylene terephthalate using specialized enzymes like PETase. Similarly, the gut microbiota of *Galleria mellonella* waxworms enables polyethylene degradation, revealing insect-associated microbial communities as novel biodegradation agents (Yang et al., 2015b; 2015a). Furthermore, marine microbial consortia have been shown to metabolize polyethylene and polypropylene, emphasizing the role of diverse microbial ecosystems in addressing plastic pollution. These studies collectively underscore the growing focus on harnessing natural biological interactions—spanning bacteria, insects, and marine microbes—to develop sustainable solutions for plastic waste remediation.

5 Conclusion and perspectives

The COVID-19 pandemic has exacerbated global plastic pollution, driven by unprecedented PPE consumption and systemic gaps in waste management. Traditional methods remain dominant but release hazardous byproducts, while 3R principles offer a framework for mitigating plastic pollution. However, challenges persist in scaling these technologies and improving sorting efficiency. PPE disposal requires pathogen decontamination prior to treatment, with incineration being effective for large volumes but limited by cost and infrastructure. Chemical/physical disinfection provides viable alternatives for smaller-scale operations, though environmental trade-offs (e.g., disinfectant byproducts) must be managed. Meanwhile, MNPs pose escalating ecological and health risks, necessitating innovative removal strategies. Emerging biological solutions demonstrate promise for degrading synthetic plastics, highlighting nature-inspired pathways for MNP remediation.

Future efforts should drive sustainable plastic transformation through multidimensional innovation. Thermochemical recycling technologies need scale up while enhancing energy efficiency and feedstock adaptability to valorize plastic waste. Concurrently, biological degradation requires advancement to address the environmental persistence of recalcitrant polymers. Globally harmonized policies should enforce waste segregation standards under frameworks with assisted by the managements of environmental monitoring networks. Moreover, the cross-disciplinary research should be strengthened to unify materials innovation, microbiome engineering, and climate-resilient governance, creating a closed-loop nexus that simultaneously tackles plastic pollution and ecosystem health. The study tried to submit a comprehensive proposal to reduce the plastic waste to reduce the environmental burden brought by the COVID-19 pandemic.

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Conflict of interest

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