

A threat or not? A global-scale investigation on microplastics inhalation during the first-ever worldwide face-mask wearing against the COVID-19 pandemic

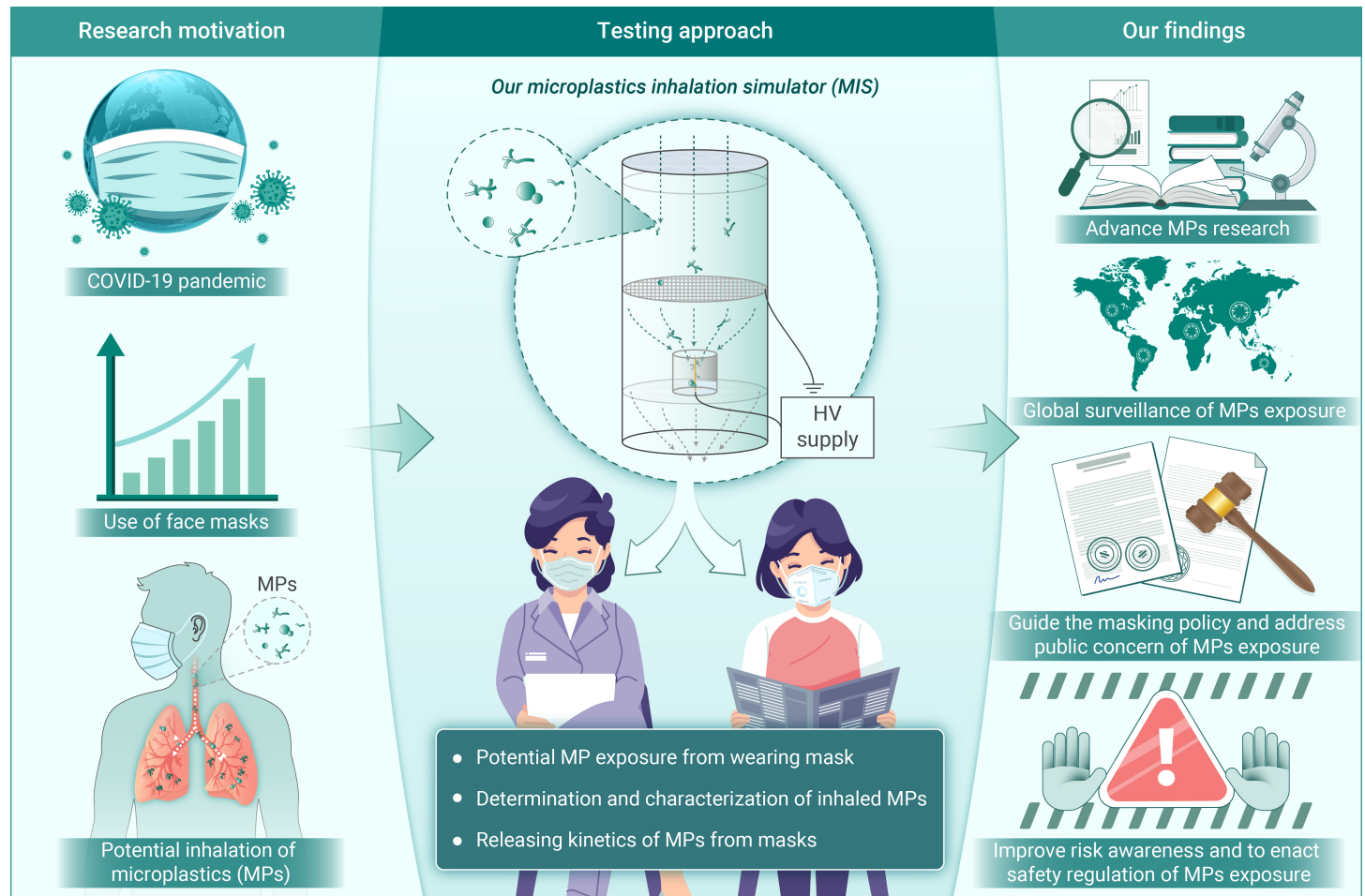
Pengfei Wu,^{1,3,4} Chiu-Wing Chan,^{1,4} Hongli Tan,¹ Sin-Yung Siu,¹ Xingchen Zhao,² Guodong Cao,¹ Zhu Yang,¹ Kangning Ren,^{1,*} and Zongwei Cai^{1,*}

*Correspondence: zwcai@hkbu.edu.hk (Z.C.); kangningren@hkbu.edu.hk (K.R.)

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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Developed a microplastic inhalation simulator system with a ventilation rate similar to that of an average person.
- Conduct a global study microplastic inhalation using 209 face masks with varying filtration grades and qualities.
- Investigate the kinetics of microplastic inhalation during mask usage in laboratory and laminar flow hood.
- Analyzed the potential global impact and risks associated with significant mask-wearing on microplastic inhalation.
- Wearing a high-standard face mask could decrease total microplastic inhalation as compared to the pre-pandemic era.

A threat or not? A global-scale investigation on microplastics inhalation during the first-ever worldwide face-mask wearing against the COVID-19 pandemic

Pengfei Wu,^{1,3,4} Chiu-Wing Chan,^{1,4} Hongli Tan,¹ Sin-Yung Siu,¹ Xingchen Zhao,² Guodong Cao,¹ Zhu Yang,¹ Kangning Ren,^{1,*} and Zongwei Cai^{1,*}

¹State Key Laboratory of Environmental and Biological Analysis, Department of Chemistry, Hong Kong Baptist University, Hong Kong 999077, China

²Department for Evolutionary Ecology and Environmental Toxicology, Goethe University, Frankfurt am Main 60438, Germany

³State Key Laboratory of Tree Genetics and Breeding; Co-Innovation Center for Sustainable Forestry in Southern China, Nanjing Forestry University, Nanjing 210037, China

⁴These authors contributed equally

*Correspondence: zwcai@hkbu.edu.hk (Z.C.); kangningren@hkbu.edu.hk (K.R.)

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A spike in public attention on whether wearing masks will increase microplastics (MPs) inhalation has recently been triggered by the major transformation in widespread masking in public ever since the pandemic. To timely address this question and provide reliable insights for public health recommendations, mask users, and producers, we developed a platform based on a custom inhalation simulator, and conducted comparative measurements to investigate masks as both a source of MP release and a barrier to MP inhalation. We examined 209 mask brands from 46 countries/regions, covering multiple filtration and quality levels. Our kinetic study revealed that MP leaching primarily occurs during the initial period of wearing a new mask. Subsequently, masks act as a barrier, reducing MP inhalation compared to not wearing a mask. Hence, frequently changing masks or using masks from improper manufacture process may not be a wise choice. We also observed significant variations in MP inhalation character among different quality levels and brands, indicating the need of future safety standards to this end. Overall, the estimated worldwide inhalation of MPs during the pandemic office hours is 1.16 times that of the pre-pandemic era. However, the impact of MP inhalation could be changed by wearing masks with higher filtration grade (and better quality). For instance, if everyone were to wear FFP-3 masks, a 28.8% reduction in MP inhalation would be expected compared to not wearing a mask.

INTRODUCTION

The novel coronavirus pneumonia (COVID-19) has boosted the global consumption of face masks to an unprecedented amount.¹⁻⁸ It is estimated that approximately 129 billion face masks are used every month during the pandemic.^{1-3,9} On the other hand, some new paradigms of mask usage have emerged.¹⁰⁻¹² For instance, probably for the first time in human history, children – usually a vulnerable group to environmental toxicants,^{13,14} have been wearing face masks as a whole population for a long period. Notably, the practice of prolonged and widespread mask wearing in public areas has become a new societal norm, partly due to the major shift in public understanding about the role of masks in mitigating the spread of airborne diseases,^{9,15-19} as well as the increased awareness of rapidly transmitting diseases in the community.²⁰ With the significantly enlarged scale of mask use, a concern has also arisen about whether face masks can be a source of microplastics (MPs; ≤ 5 mm) contamination and harm the users.^{21,22} Answer of this question will not only be useful for addressing the concern from the public and facilitating governments' policy in pandemic control measures, but also helpful in guiding the future manufacturing of face masks.

Despite made into different types and styles, face masks serving as simplified or professional filtering respirators are commonly made of different textiles containing polymeric fibers. In general, they consist of three layers: the outer and inner covers are usually made of nonwoven fabrics containing polypropylene (PP), polystyrene (PS), or nylon,²³ which are commonly produced through a spun-bond process and mainly used as protective barriers, although for some products woven fabrics are also used for these two outer layers. On the other hand, the middle layer is for particle filtration, which is usually composed of one (for surgical masks) or multiple (for respirators,

e.g., N95) layers of melt-blown PP fabric.^{23,24} The melt-blow process uses high-velocity hot air to blow molten thermoplastic resin extruded from a die into fine fibers,²⁵ which are collected on a conveyor and self-bond into a fabric web with small pores for filtration function. Whilst these processes are highly efficient in generating fabrics with high porosity and desired pore sizes, they might have chance to generate a substantial number of free or loosely bound MPs in the fabric, which would present in the produced face masks and probably be inhaled by the user,²² although there has been ongoing debate on the degree of biological effects on human that MPs could possibly induce. Notably, previous studies have already revealed that synthetic fabrics used for various purposes can release MPs due to factors such as aging (e.g., through UV exposure),²⁶ washing,^{27,28} and wearing (e.g., from friction),^{29,30} in addition to the MPs that may be present in the fabrics from the production process.^{31,32} However, the usage conditions for face masks differ from those of typical clothing. As a result, the understanding remains insufficient about the specific quantities of MPs that may be released from a typical face mask during normal usage. Moreover, a commonly missing aspect is that wearing a mask may also decrease the inhalation of MPs from ambient air, making it not necessarily connected with increased MP inhalation.³³ In this case, it is worth investigating the impact of prolonged masking to microplastics inhalation, especially considering the unprecedented boom of face mask usage triggered by the COVID-19, and the major transformation of mask use scale since then.

However, insufficient information is available at present to answer the above question. Actually, there are still some matters to deal with before the question can be discussed. Firstly, a matured method for testing the MP releasing from face masks is still missing. Notably, prior studies on the release of MPs from face masks adopted the established protocol^{34,35} which were originally designed for testing the filtration efficiency of face masks (e.g., NIOSH and ASTM).³⁶⁻³⁸ Designed for validating the protection efficiency of face masks, these protocols employ a strong vacuum power to carry the tested particles through the tested masks at high flowrate, and capture the penetrated particles on a filter membrane.³⁹ Although the protocols have been proven effective for testing the reliability of masks against bacteria and particles, it is arguable for measuring the release of MPs during usage. On the one hand, the high rate of air flow will cause a high shear stress (to the square of flow rate) to the fibers in mask membranes,^{40,41} making it possible to record exaggerated MP release; on the other hand, the MPs released from face masks were mostly the irregularly shaped fibers, which are not recommended for filter membrane-based detection. Secondly, the study needs to be based on sufficiently representative samples, considering type and manufacturer differences.²² Accordingly, a global scope study is necessary. Thirdly, it is also important to know the dynamic characteristics of the MP release, which could address some commonly raised questions from the public, e.g., whether the MP release is quicker in the initial period of mask usage or after a while instead. Finally, understanding of the overall risk of MP inhalation should not be limited to the release of MP from the mask. Instead, it should be based on comparing the total number of MPs inhaled with/without wearing a face mask. Notably, none of the above four aspects has been effectively addressed till now.

The present study aims at answering the questions through a thorough investigation to address the above four requirements. Different from the commonly used testing scheme, we created a microplastic inhalation simulator (MIS) system with ventilation rate close to that of normal people and electrostatic rather than the filter-based particle collection. We tested face masks from 46 countries/regions, covering 209 kinds with different brands, classified into categories by both filtration grades (e.g., N95, surgical masks) and qualities (e.g., imitation, in contrast to genuine) and analyzed respectively. We also studied the kinetics of MP release during the mask usage, and identified the source of MPs inhaled when a mask is used in ambient environment, e.g., the types and ratios of MPs inhaled including those released from the mask and those penetrated the mask from the outside environment. Based on these results, we discussed the correlation between MP inhalation risk and the type (filtration structure design) of mask. In addition, we briefly studied the risk of MP inhalation with regard to mask reuse. Finally, we developed an approach to estimate the overall impact of mask wearing to MP inhalation globally. We calculated the average exposure to MPs per capita of different countries/regions based on the reported mask-wearing facts and the corresponding inhalation parameters measured, and discussed various potential outcomes when using different types of masks worldwide. In this way, the present study could advance the understanding on the possible risk of MP inhalation during large-scale extensive usage of face masks for pandemic control.

MATERIALS AND METHODS

Raw materials and sample preparation

The information of the tested face masks from 46 countries or regions, covering 209 brands, four types (surgical and FFP 1-3), and two quality levels (genuine and imitation), are illustrated in Figures 1A & S1 and Table S2. The masks were tested using the MIS (Figure S2) as described in Supplemental Methods (Notes S1-S3) with the breath rate at 7 L·min⁻¹ for 8h (to simulate normal working hours of a day), respectively.⁴² At the bottom of the simulator, we designed a strong electric field to concentrate the released MPs falling into the small glass container with the assistance of electrostatic attraction (Notes S1-S3 and Figures S2-S6). Experiments of MP release via inhalation were conducted in triplicates inside a laminar flow hood.

Design principle of the MIS

A MIS has been developed in the present work to collect the MPs inhaled by the user during simulated usage of a mask. The MIS consists of four components, including a polymethyl methacrylate (PMMA) cylindrical tube (75 mm diameter; 150 mm tall) coated with antistatic reagent, a negatively charged electrode (-5.5 kV), a grounded metal mesh, and a collector which is also coated with antistatic reagent. The face mask samples were sealed on the top of the cylindrical tube, and a ventilating fan was sealed at the bottom of the tube to simulate the inhalation condition (air flowrate: ~7 L per minute for all tests expect for masks tailored for Children, for which the air flowrate was set at ~15 L per minute as seen in Table S4).⁴³⁻⁴⁵ The corona discharge current between the emitting electrode and the grounded mesh was measured with a DS1102CA digital oscilloscope (Rigol Technologies, INC, USA). The detailed information of the design and working principle of the MIS is provided in Notes S1-S2. To further enhance the validation efforts, the Rev. P wind flow sensor, a sophisticated hot wire anemometer, was employed alongside the Sensirion SFM3300 mass flow meter for cross-validation. This dual-measurement approach was pivotal in confirming the accuracy and reliability of the calibration process. The calibration data is provided in Figures S4-S5.

Identification, quantification, and characterization of collected MPs

After the simulated inhalation, MPs in the container of the MIS were washed off with Milli-Q water (Millipore Co., U.S.A.) and filtered onto a GF/C glass fiber membrane (size: 0.8 µm; Whatman, UK), which were then determined using micro-Fourier transform infrared spectrometer (µ-FT-IR) apparatus with a liquid-nitrogen-cooled micro-imaging system (Spotlight 200i, PerkinElmer, USA, Note S3).⁴⁶ The entire spectrum of each collected particle was obtained through four accumulations ranging from 650 to 4000 cm⁻¹, using which the polymer composition of the particle was identified by

comparing to the polymer database (around 16,000 reference spectrums; PerkinElmer Database, USA). A compliance degree at above 70% was regarded as reliable and used in the identification. The abundance, size, and color of the MPs were characterized using fluorescence microscopy (DM2500, Leica, Germany) with 10× magnification and determined using ImageJ software; related details are shown in Notes S4-S5. The size distribution of the detected MPs was analyzed using a strategy we reported before.^{30,46} The 3D micromorphology of the fabrics in the face masks was inspected using a confocal laser scanning microscopy (Nikon Eclipse Ti2, Japan) and a scanning electron microscope (SEM; LE01530, ZEISS, Germany); related details are provided in Notes S6-S7.

Model fitting of the simulated MP inhalation results

An 8-h simulated inhalation experiment⁴⁷ was conducted in both laminar flow hood and indoor environment to investigate the release/penetration kinetics of MPs regarding the three types of masks. Three models are compared to describe the release process of particles from the face:⁴⁸⁻⁵¹

$$\text{Power function equation: } Q_t = kt^a \quad (1)$$

$$\text{Parabolic diffusion equation: } Q_t = kt^{1/2} + d \quad (2)$$

$$\text{Elovich equation: } Q_t = k \ln(t) + a \quad (3)$$

where t stands for the testing time (h), Q_t is the MP quantity detected at time t (fibers/pieces), k and a represent the rate constants, and d is the initially released MPs.

Assessment of MP exposure associated with face mask wearing

The human inhalation of MPs in 46 countries/regions was estimated by considering the MP inhalation during mask wearing (data from this study), the exposure time (8 hours each working day),⁵² the ratios for using surgical and FFP-3 masks,⁵³⁻⁵⁶ and the rate of mask acceptance (data from the *Elsevier*⁵⁶ and Government reports; Table S1). For each region, the MP inhalation per hundred people worldwide associated with wearing face masks was assessed according to equations (4)-(9):

$$E_{mp-i} = E_{sm-i} + E_{fm-i} \quad (4)$$

$$E_{sm-i} = A_i \times R_{sm-i} \times \frac{\sum_{j=1}^k N_{sm-i}}{k} \times C_{sm} \times 100 \quad (5)$$

$$E_{fm-i} = A_i \times R_{fm-i} \times \frac{\sum_{j=1}^k N_{fm-i}}{k} \times C_{fm} \times 100 \quad (6)$$

$$RR_{sm-i} = \frac{\sum_{j=1}^k N_{sm-i} \times A_i / k + N_{nm-i} \times (1 - A_i)}{N_{nm-i}} \quad (7)$$

$$RR_{fm-i} = \frac{\sum_{j=1}^k N_{fm-i} \times A_i / k + N_{nm-i} \times (1 - A_i)}{N_{nm-i}} \quad (8)$$

$$RR_{mp-i} = \frac{\sum_{j=1}^k N_{sm-i} \times R_{sm-i} \times A_i / k + \sum_{j=1}^k N_{fm-i} \times R_{fm-i} \times A_i / k + N_{nm-i} \times (1 - A_i)}{N_{nm-i}} \quad (9)$$

$$RR'_{sm-i} = \frac{\sum_{j=1}^k N_{sm-i}}{k \times N_{nm-i}} \quad (10)$$

$$RR'_{fm-i} = \frac{\sum_{j=1}^k N_{fm-i}}{k \times N_{nm-i}} \quad (11)$$

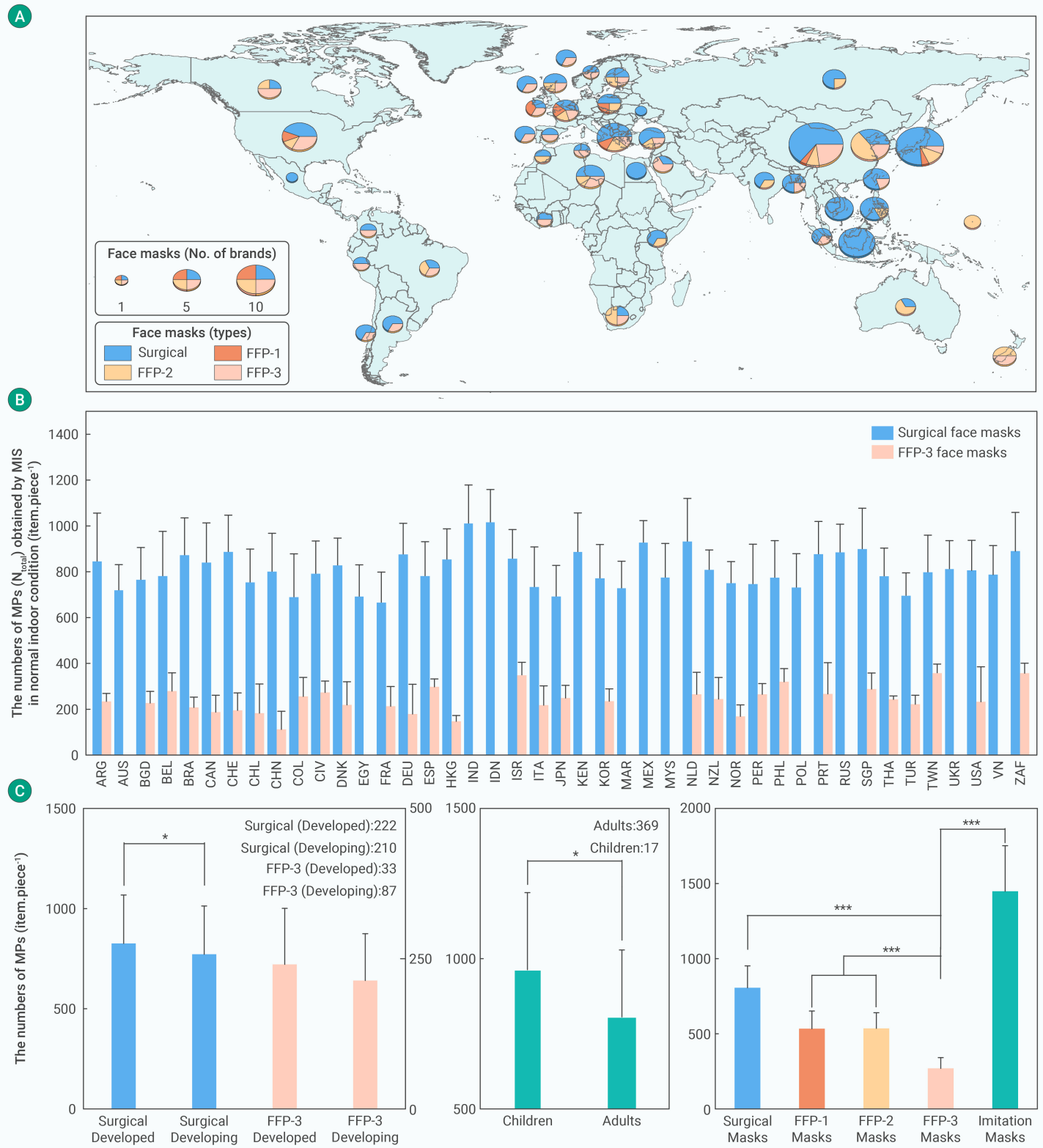


Figure 1. A worldwide investigation of microplastics found in face masks by microplastic inhalation simulator (MIS) (A) The global coverage of the collected face masks sampled in present work, which were collected from 46 countries or regions around the world. The circles represent the number (by circle size) and type (by color) of face masks collected from each country/region. (B) The number N_{total} of microplastics (MPs) detected during the tests of the surgical and face filtering piece-level 3 (FFP-3) masks with 209 brands under an office condition using a MIS. Findings in the MIS global survey results of MP inhalation with mask wearing: differences discovered among types, regions, and age groups. (C) The number of MPs collected by MIS from the face masks of developed/developing countries or regions (left panel); children/adults (middle panel); and five different types, including the surgical face masks, FFP-1, FFP-2, and FFP-3 masks (right panel).

Where E_{mp-i} is the MP exposure per 100 people during face mask wearing in the i -th region. E_{sm-i} and E_{fm-i} are people's MP inhalation during wearing the surgical masks and FFP-3 masks in the i -th region, respectively. A_i represents the mask acceptance rate per hundred people of the i -th region. R_{sm-i}

and R_{fm-i} stand for the proportions of wearing surgical and FFP-3 masks in the i -th region, respectively. C_{sm} and C_{fm} stand for the proportions of MPs originated from the surgical and FFP-3 masks during inhalation, respectively. N_{sm-i} , N_{fm-i} and N_{tm-i} refer to the inhaled MP numbers when wearing the

surgical, FFP-3, and no masks in the i -th region, respectively. RR_{sm-i} , RR_{fm-i} , and RR_{mp-i} indicate the risk ratio (RR) values when wearing surgical, FFP-3, and the actual situations with/without masks based on the mask acceptance in the i -th region, respectively, while RR'_{sm-i} and RR'_{fm-i} represent the RR value if all people wear the surgical or FFP-3 in the i -th region. If the RR value is less than one, the total inhaled MP numbers during mask wearing are less than those without wearing masks. If the RR value exceeds one, then higher abundance of inhaled MPs may occur via wearing masks than that no masks. The index i refers to the corresponded region, while j and k refer to the individual and total product number of masks in the i -th region, respectively.

Quality control and quality assurance

Quality control processes were adopted throughout the experiments. A control study was performed by placing the MIS inside the laminar flow hood for collecting airborne microfibers.^{46,57} As the face masks can also resist the air-borne MPs being inhaled, another control experiment was performed by using the MIS without wearing face masks in indoor conditions (e.g., apartment, office, and laboratory). A detailed description of the procedures can be found in Note S8.

Statistical analysis

The results of the simulated MPs inhalation were recorded as the number of MPs detected during each test per piece of the tested mask. The differences in MP inhalation character among masks of different qualities (genuine and imitation),^{33,58} types (i.e., surgical, FFP 1-3),⁵⁹ and from different countries (46 nations or regions),⁶⁰ as well as data collected under different environments (e.g., laminar flow hood, indoor condition)⁶¹ were analyzed using one-way analysis of variance (ANOVA). All statistics were processed via Statistical Product and Service Solution 16.0 (SPSS Inc., USA). A valid co-occurrence event is defined as a relevant correlation if it is statistically significant ($P < 0.05$) and the Spearman's correlation coefficient (R^2) is above 0.5.

RESULTS

Investigation approach and control results

The design principle of the testing approach used in the present work is to investigate the number of inhaled MPs with and without wearing a face mask for a certain period. To ensure reliability of the analysis, a few factors have been taken into consideration. First, masks are divided into four types (surgical and FFP 1-3 masks, corresponding to different levels of filtration efficiency) and two levels of qualities (genuine and imitation) (Figures 1A & S1, Table S2), which are studied respectively. Second, masks are tested on a MIS created in the present work, which mimics the condition that masks are used (e.g., regarding the normal ventilation rate of human adult) and ensures the collection efficiency of MPs (Figures 2A & S3-S6). More details about the MIS, theoretical simulation, and experimental validation are available in Figure 2B and Notes S1-S2. Third, comparative measurements and control tests were employed to understand not only the dynamic behavior of the MP release from the masks, but also the overall effects of wearing a face mask in a real working/living environment. Two types of measurement were conducted, by performing the test inside a laminar flow hood to measure the number of net MP releasing from the mask (denoted as N_{mask}) and on a lab bench to measure the total MP inhalation when wearing a mask under normal indoor condition (denoted as N_{total}), respectively. These measurements were performed successively to access kinetic behavior of the sample. Two control studies were conducted, by running the MIS without any mask mounted, either inside a laminar flow hood (negative control) or on a lab bench (positive control). In the negative control study, less than 10 MPs were detected after 24-h inhalation, indicating that N_{mask} could provide reliable information of MPs released from the face masks only (Table S3). For the positive control, the counting reached 328 ± 84 MPs within 2-h period, which provides an estimation of the airborne-MP density inside a research laboratory. Finally, the collected particles were analyzed using various microscopy and spectroscopy methods to not only identify and characterize but also trace the origin of the MPs in the collected particles.

Refining the understanding about MP inhalation during mask wearing

Figures 1B & 3A and Table S2 present the numbers of N_{total} from world-

wide samples. The N_{total} varied significantly among the tested masks, e.g., from 112 (FFP-3 in South Africa) to 1530 (surgical face masks in Indonesia) MPs per piece in 8 hours. When looking at the mean value of each category of masks, it is plausible that N_{total} is inversely related to the filtration efficiency of the category. This is also applied for the category of imitated masks, which is missing the melt-blown PP fabric middle layer and thus inferior in filtration efficiency to any genuine masks. On the other hand, the deviation within each category is significant too, especially for the category of normal surgical masks. For instance, a significant difference ($P < 0.05$; Figure 1C left panel) in N_{total} values was observed between surgical masks made in developed countries (765.5 ± 141.9) and those from developing countries (833.7 ± 148.3). A possible reason of this discrepancy is that masks with inferior quality were sold in underdeveloped regions.^{62,63} This speculation is consistent with Khandelwal's finding, which revealed a positive association between product quality and financial development.⁶⁴ Finally, when mimicking the breath rates of children ($\sim 15 \text{ L} \cdot \text{min}^{-1}$),^{43,44} which is higher than adults ($\sim 7 \text{ L} \cdot \text{min}^{-1}$),^{44,45} the measured N_{total} values of masks for children (mean value: 941.3 ± 275.8) were generally higher ($P < 0.05$; Figure 1C middle) than those from masks for adults (806.4 ± 146.0) (as illustrated in Table S2).

These observations lead to some interesting findings. First, the number N_{total} did not show any positive relevance to the number of microfibers (in the melt-blown PP fabric, which are susceptible sources of MP leaching) in the masks, or to some extent, the former generally exhibited an inversed relationship to the latter, suggesting that microfibers falling off the middle layer of the masks might not be the dominating factor during the whole using cycle (Figures 1B & 3A, Table S2). Actually, FFP-3 masks usually contain 4~5 layers of melt-blown PP fabric to reach the desired filtration efficiency,⁵⁹ which is greater than other types of masks; such a middle layer is simply missing in the imitation masks ($P < 0.05$; Figure 1C right panel). Second, the number N_{total} is neither linearly related to the number of particles penetrating the masks estimated based on their particle filtration efficiency rating, indicating that the MPs released from the masks are not neglectable either (Tables S2 & S7). For example, when using the result from the positive control (1470 ± 261 items over 8h) and the standard of particle filtration efficiency (PFE $\geq 99\%$) to calculate, the estimated number of MPs penetrated an FFP-3 mask is much less than that measured in the test (269.5 ± 71.8 items over 8h). This indicates that the MPs released from the masks should not be disregarded. Finally, we compared the total number (N_{total}) of microplastic particles estimated to be inhaled under the model mask-wearing condition in the present work with the reported potential microplastic inhalation levels under different indoor conditions from various locations worldwide (Table S4). This comparison revealed that, depending on the specific indoor environment, the inhalation of microplastics while wearing a mask can be either lower or higher than the number of microplastics inhaled during the same time period without wearing a mask.

Characterization and tracing of the collected MPs

Findings in the above section lead to a question: how much of the contribution from internal (mask MP leaching) and from external (airborne MP penetration) respectively are associated with each type of mask, and whether it is possible to differentiate the collected MPs between these two sources using the present approach. To address this question, we conducted systematic investigation, which is elaborated in Note S9. In brief, smaller ones (SMPs: 0-0.1 mm) took a greater portion in the detected MPs from FFP-3 masks as compared to other groups, similar to some previous reports,^{51,65} perhaps because of its finer filtration layers (Figure 3B and Tables S7-S8). Also, we developed an effective approach through building a Sankey diagram (Figures 3C-D) to identify and trace the origin of the MPs detected in the MIS test using chemical composition, color, and shape of the MPs, which is proven reliable by comparing with the N_{mask} data.⁶⁶

Kinetics of MP inhalation during mask wearing

To further understand the kinetic behavior of the particle inhalation when wearing a mask, we fitted the N_{mask} and N_{total} obtained at different time points (Figure 4A) to three models, namely power function equation, parabolic diffusion model, and Elovich model (Figure S12 and Table S9). Except for imitation masks, the parabolic diffusion model best fit the data of both N_{mask} and

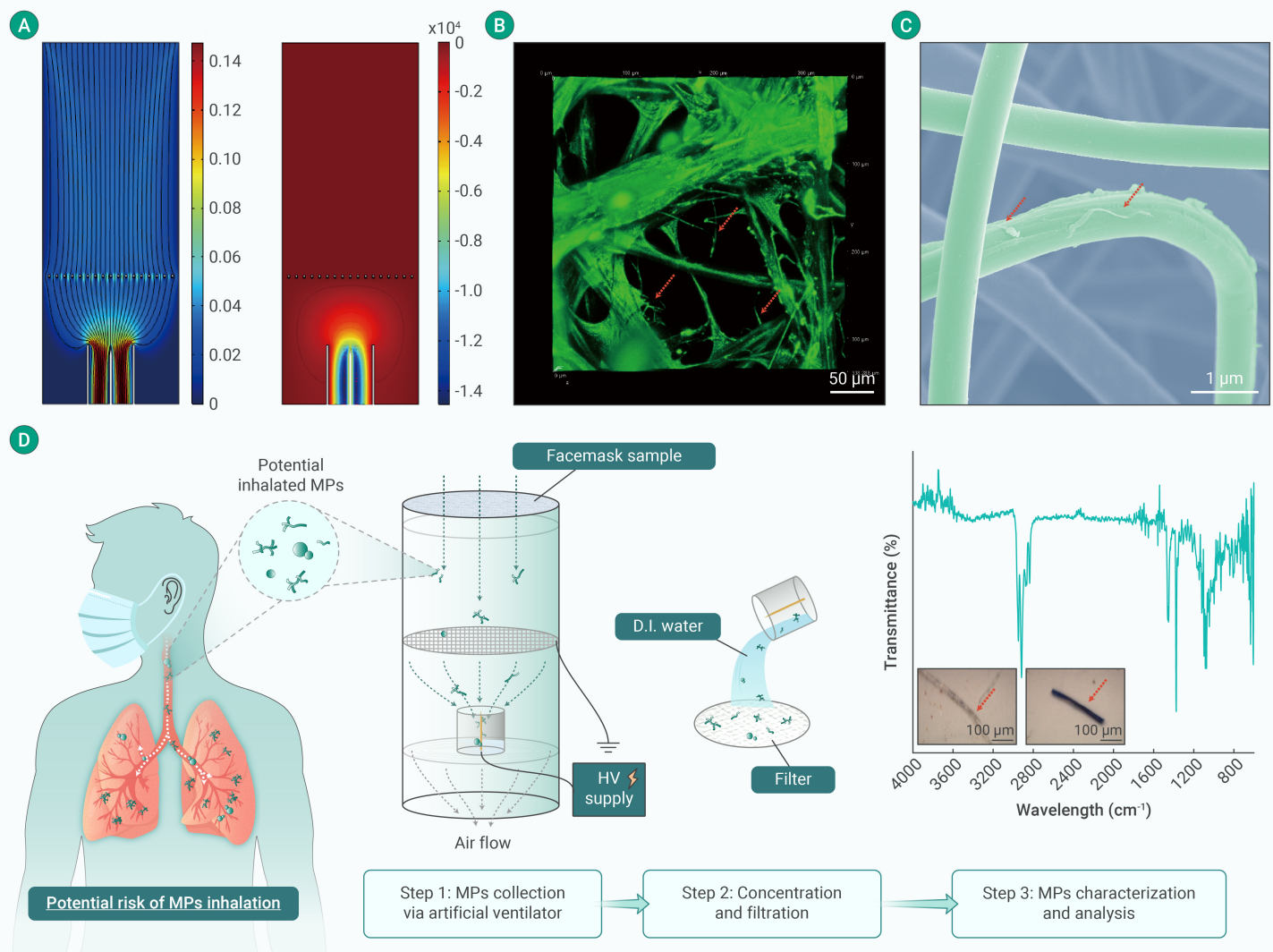


Figure 2. Testing and characterization schemes employed in the present investigation (A) MP inhalation test using the tailor-made MIS, followed by identification, quantification, and characterization of the collected MPs using microscopy and μ -FT-IR. (B) Simulation results of the flow velocity and electric potential distribution inside the MIS using finite element modeling; (C) Confocal microscope image; and (D) SEM image of the face mask sample after 8 hours of inhalation simulation testing using the MIS. The scale bar represents (A) 100 μ m, (C) 50 μ m, and (D) 1 μ m, respectively. The red arrows indicate the potential MPs which have possibility to leach from the face mask sample.

N_{total} (R^2 greater than 0.989), indicating the MP leaching behavior during the tested period (8 hours) could be generally divided into two stages (Figure 4B). Stage 1 (about 2 hours) is the substantial leaching of MPs from the masks, after which this process slows down and the penetration of the air-borne MPs takes the dormant role (Stage 2).⁵¹ This pattern suggested that manufacturing was a primary process that caused high content leaching of MPs especially in the early stage of use.^{28,31,32} In contrast, imitation masks fits best to the power function equation, indicating the penetration of airborne MPs plays the primary role throughout the test (8 h; Figure S12), perhaps because of the poor filtration efficiency.³⁰ Consequently, a large discrepancy in N_{total} and N_{mask} was observed (Figure 4A), and similarly in a values of the power function models from the two environments (Table S9).^{22,51}

By taking derivation of the results, the plotting of measured inhalation rates (7 L·min⁻¹, Figure 4B) confirmed the findings from the model fitting. Considering the rate of particle penetration could be generally assumed to be constant within a short period of time determined by the density of MP in ambient air and the filtration efficiency of the mask, the MP counting rate profiles could be further decoupled into two elements, namely the "leaching" (from mask) and "penetration" (from outside). Since the "penetration" element is absent from the data collected inside laminar flow hood, the corresponding results simply present the character of "leaching" element (Figure 4B right panel). Accordingly, the "leaching" rate was high and quickly dropping within the first 2 hours using a mask (corresponding to Stage 1 in the kinetic model). After

this 2-hour period (which corresponds to Stage 2 in the kinetic model), the number of MPs leached from the masks will be neglectable as compared to a typical MP inhalation rate at an office environment without wearing a mask. In this case, wearing a face mask indoors for a considerably long period of time even has chance to result in less total number of MP inhalation as compared to not wearing one. Whether this is true depends on at least three factors, including the MP leaching character and filtration efficiency of the mask, as well as the density of air-borne MP in the environment (measured data shown in Figure 4B and Table S3). Based on the results, roughly 1 hour (Figure 4B left panel) after wearing a fresh surgical mask in laboratory environment, the rate of MP inhalation will become lower than that of not wearing a mask. This transition point will be much earlier if an FFP-3 mask is used in the same environment. Nevertheless, it will take longer time to reach the transition point that wearing a mask leads to less total number of MP inhalation than that of not wearing a mask (Figure 4A left panel). Moreover, such transition point is also highly dependent on the environment condition. For example, it will take FFP-3 masks slightly over 3 hours to reach this point when used in office condition, while for other type of masks and even cleaner conditions (e.g., apartment condition) this transition point will be beyond 8-hour period. Finally, it is worth noting that the results here do not infer that wearing a mask for very long time will reduce the risk of MP exposure. Very long period of usage of a mask might not only cause hygiene and filtration capacity problems, but also has chance to damage some parts of the mask

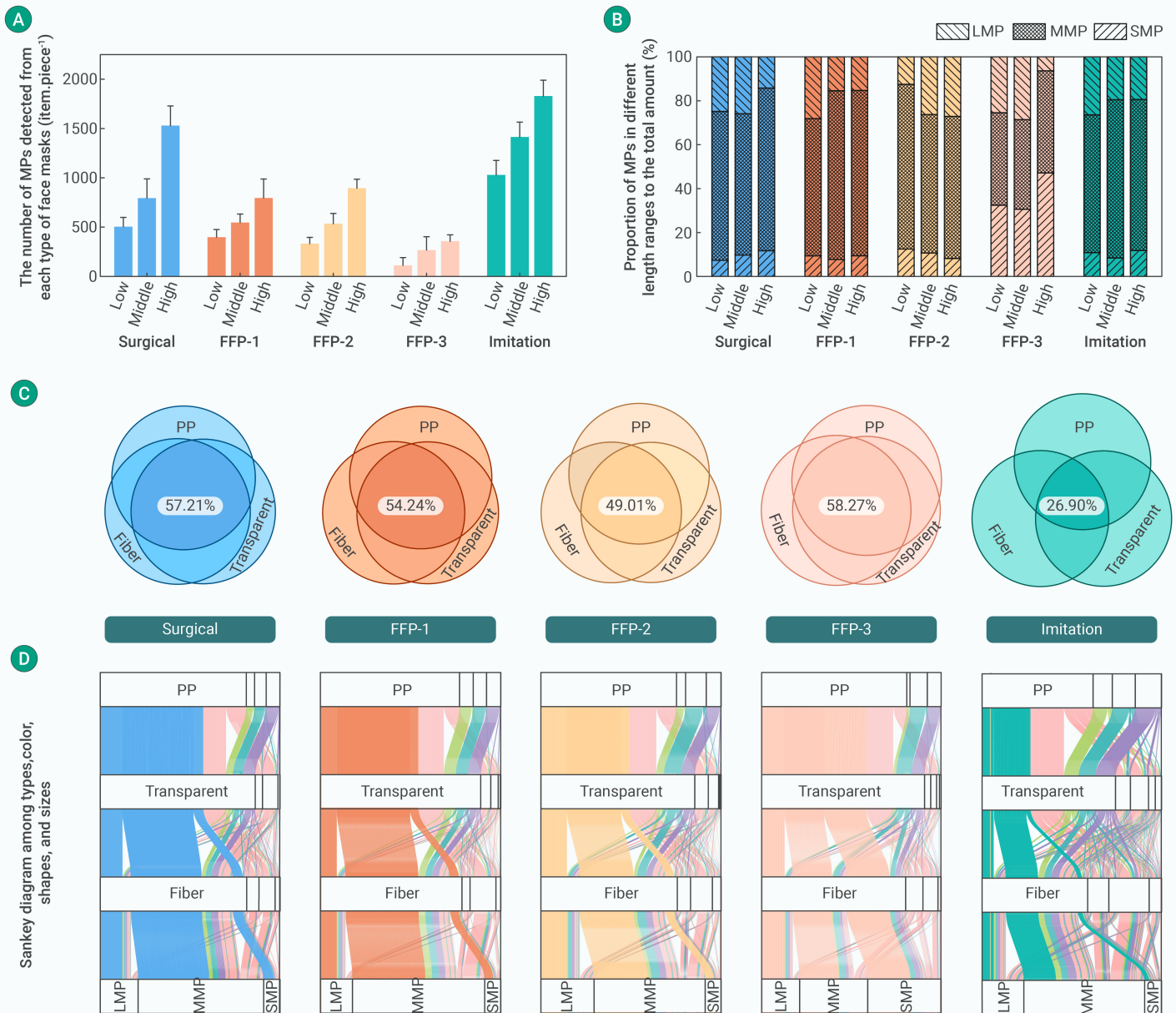


Figure 3. The abundances, sizes, and potential origins of collected MPs from the surgical, FFP (Levels 1-3), and imitation masks (A) The number of MPs detected with the surgical, FFP (Level 1, 2, and 3), and imitation masks after 8 hours of inhalation simulation testing with the MIS. As elaborated in Table S2, the masks of different filtration efficiency grades showed distinguishable total MP inhalation levels (N_{total}) when tested under normal indoor conditions. More specifically, the N_{total} was inversely related to the filtration efficiency grade of the mask, e.g., fake masks (mean $\pm$ SD: 1448.6 ± 152.2) > surgical face masks (806.4 ± 145.7) > FFP-1 (534.2 ± 117.3) $\approx$ FFP-2 (536.3 ± 104.3) > FFP-3 (269.5 ± 71.8) (as illustrated in Tables S5-S6; the quality requirements of different types of masks with regard to the filtration efficiency are listed in Table S7); (B) Size distribution of the released MPs in each type of face mask, including small microplastics (SMP: 0-0.1 mm), middle microplastics (MMP: 0.1-1 mm) and large microplastics (LMP: 1-5 mm); (C) Venn diagram showing the percentage of MPs released from each kind of face mask among all the MPs collected during the respective MIS measurement; (D) Sankey diagram showing the percentage of mask-released MPs among all the MPs collected during the MIS measurement, identified by fulfilling the following three criteria simultaneously: PP material, transparent color, and fiber shape (as described in Note S9). For the tested surgical, FFP-1, FFP-2, FFP-3, and imitation masks, the portion of MPs from the tested mask over the total MPs collected (N_{total}) are determined to be about 57.21%, 54.24%, 49.01%, 58.26%, and 26.90%, respectively, which was found to be consistent with the results obtained through running the tests inside a laminar flow hood (N_{mask}), proving the reliability of this determining formula.

owing to material fatigue.^{22,27} In publicly available guidelines, it is commonly recommended that masks to be replaced after 8 hours of continuous use. In this connection, we investigated the risk of microplastic inhalation associated with the reuse of masks. We tested different types of commonly available masks after subjecting them to various disinfection processes (Table S10). The results revealed an increase in both N_{total} and N_{mask} following the treatments. However, the levels varied depending on the conditions. For instance, the findings suggest that gentle washing does not significantly increase the risk of microplastic inhalation (Note S10). However, prolonged UV exposure significantly increases this risk during mask usage, which is consistent with the findings prior reports about other synthetic fabrics.²⁶ It can be attributed to the rapid aging and breakdown of the microstructured

polypropylene fibers under UV light (Note S10). Similarly, damage to the different layers of the mask's fibrous structure is expected in the scenario of wear and tear (Note S10), as also revealed in previous reports.²⁷⁻³⁰

DISCUSSION

The global impact of substantial mask wearing to MP inhalation

Based on the above findings, we estimated the (changed) exposure to MPs associated with mask-wearing at working hours (8h) in 46 countries/regions worldwide, as a consequence of the global pandemic control measures (Figure 5).

First, we estimated the scope of MP inhalation directly from the masks worn in each region (Figure 5A), which generally highlights those countries

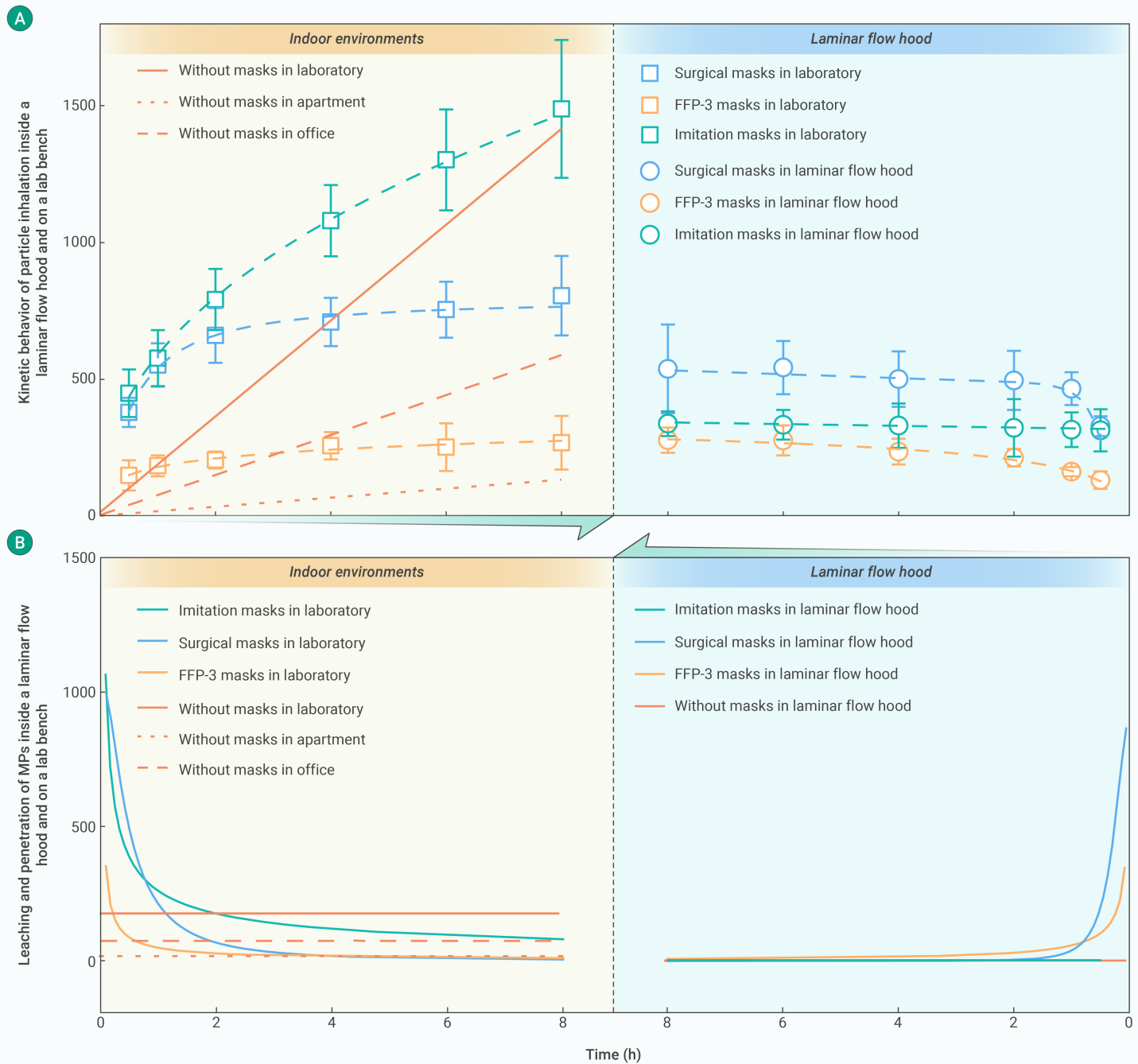


Figure 4. The kinetic behaviors and rates of MPs during simulated MP inhalation using surgical, FFP-3, and imitation masks in both laboratory and laminar flow hoods (A) Kinetic behavior of simulated MP inhalation when using surgical, FFP-3, and imitation masks respectively, measured inside a laboratory (left panel) and inside a laminar flow hood (right panel). Assisting lines are provided in the left panel to illustrate the expected MP inhalation in different environments without wearing a mask. All data presented are cumulated counting of MPs over the testing period (0.5h-8h); (B) Leaching and penetration rates of MPs from the surgical, FFP-3, and imitation masks measured inside a laboratory (left panel) and inside a laminar flow hood (right panel). All values presented are derivatives of the data shown in (A). Based on the results, roughly 1 hour (Figure 4B left panel) after wearing a fresh surgical mask in laboratory environment, the rate of MP inhalation will become lower than that of not wearing a mask. This transition point will be much earlier if an FFP-3 mask is used in the same environment. Nevertheless, it will take longer time to reach the transition point that wearing a mask leads to less total number of MP inhalation than that of not wearing a mask in laboratory environment (Figure 4A left panel). For instance, it will take approximately 1 hour and 4 hours for FFP-3 and surgical mask, respectively, to reach such a transition point when used in laboratory conditions. Moreover, such transition point is also dependent on the environment condition. For example, it will take FFP-3 masks slightly over 3 hours to reach this point when used in office condition, while for other type of masks and even cleaner conditions (e.g., apartment condition) this transition point will be beyond 8-hour period.

sensitive to the question discussed here. In general, two factors are determining the numbers, including the rate of mask-wearing acceptance and the quality of masks used. The numbers are positively related to the former factor, and negatively to the latter.⁵³⁻⁵⁶

Subsequently, we processed the data using a formula to assess the global impact of mask wearing. For each country/region, this formula takes the sum of the MP inhalation by both people who choose to wear different types of masks and people who decide to not wear a mask, and divides it by the total

MP inhalation if all the people do not wear a mask (Equations 7-9). In this way, the obtained fraction will be greater than 1 if mask wearing will increase the MP inhalation, and *vice versa*. As shown in Figure 5B, for most parts of the world with available data the current mask-wearing practice slightly increased the inhalation of MPs compared to pre-pandemic era. The main difference between those countries with enhanced MP inhalation and those with reduced inhalation is that the latter tend to use high-standard masks such as FFP-3 which, as discussed above, rather reduces the MP inhalation

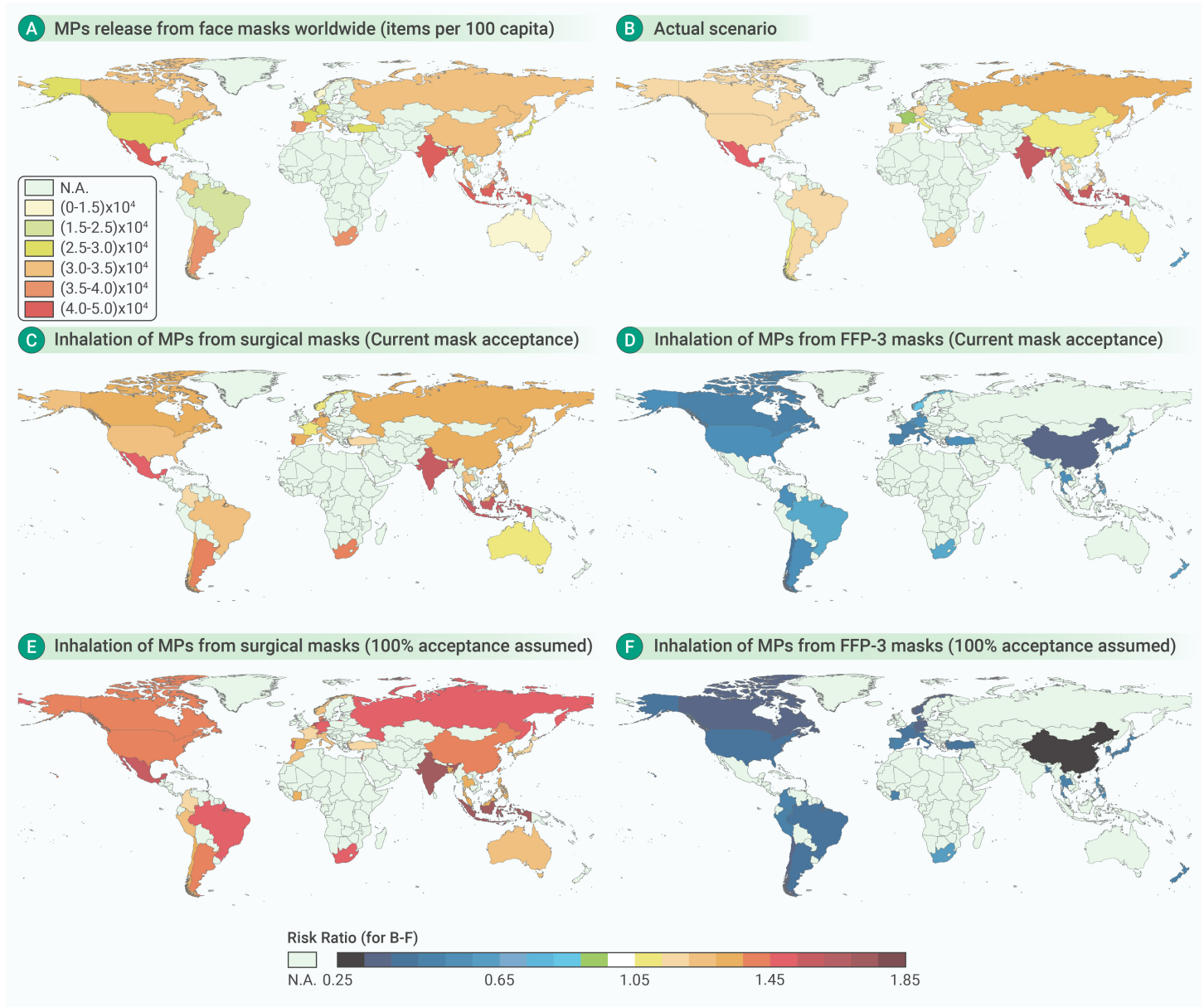


Figure 5. The global impact of substantial mask wearing to MP inhalation All the calculation was conducted by assuming the mask use is all at typical indoor environment (office as representative), and unless specially noted, using the reported data of the preference in wearing masks in global surveys regarding the COVID-19 pandemic control measures in each country/region (Table S1), and the corresponding mask characters measured for the region in the present work (Table S2). (A) Per 100 capita net number of the inhalation of MPs directly leached from the masks. Globally, the mean value of inhalation of MPs directly released from masks is estimated to be 31213 ± 8593 items per 100 capita during office time (8h), with variations among different regions. Worldwide inhalation of MPs during office time (8h) is estimated to be 1.16 times of that during pre-pandemic era. When comparing among different continents, Oceania is least sensitive to the mask-wearing MP inhalation, followed by Europe and South America, while Asia and North America are most sensitive to this matter. (B-F) Impact of extensive mask wearing to the MP inhalation in different countries: (B) calculated based on the current mask acceptance rate and mask-type preference data (e.g., Surgical and FFP-3) in each country; Particularly, countries such as India and Indonesia show relatively enhanced exposure to MP, which could be attributed to the high level of acceptance in mask wearing but low quality of the masks on the market. To the contrary, reduced MP inhalation is indeed observed in some countries such as Australia. (C-D) calculated based on the current mask acceptance rate in each country and assuming all masks used are surgical masks (C) and FFP-3 masks (D). As shown in Figure 5C, based on the current facts of mask-wearing acceptance in each country, when all the people who choose to wear a mask during a pandemic are using normal surgical masks only, the inhalation of MPs worldwide all increase compared to pre-pandemic era. In sharp contrast, if all the people who routinely wear masks wear FFP-3 masks only, the total MP inhalation will be lower than that of pre-pandemic era (D); (E-F) calculated based on assuming all people accept to wear face mask and all the masks used are surgical masks (E) and FFP-3 masks (F).

mainly by blocking the penetration of airborne MPs.⁶⁸

This interesting finding inspired us to perform some deduction. We made a hypothesis that the global MP inhalation during a pandemic would rather decrease compared to pre-pandemic era, if face masks used in all countries fulfill high standard, e.g., FFP-3. Stated differently, it is possible to block disease transmission and MP pollution simultaneously by appropriately choosing the type of mask. The corresponding calculation proved our hypothesis true (Figures 5C-D). Evidently, the present situation (Figure 5B) is close to the case of Figure 5C, indicating that better outcome could be achieved if more countries gradually increase the use of high-standard masks. Based on this discovery, we further extended the deduction. As

shown in Figures 5E-F, if ultimately all people decide to wear a mask during a pandemic, the difference in MP inhalation will be even more significant.

Last but not least, it is worth noting that all the calculation above is based on the assumption that all the mask usage are under typical indoor condition, e.g., office, similar to the situation measured in the present work and some other reports.^{69,70} Nevertheless, the situation in other conditions could also be conveniently predicted using the model discussed above, in which the “leaching” and “penetration” are analyzed separately.

CONCLUSION

In this work, we pursued a comprehensive investigation on the global

impact of population-wide mask-wearing to the inhalation of MPs. We created a MIS which can mimic the using condition of masks and ensure the collection efficiency of MPs. We also developed a strategy to trace the origin of the detected MPs. Notably, we systematically studied the masks not only as a source of MP release, but also as a barrier to reduce the inhalation of airborne MPs. We measured the masks from 46 countries/regions counting up to 209 kinds with different brands, which were analyzed respectively in categories by both filtration grades and qualities. It was found that microfibers falling off the middle layer of the masks might not be the dominating factor in the inhalation; in other words, masks containing more materials for filtration (*e.g.*, N95 masks, compared to normal surgical masks) do not leach more MPs on average. Meanwhile, most of the MP leaching takes place within the initial couple of hours of wearing, after which the mask generally serves as a barrier to block the inhalation of airborne particles, suggesting that changing masks too frequently may not be a good idea regarding MP pollution. We established a kinetic model to describe the overall MP inhalation behavior of different types of masks using the combined effects of particle leaching from and penetrating through the mask. A rule of thumb discovered was that the total MP inhalation is inversely related to the filtration grade of the mask (*e.g.*, surgical vs FFP-3) when wearing a mask in typical indoor environment for a certain period of time, *e.g.*, several hours. An interesting finding was that while using normal surgical masks would in general slightly increase the overall exposure to MPs, wearing a high-standard respirator such as FFP-3 mask indoors for a long period might even reduce the total MP inhalation compared to not wearing a mask. We estimated the global impact of masking on the inhalation of MPs. The calculation revealed that although overall the inhalation of MPs worldwide is slightly increased due to masking, individual countries have either increased or decreased MP exposure, largely depending on the quality standard of the masks commonly used in the country. Our simulation suggested that if high-standard masks are used in all countries, the total MP exposure globally would rather decrease as compared to the pre-pandemic era, not to mention the enhanced transmission blocking performance, indicating to encourage using high-standard masks worth consideration by governments and global organizations. The findings of this study could also be valuable for manufacturers seeking to improve mask technology to reduce MPs generated during the production and for mask users in guiding their selection and usage, as well as for all the mask users to guide mask selection and usage. Nevertheless, the overall impact of mask wearing should certainly include more aspects of assessment, such as volatile organic compounds (VOC) and breathing resistance.^{71,72} Also, the actual MP inhalation is also determined by the varying ventilation rates, not only among different users but also for each individual user across different scenarios. Moreover, the recommended mask replacement cycle is also determined by other factors such as material fatigue, filtration capacity, and hygiene requirements.⁷³⁻⁷⁵

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AUTHOR CONTRIBUTIONS

P. W., C.-W. C., K. R. and Z. C. designed the study; P. W., K. R. and Z. C. received funding for the research; P. W., H. T. and X. Z. conducted the sample pretreatment and analyses; G. C. and Z. Y. carried out microplastic analyses; C.-W. C., S. -Y. S. and K. R. designed the microplastic inhalation simulator; P. W., C.-W. C. and G.C. conducted the statistical analyses; P. W. C.-W. C., K. R. and Z. C. drafted the initial manuscript, with all authors contributing to subsequent editing and final approval.

DECLARATION OF INTERESTS

The authors declare no competing interests.

ETHICAL STATEMENT AND PATIENT CONSENT

Not applicable.

DATA AND CODE AVAILABILITY

Parts of the face mask acceptance rate in countries or regions were obtained from Imperial College London Big Data Analytical Unit and YouGov Plc. Imp. Coll. London YouGov Covid Data Hub, v1.0. (Jones, S.P.; 2020) and COVID-19 pandemic statistics (Statista; 2020).

SUPPLEMENTAL INFORMATION

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LEAD CONTACT WEBSITE

Zongwei Cai: <https://chem.hkbu.edu.hk/cai>
Kangning Ren: <https://chem.hkbu.edu.hk/ren>