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Release of microplastics and nanoplastics in water from disposable surgical masks after disinfection

Hao Liang a, Na Wang a, Di Liu a, Wei Ge b, Ningning Song a, Fangli Wang a, Chao Chai a, a
a School of Resources and Environment, Qingdao Engineering Research Center for Rural Environment, Qingdao Agricultural University, Qingdao 266109, China
b School of Life Sciences, Shandong Province Key Laboratory of Applied Mycology, Qingdao Agricultural University, Qingdao 266109, China

ARTICLE INFO

Keywords:
- Microplastics
- Nanoplastics
- Plastic pollution
- Face mask
- Disinfection

ABSTRACT

During the COVID-19 pandemic, disposable surgical masks were generally disinfected and reused due to mask shortages. Herein, the role of disinfected masks as a source of microplastics (MPs) and nanoplastics (NPs) was investigated. The amount of MPs and NPs released from masks disinfected by UV ranged from 1054 ± 106 to 2472 ± 70 and from 2.55 ± 0.22 × 109 to 6.72 ± 0.27 × 109 particles/piece, respectively, comparable to that of the undisinfected masks, and the MPs were changed to small-sized particles. The amount of MPs and NPs released after alcohol and steam treatment were respectively lower and higher than those from undisinfected masks, and MPs were shifted to small-sized particles. The amount of MPs and NPs released in water after autoclaving was lower than for undisinfected masks. In all, the amount of fibers released after disinfestation decreased greatly, and certain disinfection processes were found to increase the amount of small-sized NPs released from masks into aqueous environments.

1. Introduction

The coronavirus disease 2019 (COVID-19) pandemic has spread to 212 countries and territories on an unprecedented scale since 2019 (WHO, 2020a). Globally, >146 million people have been infected with COVID-19 (De et al., 2022). Recently, UK authorities have made new findings on COVID-19, suggesting that a new variant exists that is more transmissible than the original strain (WHO, 2020b). The continuation of the COVID-19 epidemic in the foreseeable future is likely.

Disposable surgical masks (e.g., N95 masks), medical/surgical masks, and normal medical masks are often used for epidemic prevention and control and made of nonwoven or melt-blown fabrics. As polypropylene (PP) is low-cost and easy to process, it is often processed to produce nonwoven and melt-blown fabrics (Chua et al., 2020). Disposable surgical masks have been identified as a new source of microplastics (MPs) and nanoplastics (NPs) (Canning et al., 2020; Selvakumar et al., 2021; Ma et al., 2021; Wu et al., 2022). Plastic particles smaller than 5 mm in size are commonly referred to as MPs (Gigault et al., 2018). MPs can be ingested by organisms and transferred through the food chain, posing potential risks to human health and ecosystems (Browne et al., 2008). Plastic particles ranging in size from 1 to 1000 nm are defined as NPs, which diffuse into water and interact with microorganisms, organic matter, and metals (Bouwmeester et al., 2015). Due to their nanoscale properties, NPs can cross all biological barriers (e.g., cells and tissues) into organisms, posing a great threat to organisms and ecological environments (Manfra et al., 2017). Masks are reported to be discarded on litter city streets and flow into aquatic environments such as rivers, lakes and oceans through urban sewage channels (De-la-Torre et al., 2021; Okoku et al., 2021).

At the beginning of the epidemic, most countries and regions were unprepared for the surge in demand for masks. Even now, some low- and middle-income countries face mask shortages (Rohit et al., 2021). Insufficient supply has led to the reuse of masks after disinfection via soapy water, ultraviolet irradiation (UV), steam, hydrogen peroxide vapor, heat, autoclaving, ozone gas, microwave, alcohol, bleach soaking, ethylene oxide, ionizing radiation, or high temperatures (Rubio-Romero et al., 2020; Kim et al., 2020) found that disinfection with 70 % ethanol could eliminate the electrostatic charge on masks and reduce their filtering performance. In addition, Grinshpun et al. (2020) found that autoclaving and ethanol affected the performance and integrity of the masks, with autoclaving leading to physical damage. During UV disinfection, low UV-C doses resulted in the incomplete decontamination of the masks, but high UV-C doses damaged the mask structure (Hamzavi et al., 2020). Heating changed the hydrophobicity of the...
surface of the masks; cracks in the fibers were observed at 70 °C, and the fibers were melted at 157 °C (Sales et al., 2021). The surface structure and oxygen-containing functional groups of MPs and NPs may change because of UV and ozonation, thereby affecting the decomposition release and adsorption capacity of MPs and NPs in the environment (Lin et al., 2020; Tian et al., 2017). MPs and NPs mainly originate from the fiber structure of masks. The disinfection process is likely to damage the fiber structure, which may affect the release of MPs and NPs. MPs and NPs in aquatic environments can be easily ingested by organisms, and can adsorb chemical substances in the water (PAHs, heavy metals, PCBs, etc.) (Liu et al., 2022). The altered adsorption capacity of disinfected MPs and NPs for chemical substances may exacerbate adverse effects on living organisms (Wang and Wang, 2018; Wu et al., 2020). It is of great significance to study the MPs and NPs released from disinfected masks. Thus far, the effect of disinfection on the release of MPs and NPs from masks into the water has not been investigated.

In this study, four common disinfection methods (i.e., steam, alcohol, UV irradiation, and autoclaving) were used to decontaminate three types of disposable surgical masks, and the structures of the masks after disinfection were observed by microscopic imaging. The MPs and NPs released from the masks into the water were respectively quantified by optical microscopy and nanoparticle tracking analysis technology, and the morphology and size of MPs and NPs were characterized. This study will contribute to a comprehensive assessment of the environmental risks of MPs and NPs from disposable surgical masks.

2. Materials and methods

2.1. Selection of masks and disinfection methods

Six brands of three types of disposable masks including N95 masks, medical/surgical masks, and normal medical masks were purchased from different manufacturers (China, Table 1). All masks were new and intact and met the corresponding Chinese implementation standards for medical devices. There were no respirators on these masks, and no accessories were removed in the experiment.

The masks were disinfected by four methods, namely UV irradiation, steam, alcohol, and autoclaving. The detailed steps of the disinfection processes were as follows:

UV: The masks were irradiated with a 250–275 nm, 17.1 W/m² UV lamp for 30 min (Ivo et al., 2020; Ludwig-Begall et al., 2020).

Steam: The masks were steamed in a household electric cooker for 30 min and then dried overnight at room temperature (Rubio-Romero et al., 2020).

Alcohol: The masks were sprayed completely with 70 % alcohol for 30 min and then dried overnight at room temperature (Grinshpun et al., 2020).

Autoclaving: The masks were autoclaved at 121 °C at 1 atm for 30 min and then dried overnight at room temperature (Kim et al., 2020).

2.2. Plastic particles release experiment

A 24-h experiment was conducted to analyze the amount of MPs and NPs released into the water from six brands of masks after different disinfection processes. The mask was placed in a 250 mL conical flask with a stopper, and 200 mL of deionized water was added. The shaker temperature was maintained at 25 °C. Then, the conical flask was placed on a shaker and shaken at 220 r/min for 24 h. After shaking, the deionized water in the conical flask was filtered through a 1 µm cellulose ester membrane, and the filters and filtrate were used for subsequent analysis. The masks were put into a clean glass dish and weighed after drying, and the weight loss of the masks was calculated. A flask without a mask was also set up as a blank group to monitor contamination. Three replicates were used for each sample.

2.3. Microplastic analysis

The MPs retained on the filter were observed with an optical microscope (Olympus CX23), and the images were captured by a digital camera module of the microscope. The MPs were then counted according to the previous method (De et al., 2018), and the characteristics of MPs, such as their shape, size, and color, were recorded using S-EYE software. Fibers and debris were randomly selected as representative MP samples, respectively. They were picked with tweezers for the identification of polymer components under a Raman microscope (LabRAM HR800), and the Raman spectra were recorded from 100 to 4000 cm⁻¹ at a laser wavelength of 532 nm.

2.4. Nanoplastic analysis

Particles 0–1000 nm in size in the filtrate were analyzed by nanoparticle tracking analysis (NTA) using ZetaView (Particle Metrix, Germany). The instrument was calibrated using 100 nm PP standards, and the water sample was pushed into the sample chamber at a constant speed with a 5 mL glass syringe. Each sample was monitored for 60 s, and the instrument was washed with deionized water between each sample until no particles passed through. The camera level was adjusted according to the dispersion to ensure that the particle size was moderate, and the low-intensity particles were observed to the maximum extent. The detection threshold was unified each time. The minimum track size and minimum expected particle size were both set to automatic, and the blur was set to 5 × 5 (Lambert and Wagner, 2016; Caputo et al., 2021).

2.5. Quality assurance and quality control

Particle-free nitrile gloves and a lab coat were worn during the

| Type                  | Brand no. | Standard       | Color       | Weight (mg) | Layer | Description                                                                 | Manufacturer                                      |
|-----------------------|-----------|----------------|-------------|-------------|-------|----------------------------------------------------------------------------|---------------------------------------------------|
| N95 mask              | Mask A1   | GB19083-2010   | White       | 5.43        | Four  | Sterile, filtration rate ≥ 99 %, the products are composed of PP spunbond non-woven fabric, melt-blown non-woven fabric, and hot-air cotton | China, Jiangsu Xianyao Medical Equipment Co., Ltd. |
|                       | Mask A2   |               | White       | 4.21        | Four  | Sterile, filtration rate ≥ 95 %, inner and outer layers of PP non-woven fabric, middle layer of PP meltblown fabric | China, Henan Yubei Eisai Co., Ltd.                 |
| Medical surgical mask | Mask B1   | YY/0469-2011   | Blue        | 2.95        | Three | Sterile, filtration rate ≥ 95 %, inner and outer layers of PP non-woven fabric, middle layer of PP melt-blown fabric | China, Jiangsu Huicheng Medical Technology Co., Ltd. |
|                       | Mask B2   |               | Blue        | 3.27        | Three | Sterile, filtration rate ≥ 95 %, inner and outer layers of PP non-woven fabric, middle layer is PP melt-blown fabric | China, Qingdao Hainuo Biological Engineering Co., Ltd. |
| Normal medical mask   | Mask C1   | YY/T0969-2013  | Blue        | 3.17        | Three | Non-stereile, filtration rate ≥ 95 %, inner and outer layers of PP non-woven fabric, middle layer of PP meltblown fabric | China, Henan Chaoya Medical Equipment Co., Ltd.     |
|                       | Mask C2   |               | Blue        | 3.31        | Three | Non-stereile, filtration rate ≥ 95 %, inner and outer layers of PP non-woven fabric, middle layer of PP meltblown fabric | China, Jining Aide Biotechnology Co., Ltd.          |
experiment. The deionized water used in the release experiments was filtered through a 1 μm cellulose ester membrane, and all glassware was rinsed with deionized water before use. The filtration process was carried out in an ultra-clean environment, and the top of the filter was sealed with aluminum foil. Both MPs and NPs detected in the blank were subtracted from the results.

2.6. Data analysis

Statistical analysis was performed using SPSS version 26.0 (SPSS Inc., Chicago, IL, USA). Analysis of variance (ANOVA) was used to analyze the differences in the amount of plastics released into the water from the masks, and the levels of significance were released set at p < 0.05.

3. Results and discussion

3.1. Deterioration of masks after disinfection

The appearance of the masks was visually inspected and the micro-structural changes of the masks were examined under the optical microscope. After disinfection by steam and autoclaving, the masks remained intact without damage while there was slight wrinkling on the surface. All masks in this study were composed of an inner, middle, and outer layer, and the middle layer of N95 masks was superimposed by two layers of melt-blown cloth. The changes in the microstructure of different types of masks caused by the same disinfection method were similar (Fig. 1). No obvious changes in the microstructure of masks disinfected with UV irradiation were observed. However, the fiber structure of the inner and outer layers of the masks was broken and deformed, and some fibers in the middle layer were fused after the masks were sterilized by steam and autoclaving. Compared to steam treatment, the fracture, deformation and fusion phenomena of the fiber structure of the masks after autoclaving are more obvious.

Li et al. (2021) found that the multilayered internal structure of the ordered crystalline layer and the amorphous layer in PP deteriorated after PP-produced baby bottles were sterilized by autoclaving at 100 °C. Viscusi et al. (2009) reported that the exposure of masks to high temperatures can damage the integrity of the fiber structure. In this study, the steam temperature was 100 °C and the temperature during autoclaving was 121 °C. The fiber structure of the masks after steam or autoclaving treatment was deformed and ruptured while that of the masks following treatment with alcohol was not, indicating that steam and autoclaving can cause more damage to masks than alcohol. Previous studies found that the structural degradation and damage to the integrity of the fibers may occur when the masks were exposed to chemicals such as alcohol (Centers for Disease Control and Prevention, 2020; Grinshpun et al., 2020). Structural changes may not be detectable in masks disinfected with alcohol due to the limited visibility of light microscopy.

3.2. Total release amount of micro/nanoplastics

The total amount of MPs released from masks after disinfection is shown in Fig. 2a. UV-disinfected masks released the highest amount of MPs (1054 ± 106 to 2472 ± 70 particles/piece), which presented no significant difference from the control (CK, p > 0.05). The amount of MPs released from masks disinfected by steam, alcohol, and autoclaving were 554 ± 10 to 930 ± 25, 396 ± 8 to 641 ± 31, and 400 ± 8 to 978 ± 46 particles/piece, respectively, which were lower than that of UV-disinfected masks.

The total amount of NPs released from the masks is shown in Fig. 2b. Masks disinfected by UV released 2.55 ± 0.22 × 10^9 to 6.72 ± 0.27 × 10^9 particles/piece which was comparable to that of the CK. Masks disinfected with alcohol released the most NPs (5.79 ± 0.14 × 10^9 to 43.29 ± 1.93 × 10^9 particles/piece), followed by steam treatment masks (3.99 ± 0.14 × 10^9 to 24.39 ± 3.33 × 10^9 particles/piece), with autoclaving releasing the lowest amount (1.2 ± 0.27 × 10^9 to 1.86 ± 0.26 × 10^9 particles/piece).

No significant difference in the release of MPs and NPs was observed between the types of masks (p > 0.05), but significant differences were found between the disinfection processes (p < 0.05). The amount of MPs and NPs released from UV-disinfected masks was comparable to the CK. However, the amount of MPs released from masks disinfected by alcohol and steam was lower, while that of NPs was higher than those from the CK. In addition, the amount of released MPs and NPs following

![Fig. 1. Optical microscope image of the mask structure after disinfection (scale bar = 0.5 mm).](image-url)
autoclaving treatment was lower than that of the CK. The amount of MPs and NPs released from masks disinfected by UV irradiation did not differ from that of the CK, as minimal damage to the mask material or surface structure was incurred following UV disinfection during this short period (Ivo et al., 2020; Ludwig-Begall et al., 2020). Disinfection using alcohol may change the mask structure and result in the easier release of MPs and NPs attached to the masks. Since NPs are lighter and smaller than MPs, NPs are more easily blown away by the gas. To confirm this, we collected water samples in the steam and autoclaving equipment and found that the amount of MPs and NPs was 595–1221 and $0.5 \times 10^6$–$7.9 \times 10^8$ particles, respectively. Moreover, the amount of MPs and NPs trapped in the autoclaving device was higher than in the steam device, as autoclaving generates higher pressures and a stronger airflow than steam. Therefore, the loss of MPs and NPs during the disinfection process resulted in fewer MPs and NPs released into the water after disinfection using steam or autoclaving.

3.3. Size of released micro/nanoplastics

The sizes of the MPs released from masks after disinfection were divided into 1–100, 100–500, 500–1000, 1000–2000, and >2000 μm (Fig. 3). MPs released from all of the disinfected masks and the CK were mainly 1–500 μm in size. As reported by Chen et al. (2021), MPs measuring 1–500 μm were predominant and originated from the direct release of MPs from the masks as well as the rupture of larger MPs. The release amount of 1–100 μm MPs (519 ± 11 to 1795 ± 117 particles/piece) from most masks disinfected by UV irradiation was higher than that of the CK while those of 100–500 μm MPs (374 ± 8 to 1336 ± 66 particles/piece) and 500–1000 μm MPs (20 ± 3 to 201 ± 9 particles/piece) were lower (Fig. 3), indicating that the MPs released from UV-disinfected masks changed from medium-sized to small-sized MPs. The strength of the mask material decreased under UV irradiation but this degree of decline varied by the type of mask (Lindsley et al., 2015). The non-woven fabrics of the inner and outer layers of the masks experienced weak UV penetration, and UV disinfection caused minor damage to the masks’ surface (Rubio-Romero et al., 2020). This may result in larger MPs being more easily broken into MPs measuring 1–100 μm. When most masks were disinfected by alcohol, steam, or autoclaving, the release amount of MPs with different size into the water significantly decreased (Fig. 3). This is because alcohol, steam, and autoclaving damage the fiber structure of the masks, resulting in the breakage of larger MPs into smaller MPs and NPs. Due to differences in the mask brands, the size distribution of MPs and changes caused by disinfection presented minor differences.

The size distribution of the NPs released from the masks after disinfection is shown in Fig. 4. The NPs released from masks form the CK and after UV irradiation and autoclaving were mainly concentrated in the 100–300 nm range, while the NPs released after steam and alcohol treatments were mainly concentrated in the 0–300 nm range. The NPs of 0–100 nm increased after the masks were disinfected by alcohol and steam. Disinfection by alcohol and steam led to rupture of MPs and NPs, resulting in smaller size and increased amount of NPs. These disinfected masks were further damaged by washout upon entering the water, resulting in the rupture of larger MPs and NPs into smaller ones. However, variation in the sizes of NPs released significantly decreased after autoclaving, as the autoclaving device captured a large amount of MPs and NPs. Silvia et al. (2021) found that the sizes of the NPs released from masks with different degrees of deterioration were mainly concentrated in the 0–500 nm range, which was similar to our results. In addition, the toxicity of NPs is related to its size, and the smaller the size, the greater the potential toxicity to marine zooplankton (Novotna et al., 2019). NPs can also threaten human health through the food chain (Jiang et al., 2019).

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**Fig. 2.** Amount of (a) MPs and (b) NPs released from disposable surgical masks after disinfection and (c) weight loss.
Therefore, the NPs of 0–100 nm in size generated from masks disinfected by steam and alcohol have greater potentially hazardous, and the pollution in aqueous environments caused by the release of MPs and NPs from disinfected masks requires attention.

3.4. Shapes and colors of the released microplastics

The shapes of the MPs released from masks after disinfection included debris and fibers (Fig. 5a). Aggregates, fragments, and mixture of the both were classified as debris. The MPs released from the CK were mainly fibers. The shapes of the MPs did not change noticeably after UV disinfection, as UV disinfection did not affect masks greatly. However, the amount of fibers released from masks after disinfection using steam,
alcohol, or autoclaving declined greatly (before disinfection, 887 ± 21 to 2165 ± 89 particles/piece; after disinfection, 309 ± 11 to 756 ± 20 particles/piece) while the reduction in the amount of debris released was smaller (before disinfection, 94 ± 3 to 349 ± 14 particles/piece; after disinfection, 30 ± 2 to 218 ± 4 particles/piece). The main structure of the masks is interwoven made up of disordered fibers, so more MPs were released as fibers than as debris (Shen et al., 2021). In addition, Alcohol, steam, and autoclaving can damage the mask structure, causing microplastic fibers to break into nanoplastic fibers, and microplastic debris are more difficult to break down than fibers.

Fig. 5. Characteristics of MPs released from disposable surgical masks after disinfection: (a) shape; (b) color.
The colors of the MPs released from masks after disinfection were divided into six groups: transparent, blue, red, black, yellow, and brown (Fig. 5b). White and translucent MPs were classified as transparent MPs because they were difficult to distinguish (Asamoah et al., 2019). Transparent MPs released from CK accounted for the largest proportion (77–87 %), since masks are mainly composed of colorless fibers (Fadare and Okofo, 2020). Blue, red, black, yellow, brown, and other colored MPs were created from impurities mixed into the mask during manufacturing and transportation (Christian et al., 2019). After the masks were disinfected by the 4 methods, the color distribution of MPs did not change greatly and the transparent MPs were still dominate, indicating that transparent and other colored MPs were reduced to a similar extent after disinfection.

4. Conclusions

The disinfection via autoclaving caused the most damage to the microstructure of the masks, followed by steam and alcohol treatment, while disinfection by UV irradiation had little effect on the microstructure of the masks. The total amount of MPs and NPs released from UV-disinfected masks were comparable to the CK; however, the released MPs changed from medium-sized MPs to small-sized MPs but the sizes of the NPs did not change significantly. The total amount of MPs released after alcohol and steam treatment decreased, but the total amount of NPs increased and smaller NPs were observed. Hence, MPs with various sizes released from alcohol and steam treatments changed to NPs, and NPs also became smaller in size. Since some MPs and NPs were trapped in the disinfection equipment, the total amount of MPs and NPs released into the water decreased, and the amount of MPs with a size of 100–500 μm decreased most and the NPs with each size decreased. The amount of released fibers from masks after disinfection by alcohol, steam, or autoclaving decreased significantly, while the amount released following UV treatment did not change significantly. There was no obvious change in the color distribution of the masks after disinfection by any of the four disinfection methods. Therefore, pollution in aqueous environments caused by the release of MPs and NPs from disinfected masks cannot be ignored.

CRediT authorship contribution statement

Hao Liang: Methodology, Data curation, Formal analysis, Writing – original draft. Na Wang: Visualization, Writing – review & editing. Di Liu: Formal analysis, Writing – review & editing. Wei Ge: Supervision, Formal analysis. Ningning Song: Methodology, Writing – review & editing. Fangli Wang: Visualization. Chao Chai: Conceptualization, Supervision, Project administration, Funding acquisition.

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.

Data availability

The data that has been used is confidential.

Acknowledgments

This work was supported by the Shandong Provincial Natural Science Foundation (ZR2020MD107).

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