ABSTRACT: Face masks, which serve as personal protection equipment, have become ubiquitous for combating the ongoing COVID-19. However, conventional electrostatic-based mask filters are disposable and short-term effective with high breathing resistance, causing respiratory ailments and massive consumption (129 billion monthly), intensifying global environmental pollution. In an effort to address these challenges, the introduction of a piezoelectric polymer was adopted to realize the charge-laden melt-blown via the melt-blowing method. The charge-laden melt-blown could be applied to manufacture face masks and to generate charges triggered by mechanical and acoustic energy originated from daily speaking. Through an efficient and scalable industrial melt-blown process, our charge-laden mask is capable of overcoming the inevitable electrostatic attenuation, even in a high-humidity atmosphere by long-wearing (prolonging from 4 to 72 h) and three-cycle common decontamination methods. Combined with outstanding protective properties (PM$_{2.5}$ filtration efficiency ≥99.9%), breathability (differential pressure <17 Pa/cm$^2$), and mechanical strength, the resultant charge-laden mask could enable the decreased replacement of masks, thereby lowering to 94.4% of output masks worldwide (∼122 billion monthly) without substituting the existing structure or assembling process.

KEYWORDS: face masks, COVID-19, speaking, charge-laden, durable protectiveness

INTRODUCTION

Human-to-human transmission via virus-laden respiratory droplets has aroused widespread concern during the coronavirus disease 2019 (COVID-19) pandemic. As a result, daily mask-wearing has been considered as an effective way of public epidemic prevention. Posed by the virus’ susceptibility, the short lifetime and disposability of masks would bring about 129 billion masks monthly for 7.8 billion residents worldwide. In general, a face mask is composed of a three-layer structure, namely, outer spunbond, interlayer melt-blown (MB), and inner spunbond (SMS structure), in which the MB layer mainly plays the crucial role of a filter. By virtue of the superfine fiber inside the three-dimensional structure, polypropylene (PP) MB has exclusive advantages in the mechanical barrier including direct interception, Brownian diffusion, gravity sedimentation, inertial collision, and electrostatic interactions toward particles. Traditional melt-blown is mainly manufactured by the melt-blown method or electrospinning, during which the polymer solution or melt undergoes extrusion and the stacking is quickly carried out by the thermal current or high voltage electrostatic fields to fabricate superfine fibers on the submicron or micron scale. In this regard, the current method of producing mask filters with qualified protective performance ($\text{PM}_{0.3}$ removal efficiency ≥ 65%, differential pressure (DP) ≤ 60 Pa/cm$^2$) is the introduction of electrostatic adsorption toward virus and aerosol. However, the formed electret is vulnerable to plummeting due to friction and water vapor during long-time wearing (maximum 4 h) due to the inevitable electrostatic attenuation effect. Up to now, some innovative methods of making masks have sprung up, including improving the electret properties, etching porous membranes, inserting nanoparticles, involving inorganic materials, super-hydrophobic coatings, and self-powered filters. However, without increasing the cost and fabrication duration, the preservation of the durability of filters remains challenging when using conventional technology and is urgent because of the long-standing coexistence with COVID-19 and the ever-increasing demand for masks globally.

Received: January 18, 2022
Accepted: March 22, 2022
Herein, we report an elaborate strategy to fabricate the charge-laden melt-blown (CMB) that integrates a piezoelectric polymer into the melt-blown process of polypropylene (PP). Inspired by our previous works on piezoelectric and triboelectric nanogenerators (PENG and TENG),33−35 polyvinylidene fluoride-trifluoroethylene (P(VDF-TrFE)), with the advantage of no biological toxicity,36,37 was applied to generate charges initiated by mechanical and acoustic energy during daily speaking. Intriguingly, we find that the CMB exhibits outstanding performances including enhanced protective performance after harvesting external vibrations and sound waves (filtration efficiencies for PM$_{2.5}$ and PM$_{0.3}$ exceed 99.9 and 90%, respectively), excellent breathability (DP < 17 Pa/cm$^2$), and applicable mechanical properties. Compared with electrostatic-based masks, our aging tests and decontamination experiment show that the effective time of the CMB mask increases by over 1800% from 4−8 to 72 h, which thus may provide a solution to alleviate the massive global demand (decreased 18 times) for masks. Without alteration of the structure or processing, the facile CMB fabrication can be a general method of realizing mass industrial production of other protective products of great concern for medical or civil use.

■ RESULTS AND DISCUSSION
The dominant mechanical effect of conventional purification can minimize the transmission of micron particles from the airflow; disappointingly, its performance is limited, especially for fine particle and aerosol filtration.38−40 Because of this, current melt-blowing is required to be applied with electrostatic technology to meet the eligible protection criterion. Despite this manufacture having been extensively used in mass production for decades, rapid attenuation of electrostatic adsorption results in the short effective lifetime of masks.41 Subject to the excellent melt fluidity of PP (raw materials of MB), the mixed PP/P(VDF-TrFE) granules (MFI > 1000 g/10 min; Figure S1) were capable of fabricating the CMB with different P(VDF-TrFE) weight compositions including 0.5, 1, 3, 5, and 10 wt % (named as CMB-X, where X is the concentration of P(VDF-TrFE)) by employing the melt-blow method (Figure 1a). Polarized $\beta$-PVDF results (Experimental Section and Supporting Information) show that CMB was available to convert mechanical energy and acoustic energy into electrical energy. Figure 1a shows the filtration process of CMB, during which the micron particles were hindered by the stacked fibers, nanoparticles, and aerosol that were adsorbed via electrostatic interaction. Taking advantage of the charge-laden performance, the weight (Figure 1a, inset, 16−18 g/m$^2$) of CMB can be reduced by 28−36% compared to that of standard industrialized MB (25 g/m$^2$).42 Similarly, the differential pressure (DP) experienced an obvious decrease compared with the normative requirement of melt-blown (MB, 40 or 60 Pa/cm$^2$),43 distributing in 13−17 Pa/cm$^2$, more than halved. Decreased DP led to low respiratory resistance, according to Pillarisetti et al.,21 and could improve the wearing comfort and further reduce the risk of respiratory diseases caused by prolonged wearing of masks. With the increase in the P(VDF-TrFE) concentration, both the weight and DP exhibited a tendency to go up and down because the excessive P(VDF-TrFE) would markedly lower the MFI (from 1498.5 to 1203.3 g/10 min; Figure S1), thus rendering the uneven fiber

Figure 1. (a) Schematic picture of the fabrication process of the CMB by using five different concentrations of P(VDF-TrFE) compared to PP: melt-blowing under 230 °C, polarization with a molybdenum wire array, and rolling; the inset shows the microstructure of CMB; the charge-laden filtration process. (b) Output voltage of CMB with different concentrations under an external pressure at 30 Hz. (c) Output voltage of CMB with different concentrations under an acoustic wave at 150 Hz. (d) Comparison of PM$_{0.3}$ filtration efficiencies of CMB before and after beating and acoustic wave. The error bar represents the standard deviation of five replicate measurements.
structure. Thus, although seven groups of granules of mixtures (Experimental Section) with different concentrations of P(VDF-TrFE) were prepared, only five groups had been fabricated as CMB (CMB-0.5, CMB-1, CMB-3, CMB-5, and CMB-10).

The CMB with different concentrations of P(VDF-TrFE) (named as CMB-X) could generate charges, employing pressures and sound frequencies (Figure 1b,c), which illustrated that it can convert the mechanical and sound energy during breathing and speaking into electricity. To investigate the electrostatic adsorption of CMB, the filtration efficiency was measured, including the filtration efficiencies toward PM0.3 (Figure 1d) and PM2.5 to PM5 (Figure S2), which were compared with the unpolarized pristine PP MB filter. The results directly suggested that, without the external beating (named as BT) and acoustic wave (named as AW), the filtration efficiency for PM0.3 only remained at 40–50%, and after that, it amounted to 75–90 and 70–85%, respectively, presenting a marked improvement. Additionally, the filtration efficiency for PM0.5 to PM5 of CMB with five different concentrations all outstrip 99% (Figure S2). On the basis of the EN 14683:2019 standard,44 the filtration efficiency for PM0.3 >30% and filtration efficiency for PM2.5 >90% indicate the applicable use in daily life. Considering the common wearing of the mask, the MB is in the state of being stretched for a long time, and the mechanical properties were investigated through the tensile test (Figure S3), among which the CMB-1 exhibited the highest filtration efficiency and tensile strength.

To probe the underlying mechanism of CMB, the charge-generation process is depicted in Figure 2a. The deformation of CMB under the periodic BT will lead to the change of dipole moment, thereby generating piezoelectric charges. As shown in Figure 2b, the output properties of CMB improved with the increase in the PVDF-TrFE concentration, among which the optimal output voltage was 220 V (CMB-5); exceptionally, the output of CMB-10 fell instead, attributed to the viscous P(VDF-TrFE) partially filtered by the strainer. With the sensitive response to AW, the optimal output voltage of CMB was 36.8 V (CMB-1; Figure 2c), corresponding to the 150 Hz frequency. Furthermore, the response performance under different decibels at 150 Hz is depicted in Figure S4; the output increased with the decibels and peaked at 110 dB (33.6 V), indicating that CMB can generate charges driven by the acoustic signal. Another comparison result was that the pristine PP MB was almost unresponsive, confirming the piezoelectric and triboelectric properties of CMB. Figure 2d records the zeta potential, in which the value of the five polarized CMB samples
was higher than that of pristine PP MB (58.2 V), and the CMB-1 was 68.5 V. Despite this, without the polarization, the zeta potential of unpolarized CMB-1 was almost equal to the figure of pristine PP MB, shedding light on the superiority of polarization. To further demonstrate the crystal phase and functional group transition of CMB, X-ray diffraction (XRD) and Fourier transform infrared (FTIR) measurements were conducted (Figure S5), showing that the β-phase PVDF of CMB was observed.\(^{45}\) In addition, the CMB microstructure was characterized by scanning electron microscopy (SEM), which illustrated that the fibers ejected through the spinneret hole were bonded to each other, thus forming a complex capillary structure composed of microfibers (Figure 2e). This capillary structure allowed for the large specific surface area and good filtration performance of CMB, in which the diameter of a single fiber generally ranged from 0.5 to 10 μm, meeting the demands of standard MB. Thus, the CMB has potential to be manufactured for the mass production of masks, protection suits, and other types of protection commodities.

As filter materials of personal protective equipment (PPE, e.g., masks and protective gowns), owing to the fact that the user breathes or sweats, MB is vulnerably exposed to high-humidity conditions, which can lead to the gradual decrease in static electret and filtration efficiency. To further demonstrate the effectiveness of protective properties, the electrostatic charge attenuation and retention performance had been investigated. Considering the daily use and some extreme conditions, high relative humidity (60% RH) and high temperature (60 °C) were carried out during hydrothermal aging to examine the charge decay phenomena (Figure S6). Figure 3a presents that the electrostatic voltage (EV) of fiber went down with the aging time under 60% RH; when placed for 72 h, the pristine PP MB only remained 30% EV of the initial value, and comparatively, CMB still maintained over 50%. Meanwhile, the level of EV had a marked influence on the filtration efficiency for PM\textsubscript{0.3} of samples due to the dependence on electrostatic adsorption. The filtration efficiency for PM\textsubscript{0.3} variation of five CMB groups is depicted in Figure 3b; the exposure to high humidity conditions led to a slight decrease in filtration efficiency of CMB, and the degree of decline ranged from 2 to 15%. Additionally, the filtration efficiencies for PM\textsubscript{0.3} and PM\textsubscript{2.5} of CMB samples were still over 65 and 98%, respectively, much higher than those of pristine PP MB corresponding to 10 and 83.6%, respectively (Figure 3b and Figure S7), indicating the preferable charge retention of CMB. Among the five CMB groups, CMB-1 exhibited superior combined performances. Thus, the filtration efficiency of CMB-1 before and after external BT was compared (Figure 3c and Figure S8), in which those for PM\textsubscript{0.3} and PM\textsubscript{2.5} arrived at...
89.97 and 99.98%, respectively. The EV improved from 1.3 to 5 kV, approaching the initial value, which confirmed the responsively charge-laden properties. Similar to that, after AW, the filtration efficiency for PM0.3 and EV of CMB-1 elevated to 80% and 4.3 kV, respectively.

The influence of temperature on charge retention and attenuation was investigated as well (Figure 3d). Interestingly, after being exposed to 60 °C for 36 h, the EV of six samples all experienced a rise with different degrees, probably attributed to the impairment of electrostatic attenuation under heating and drying conditions.46 Correspondingly, the filtration efficiency for PM0.3 increased during the early stage of thermal aging as well and reached the highest point at 48 h; subsequently, both the EV and filtration efficiency decreased (Figure 3e). In this regard, the filtration efficiencies for PM0.3 and PM0.5 to PM5 (Figure S9) of five CMB samples remained much higher than the figure of pristine PP MB throughout the measurements. Similarly, the role of BT and AW toward the EV and filtration efficiency of CMB-1 is depicted in Figure 3f and Figures S8 and S9, in which enhanced EV was achieved (>2.5 kV); correspondingly, filtration efficiency toward PM0.3 jumped to over 80% as well. In addition, the DP had been investigated (Figure S10), which was insensitive to humidity and temperature. The microstructure and contact angle of CMB-1 (inset, Figure 3b,c,e,f) had been characterized to demonstrate the stable structure and hydrophobicity of CMB before (142.5 and 140°) and after the heat and wet aging (141.7 and 141.9°). On the basis of these experiments, CMB exhibited applicable long-term filtration performance, and the filtration efficiency can be improved by external BT and AW to improve the service time, enabling the durable use of protective products adopting MB fibers.

Figure 4. (a) Snapshot of the fabricated CMB. Scale bar, 100 cm (0.6 m, width, 40 m, length). (b) Photographs of E. coli colonies on agar plates through two common decontaminations after co-culturing for 24 h. (c) Water contact angles of CMB with respect to three decontamination methods. The output performance of the two groups of CMB: (d) after BT and (e) after AW. (f) Improvement of EV after BT and AW. (g) Increase in filtration efficiency toward PM0.3 after BT and AW. The increase in filtration efficiency toward PM0.5 to PM5 after BT and AW: (h) A group and (i) B group. The error bar represents the standard deviation of five replicate measurements.
The fabricated CMB with excellent protection performance was adaptable for mass production by the melt-blown process. To validate the effective performance of CMB in pragmatic scenarios, CMB in quantity was prepared (Figure 4a, width in 0.6 m, length in 40 m), serving as the filter layer to meet the requirements of PPE manufacturing. During the fabrication, CMB-1 had been applied in mass production owing to its excellent performance combining protective, output, and mechanical properties. To demonstrate the multiple uses of CMB in practical applications, the common and facile decontamination methods had been utilized to process CMB including 75% alcohol immersion and 100°C water bathing (named as the A and B group) for three cycles (every cycle includes 20 min of decontamination and 4 h of drying). As shown in Figure 4b, *Escherichia coli* (*E. coli*) can be inactive through the two typical decontamination methods (the original group was for comparison). The stabilities of the surface property and structure can be illustrated through the water contact angle (Figure 4c), which were 142.8 and 141.1°, corresponding to A and B groups, respectively, showing little difference from the original (142.9°). Moreover, the output voltage after BT (Figure 4d) and AW (Figure 4e) was characterized, and the B group has the optimal output performance, which were 96 and 43.2 V, respectively. The reason might be that, unlike alcohol, boiling water would not infiltrate the hydrophobic CMB. Furthermore, EV and filtration efficiency were critical for the protection properties of CMB (Figure 4f–i) as well. The improvement of EV between before (about 1 kV) and after BT and AW (>2.5 kV) samples verified that CMB can be triggered by BT and AW after decontamination procedures. The same increase had been observed in filtration efficiency toward PM0.3 after BT and AW (Figure 4g), which were from 26.61 to 66.1 and 57.21% for the A group and from 46.41 to 86.02 and 77.64% for the B group. The filtration efficiency toward PM0.5 to PM1 experienced an obvious rise as well; especially for PM2.5, the filtration efficiency improved to 99.98% for both groups (Figure 4h,i); thus, these responsive increases indicated that our CMB can be recharged for reutilization.

Focusing on the mask example, the disposable mask with the SMS structure had been analyzed, and the comparison of filtration efficiency between different layers is depicted in Figure 5a. The outer and inner layers of the mask were made of hydrophobic non-woven PP, applied for obstructing the moisture from the inhaled and exhaled air to the filter layer, respectively. In this regard, the filtration efficiency in the micron particle regime (<1 μm) of two non-woven layers remained at a rather lower level (<5%); in comparison, the filtration efficiency toward PM0.3 of the mask reached 50%, principally attributed to the filtration performance of the melt-blown layer. Of note, the SMS structure composed of one-layer CMB-1 with inner and outer non-woven layers had been achieved successfully (Figure 5b). It could be seen that the shape and wearing manner of the CMB mask were the same as the conventional masks, indicating its practicability. Comparatively, the filtration efficiency toward PM0.3 of 4 h worn masks only reached approximately 50%; after BT and AW, the filtration efficiency of the CM mask experienced a marked enhancement, especially for micron and nanoparticles, which increased to 90 and 87%, respectively (Figure 5c and Figure 5d).
S12). According to the former aging experiments and decontamination process, although the filtration efficiency of CMB decreased slightly, that figure can be improved through external BT and AW. Of crucial importance in the wearing comfort for the mask is the DP, particularly for the long-time mask-wearing group. In contrast to the high DP level of conventional masks with the SMS (>60 Pa/cm²) and SMMS structure (>80 Pa/cm²), the mask equipped with the CMB filter exhibited much lower DPs, which were 24.3 and 37 Pa/cm², providing a better comfort level for the end user. In addition, human voice recording was applied to the SMS structure using CMB as the core layer to simulate the actual scenario (Figure 4d and Figure S12c). Although the CMB was sandwiched between two spunbond PP fabrics, it can be triggered to generate charges, of which the output depends on the decibels and frequency of AW (Figure S4). Benefiting from the compatibility with commercial melt-blown techniques, the CMB mask is readily capable of achieving daily production for industrialization (above 5 million per day), further mitigating the shortage and pollution of disposable masks globally. In parallel, the increased economic costs of every face mask were calculated to be 0.002 RMB, which was tiny and negligible compared with current PP face mask filter manufacturing technologies (details in the Supporting Information). Similarly, durable CMB with outstanding breathability is desirable for commercial applications such as protective suits, protective gloves, isolation gowns, etc.

### CONCLUSIONS

In this work, we proposed an efficient approach with the introduction of the PENG and TENG technology into the fabrication of charge-laden melt-blown. Compared with the rapid decay of electrostatic effects intrinsically like the conventional filter layer, the engagement of P(VDF-TrFE) enabled CMB to quickly respond toward mechanical and sound waves during daily speaking to produce charges, which facilitate blocking of the invisible but ubiquitous micro/nanoparticles and aerosols. Exceptionally, results revealed that, after 72 h of hydrothermal aging, an enhanced filtration efficiency toward PM₈.₅ to PM₂₀ of CMB was observed during daily wear for end users. Attributed to high filtration efficiency (>90%), low respiratory resistance (<17 Pa/cm²), and practicable mechanical properties, through the melt-blown process, the CMB can be put into mass production to serve as the core filter layer. Furthermore, after three cycles of current decontamination methods, the filtration efficiency toward PM₂.₅ increased from the original value from 77.64 to 99.3%, prolonging the wearing time of face masks and verifying the reutilization of CMB. With high cost-effectiveness, durable protectiveness could remarkably lessen the consumption of PPE items, further drastically reducing the environmental pollution.

### EXPERIMENTAL SECTION

**Materials.** Polypropylene granule (PP, Henan Tuoren Medical Device Co., Ltd., China) and polyvinylidene fluoride-trifluoroethylene (P(VDF-TrFE), PVDF-TrFE = 70/30, Dongguan Huangjiang Shengbang Plastic Co., Ltd., China) were used to fabricate melt-blown.

**Granulation Process of PP and PVDF-TrFE.** To meet the requirement toward melt fluidity of the melt-blown method, P(VDF-TrFE) powder was mixed evenly with PP via a blender for 10 min; subsequently, the mixture was extruded to produce hybrid granules under 230 °C followed by circulated cooling water to avoid crystallinity of PP. Different mass fractions of P(VDF-TrFE)/PP were used during the granulation, which were 0.5, 1, 3, 5, 10, 15, and 20 wt % (granules named as P-PT-0.5, P-PT-1, P-PT-3, P-PT-5, P-PT-10, P-PT-15, and P-PT-20, respectively, and the corresponding CMB named as CMB-0.5, CMB-1, CMB-3, CMB-5, and CMB-10; note that the latter two granules were unable to be made into applicable CMB).

**Preparation of Charge-Laden Melt-Blown (CMB).** Premixed granules were blended with pristine PP granules uniformly at room temperature, which was crucial to refrain from blocking the spinneret plate from the processing. The feeding channel was divided into five zones with different temperatures (160, 180, 200, 220, and 230 °C) and the melt-pump maintained at 230 °C for the sake of completely melting the granules, followed by polarization with a molybdenum wire array consisting of eight molybdenum wires, the distance between which was 5 cm each, which was applied with a voltage of 20 kV. The whole polarization process lasted for 20 min. After that, the charge-laden melt-blown (CMB) was rolled and pressed.

**Measurements.** **Filtration Efficiency/Differential Pressure Characterizations.** The mask filtration performance test (Suxin Environment Technology Co., Ltd., China) was applied to characterize the filtration efficiency by using a 100 m² sample with an airflow of 32 L/min. A particle counter was used to measure the sodium chloride aerosol concentration in the upstream and downstream of the filter material, and the filtering efficiency toward particles ranging from 0.3 to 5 µm was characterized. The differential pressure was analyzed by a mask resistance tester (Junray Intelligent Instrument Co., Ltd., China) under 8 L/min. The tensile test was conducted on an electronic dynamic and static fatigue machine (E3000, Instron, UK) with a 5 cm × 25 cm sample. Five samples were tested under 25 °C during both characterizations.

**Output Performance of the CMB.** The output performance of CMB was characterized through an oscillation excitation system. The measurement platform is composed of an excitation system and a signal sampling system, which can simulate the vibration of the actual environment and collect the output signals, respectively. The excitation system consists of a vibration exciter (DH 40050, Donghua Test Technology Co., Ltd., China), a power amplifier (DH 5871, Donghua Test Technology Co., Ltd., China), and a signal generator (DH 1301, Donghua Test Technology Co., Ltd., China). A pressure sensor (PCB PIEZOTRONICS, 208C02) and a PXI system (Quad-core embedded controller, NI PXIe-8135; Chassis, NI PXIe-1082; acquisition card, NI PXIe-4499, National Instruments, USA) were used to measure the external pressure exerted on the CMB. Moreover, acoustic waves at different decibels and frequencies were produced by a microphone. A signal generator generates frequency and voltage signals. A power amplifier increases the voltage signal and drives the exciter to work. Signal sampling systems include oscilloscopes (TBS 1012, Tektronix, US) and bass noise amplifiers (A Stanford Research SR570), which sample the output voltage. Five samples were tested under 25 °C during both characterizations.

**Electrostatic Voltage Test of CMB.** The electrostatic voltage was measured through a non-contact electrostatic fieldmeter (FMX-003, SIMCOION, USA), which was vertical to the samples (10 different parts of each sample were tested, and every group contained five samples). The distance between each sample and electrostatic fieldmeter was 25 mm ± 5 mm, controlled by two focus LED lights.

**Decontamination Experiment.** CMB-1 groups, sterilized with ethylene oxide, were cut into desired dimensions (diameter of 0.75 cm). E. coli suspension (ATCC 25922, 500 μL, 105 CFU/mL) was added into each well of a 24-well plate to completely immerse the filter and then incubated at 37 °C for 24 h. After incubation, all the filters were taken out and washed with sterile water three times to remove the unattached bacteria and then dried at room temperature (25 °C). To separate the inoculated bacteria, dried filters were immersed in 5 mL of Ringer’s solution and shaken for 5 min. Subsequently, 100 μL of bacterial solution obtained in the previous step was evenly distributed in the LB agar solid plate and incubated at 37 °C for 24 h. After that, the bacterial colony was counted. Finally, ...
to evaluate the decontamination method, dried CMB-1 filters, disinfected by 20 min 75% alcohol immersion or 20 min 100 °C water bathing for three cycles, were shaken in 5 mL of Ringer’s solution and then incubated as previously described.

## ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsami.2c01077.

Detailed information of characterization methods, forming mechanism, melt flow index of P(VDF-TrFE) granules, filtration efficiency, mechanical properties, AW output, structure characterizations, hydrothermal aging, decontamination methods, and output testing devices toward the charge-laden melt-blown (PDF)

## AUTHOR INFORMATION

### Corresponding Authors

Yunming Wang — State Key Laboratory of Materials Processing and Die & Mould Technology, School of Materials Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China; orcid.org/0000-0002-8557-0349; Phone: +86 027-87543492; Email: wang653@hust.edu.cn

Hua Min Zhou — State Key Laboratory of Materials Processing and Die & Mould Technology, School of Materials Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China; Phone: +86 027-87559433; Email: hmzhou@hust.edu.cn

### Authors

Dan Chen — State Key Laboratory of Materials Processing and Die & Mould Technology, School of Materials Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

Lianwei Tang — State Key Laboratory of Materials Processing and Die & Mould Technology, School of Materials Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

Yongyao Tan — Department of Ophthalmology, Tongji Hospital, Tongji Medical College, Huazhong University of Science and Technology, Wuhan 430074, China

Yue Fu — State Key Laboratory of Materials Processing and Die & Mould Technology, School of Materials Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

Weihao Cai — State Key Laboratory of Materials Processing and Die & Mould Technology, School of Materials Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

Zhaoan Yu — State Key Laboratory of Materials Processing and Die & Mould Technology, School of Materials Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

Shuang Sun — State Key Laboratory of Materials Processing and Die & Mould Technology, School of Materials Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

Jiaqi Zheng — State Key Laboratory of Materials Processing and Die & Mould Technology, School of Materials Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

Jingqiang Cui — Henan Key Laboratory of Medical Polymer Materials Technology and Application, TuoRen Medical Device Research & Development Institute Co., Ltd., Changyuan, Henan 453000, China

Guosheng Wang — Henan Key Laboratory of Medical Polymer Materials Technology and Application, TuoRen Medical Device Research & Development Institute Co., Ltd., Changyuan, Henan 453000, China

Yang Liu — State Key Laboratory of Materials Processing and Die & Mould Technology, School of Materials Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

Complete contact information is available at: https://pubs.acs.org/doi/10.1021/acsami.2c01077

### Notes

The authors declare no competing financial interest.

### ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation Council of China (grant no. 52075196) and the Fundamental Research Funds for the Central Universities (grant no. 2016YXZD059). The authors thank Y. K. Zhang for assistance for valuable discussion and to Y. Li with equipment.

### REFERENCES

(1) Ranney, M. L.; Griffeth, V.; Jha, A. K. Critical Supply Shortages - the Need for Ventilators and Personal Protective Equipment During the COVID-19 Pandemic. N. Engl. J. Med. 2020, 382, 3.

(2) Chu, D. K.; Akl, E. A.; Duda, S.; Solo, K.; Yaacoub, S.; Schünemann, H. J.; Chu, D. K.; Akl, E. A.; El-harakeh, A.; Bognanni, A.; Lotfi, T.; Loeb, M.; Hajizadeh, A.; Bak, A.; Izcovich, A.; Cuello-Garcia, C. A.; Chen, C.; Harris, D. J.; Borowiack, E.; Chamseddine, F.; Schünemann, F.; Morgano, G. P.; Mutt Schünemann, G. E. U.; Chen, G.; Zhao, H.; Neumann, I.; Chan, J.; Khabsa, J.; Hnegy, L.; Harrison, L.; Smith, M.; Rizk, N.; Giorgi Rossi, P.; AbiHanna, P.; El-khoury, R.; Stalteri, R.; Baldeh, T.; Piggott, T.; Zhang, Y.; Saad, Z.; Khamis, A.; Reinap, M.; Duda, S.; Solo, K.; Yaacoub, S.; Schünemann, H. J. Physical Distancing, Face Masks, and Eye Protection to Prevent Person-to-Person Transmission of Sars-Cov-2 and Covid-19: A Systematic Review and Meta-Analysis. Lancet 2020, 395, 1973–1987.

(3) Turok-Molina, A.; Takayanagi, K.; Redwan, E. M.; Uversky, V. N.; Andres, J.; Serrano-Aroca, A. Protective Face Masks: Current Status and Future Trends. ACS Appl. Mater. Interfaces 2021, 13, 56725–56751.

(4) Leung, N. H. L.; Chu, D. K. W.; Shiu, E. Y. C.; Chan, K. H.; McDevitt, J. J.; Hau, B. J. P.; Yen, H. L.; Li, Y.; Ip, D. K. M.; Peiris, J. S. M.; Seto, W. H.; Leung, G. M.; Milton, D. K.; Cowling, B. J. Respiratory Virus Shedding in Exhaled Breath and Efficacy of Face Masks. Nat. Med. 2020, 26, 676–680.

(5) Adyel, T. M. Accumulation of Plastic Waste During Covid-19. Science 2020, 369, 1314–1315.

(6) Palmieri, V.; De Maio, F.; De Spriito, M.; Papi, M. Face Masks and Nanotechnology: Keep the Blue Side Up. Nano Today 2021, 37, 101077.

(7) Khoo, K. S.; Ho, L. Y.; Lim, H. R.; Leong, H. Y.; Chew, K. W. Plastic Waste Associated with the Covid-19 Pandemic: Crisis or Opportunity? J. Hazard. Mater. 2021, 417, 126108.

(8) Patricio Silva, A. L.; Prata, J. C.; Walker, T. R.; Duarte, A. C.; Ouyang, W.; Barcelo, D.; Rocha-Santos, T. Increased Plastic Pollution Due to Covid-19 Pandemic: Challenges and Recommendations. Chem. Eng. J. 2021, 405, 126683.

(9) Prata, J. C.; Silva, A. L. P.; Walker, T. R.; Duarte, A. C.; Rocha-Santos, T. Covid-19 Pandemic Repercussions on the Use and Management of Plastics. Environ. Sci. Technol. 2020, 54, 7760–7765.
Outstanding Superhydrophobic and Photothermal Performances. ACS Nano 2020, 14, 6213−6221.
(29) Shan, X.; Zhang, H.; Liu, C.; Yu, L.; Di, Y.; Zhang, X.; Dong, L.; Gan, Z. Reusable Self-Sterilization Masks Based on Electrothermally Graphene Filters. ACS Appl. Mater. Interfaces 2020, 12, 56579−56586.
(30) Gogoi, P.; Singh, S. K.; Pandey, A.; Chattopadhyay, A.; Gooh Pattader, P. S. Nanometer-Thick Superhydrophobic Coating Renders Cloth Mask Potentially Effective against Aerosol-Derived Infections. ACS Appl. Bio Mater. 2021, 4, 7921−7931.
(31) Zhang, G.-H.; Zhu, Q.-H.; Zhang, L.; Yong, F.; Zhang, Z.; Wang, S.-L.; Wang, Y.; He, L.; Tao, G.-H. High-Performance Particulate Matter Including Nanoscale Particle Removal by a Self-Powered Air Filter. Nat. Commun. 2020, 11, 1653.
(32) Zhang, R.; Xu, Q.; Bai, S.; Hai, J.; Cheng, L.; Xu, G.; Qin, Y. Enhancing the Filtration Efficiency and Wearing Time of Disposable Surgical Masks Using Teng Technology. Nano Energy 2021, 79, No. 105434.
(33) Su, Y.; Chen, G.; Chen, C.; Gong, Q.; Xie, G.; Yao, M.; Tai, H.; Jiang, Y.; Chen, J. Self-Powered Respiration Monitoring Enabled by a Triboelectric Nanogenerator. Adv. Mater. 2021, No. e2101262.
(34) Yu, Z. H.; Wang, Y. M.; Zheng, J. Q.; Xiang, Y.; Zhao, P.; Cui, J.; Qiao, Z.; Zhou, H. M.; Li, D. Q. Rapidly Fabricated Triboelectric Nanogenerator Employing Insoluble and Insufible Biomass Materials by Fused Deposition Modeling. Nano Energy 2020, 68, 7.
(35) Yu, Z. H.; Chen, M.; Wang, Y. M.; Zheng, J. Q.; Zhang, Y. K.; Zhou, H. M.; Li, D. Q. Nanoporous PdF Hollow Fiber Employed Piezo-Tribo Nanogenerator for Effective Acoustic Harvesting. ACS Appl. Mater. Interfaces 2021, 13, 26981−26988.
(36) An, Z.; Li, Y.; Xu, R.; Dai, P.; Zhao, Y.; Chen, L. New Insights in Poly(Vinylidene Fluoride) (PvfD) Membrane Hemocompatibility: Synergistic Effect of PvdF-G-(Acryloyl Morpholine) and PvdF-G-(Poly(Acrylic Acid)-Argatroban) Copolymers. Appl. Surf. Sci. 2018, 457, 170−178.
(37) Sun, Q.; Leung, W. W. Enhanced Nano-Aerosol Loading Performance of Multilayer PdF Nanofiber Electroilters. Sep. Purif. Technol. 2020, 240, No. 116606.
(38) Javidpour, L.; BoZic, A.; Najj, A.; Podgornik, R. Electrostatic Interactions between the Sars-Cov-2 Virus and a Charged Electret Fibre. Soft Matter 2021, 17, 4296−4303.
(39) Chughtai, A. A.; Stelzer-Braid, S.; Rawlinson, W.; Pontivivo, G.; Wang, Q.; Pan, Y.; Zhang, D.; Zhang, Y.; Li, L.; MacIntyre, C. R. Contamination by Respiratory Viruses on Outer Surface of Medical Masks Used by Hospital Healthcare Workers. BMC Infect. Dis. 2019, 19, 491.
(40) Wang, N.; Ferhan, A. R.; Yoon, B. K.; Jackman, J. A.; Cho, N. J.; Majima, T. Chemical Design Principles of Next-Generation Antiviral Surface Coatings. Chem. Soc. Rev. 2021, 50, 9741−9765.
(41) Fischer, E. P.; Fischer, M. C.; Grass, D.; Henrion, I.; Warren, W. S.; Westman, E. Low-Cost Measurement of Face Mask Efficacy for Filtering Expelled Droplets During Speech. Sci. Adv. 2020, 6, No. eabd3083.
(42) Ohnishi, K.; Ohgata, H. Disposable Garment Comprising Melblown Nonwoven Backsheet. US 07,967,805, Jun 28 2011, 2011.
(43) Standards, B. Medical Face Masks - Requirements and Test Methods; British Standards Institute Staff, 1914.
(44) Davies, C. N. J. A. P. Air Filtration; Elsevier B.V., 1973.
(45) Yu, S.; Zhang, Y.; Yu, Z.; Zheng, J.; Wang, Y.; Zhou, H. Pani/ PvdF-Trife Porous Aerogel Bulk Piezoelectric and Triboelectric Hybrid Nanogenerator Based on in-Situ Doping and Liquid Nitrogen Quenching. Nano Energy 2021, 80, 9.
(46) Ou, Q.; Pei, C.; Chan Kim, S.; Abell, E.; Pui, D. Y. H. Evaluation of Decontamination Methods for Commercial and Alternative Respirator and Mask Materials - View from Filtration Aspect. J. Aerosol Sci. 2020, 150, No. 105609.
(47) Armamento, L.; Barbera, J.; Carota, E.; Crognaile, S.; Marconi, M.; Rossi, S.; Rubino, G.; Scungio, M.; Taborri, J.; Calabrò, G. Polymer Materials for Respiratory Protection: Processing, End Use, and Testing Methods. ACS Appl. Polym. Mater. 2021, 3, 531−548.