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Self-Charging Textile Woven from Dissimilar Household Fibers for Air Filtration: A Proof of Concept

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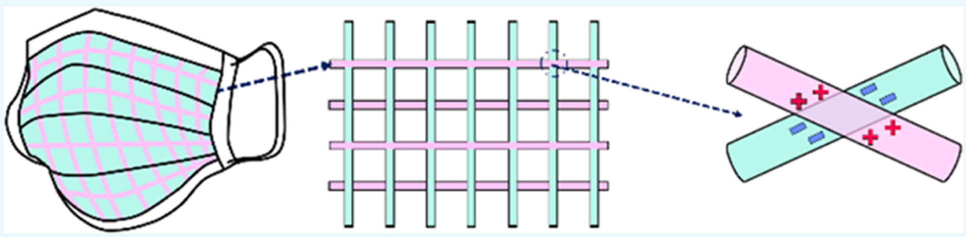

ABSTRACT: A proof of concept is demonstrated concerning self-charging fabrics for air filtration purposes based on common household fibers. Triboelectrically dissimilar fibers, such as wool and polyester, were interwoven into a single-layer fabric, so that local charges can be developed and partially retained at the junctions of the insulating fibers as a result of their constant frictional contact. Voluminous fibers that are typically used for knitting were chosen here, leveraging their broad availability and ease of use, so that they can be handwoven into a leak-free fabric, preventing unfiltered air to pass through directly. When tested for $PM_{2.5}$ and PM_{10} removal, this hybrid fabric outperforms a single-material fabric made similarly from household cotton yarns. And its pressure drop and filtration efficiency were found to be in between those of a common surgical mask and a KN95 mask.

INTRODUCTION

Face masks are used ubiquitously to inhibit the uptake of pollutive particulate matter (such as $PM_{2.5}$) and respiratory droplets or nuclei that may contain infectious pathogens. The COVID-19 pandemic has spurred the development of many new filtration concepts,[1−3] including masks with enhanced antiviral functions to protect the wearers[4−6] or to deactivate outgoing droplets,[7,8] protocols for sanitizing masks for emergency reuse,[9−13] and temporary face covers made from household fabrics.[14−22] There is generally a trade-off between the comfort of the filtering media and its filtration efficiency. Thicker or additional layers of materials can block more respiratory droplets or airborne particles, but this reduces the permeability, thereby increasing the resistance to airflow and making the mask less breathable. This trade-off is imminently clear in N95 or KN95 respirators, which are capable of filtering at least 95% of 0.3 μm airborne particles through mechanical and electrostatic mechanisms but have low breathability caused by their four polypropylene layers.[21,23] The original scarcity of N95 masks prompted the US Centers for Disease Control and Prevention (CDC) to recommend the use of cloth face coverings to mitigate the spread of COVID-19, yet commonly available textiles have vastly different filtration efficiencies.[14−22] Although some masks constructed from household materials report filtration efficiencies of 70−90%, other studies determined that cloth masks have a much higher penetration of particles and droplets.[19,22] Most of the existing techniques to improve cloth face masks involve adding extra layers of fabric to enhance the filtration capability, but this adjustment will also increase the pressure drop and decrease the mask's comfort level. While regular woven fabrics provide protection from larger particles via physical blocking, smaller aerosols can still enter in through gaps in the material. Electrostatic attraction is typically more efficient for removing small particles than mechanical mechanisms like inertial impact or gravitational setting.[17] The filtration efficiency of cloth face coverings displayed improvement after the masking layer was triboelectrically charged through rubbing with a layer of a different material.[20]

Triboelectricity is the phenomenon in which frictional contact between dissimilar materials induces an electrical charge on an insulator.[24] The triboelectric series delineates the relative tendencies of materials to gain or lose electrons during contact electrification. Woven fabrics can take advantage of triboelectricity when two dissimilar yarns are interlaced together to create a single textile. This method of generating electric charge has recently been employed for the creation of triboelectric nanogenerator-based wearable electronics and face masks.[25−28] Other filtration media have historically been

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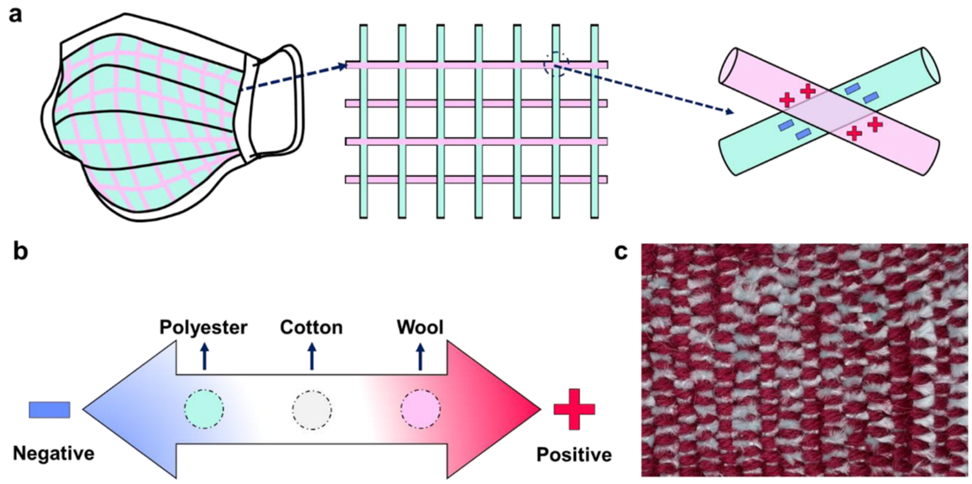

Figure 1. Concept behind the self-charging textile and an example material. (a) Schematic drawing showing the working principle of the self-charging woven textile. When two dissimilar insulative materials rub against each other, one gains a net positive charge, while the other acquires a net negative charge. Woven fabrics have many points of contact, where the warp and weft fibers cross. The insulative nature of the fibers allows these triboelectrically generated charges to stay localized on the fibers without being fully neutralized or dissipated for the purpose of enhanced electrostatic filtration. (b) Triboelectric series delineates an insulator's relative tendency to gain or lose electrons. Polyester is negative, cotton is neutral, and wool is positive. Combinations of these yarns should therefore yield a net charge on each material. (c) Example of the wool (red yarn) and polyester (light blue yarn) hybrid fabric, where the numerous junctions between the overlapping fibers are clearly visible.

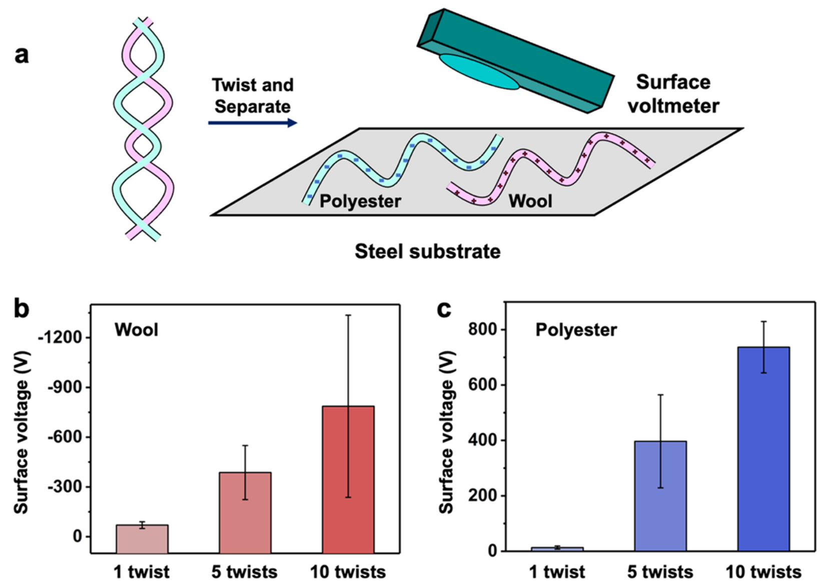

Figure 2. Assessment of tribologically generated charges in different yarns. (a) Two dissimilar fibers that were initially twisted together were pulled apart to generate charges and mimic the contacts between overlapping fibers. Individual strands were then placed on a steel substrate, where the surface voltage was measured independently. Surface voltage values as a function of the number of twists for the (b) wool and (c) polyester fibers are displayed in these graphs. The error bars represent the standard deviation of the collected data points. Each measurement was repeated three times. Additional contacts between the yarns tended to increase the magnitude of their surface voltage values.

developed by carding together fibers of resin and wool or polypropylene and modacrylic to generate triboelectric charges.[29,30] Air filters relying on the triboelectric charging of these dissimilar materials had higher filtration efficiencies than corona-charged carded air filters.[30] Inspired by the working principles of N95 and KN95 masks, triboelectric nanogenerators, and existing air filters, we tested the charging, breathability, and filtration of a handwoven sample that incorporates two distinct types of household fibers, wool and polyester, in its warp and weft. In this proof of concept, a single-layer, self-charging textile made from these triboelectrically dissimilar fibers was found to have pressure drop and filtration efficiency in between those of a common surgical mask and a KN95 mask.

■ RESULTS AND DISCUSSION

Figure 1 illustrates the design of the single-layer hybrid fabric made from fiber materials that are on the opposite ends of the triboelectric series intended to exploit triboelectric effects to provide coverage against smaller particles. Local charges can be generated and regenerated at the junctions of woven threads due to the constant frictional contact that the yarns experience (Figure 1a). The insulative nature of the fibers limits the mobility of these charges. Also, since the yarns are voluminous

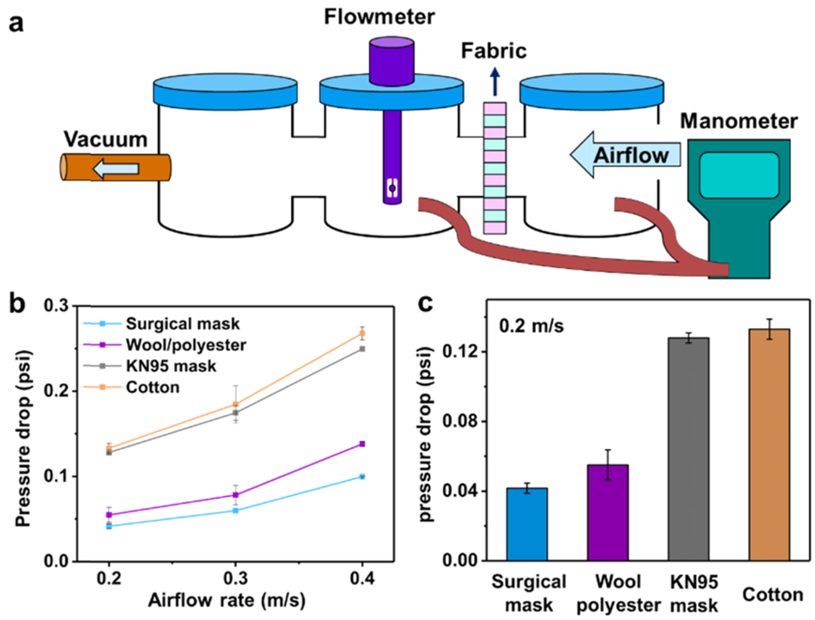

Figure 3. Experimental method and results for evaluating the pressure drop across the filter fabrics. (a) Air was pulled through the samples using vacuum at a variety of airflow speeds, determined by the flowmeter, while the manometer measured the pressure drop across the material. (b, c) Results of this experiment demonstrated that the experimental fabrics had pressure drops in the same range as commercially available surgical and KN95 masks within an airflow speed range of 0.2−0.4 m/s. On these graphs, the error bars represent the standard deviation of the three data points collected.

and fluffy, when they are rubbed against one another, they may not return to their original position, so the charges on one fiber will not be easily canceled out by those on the fiber of the other material. Both of these qualities hinder the neutralization of the opposite charges generated locally at the contacting fibers. Therefore, although the triboelectric effect may not generate significant net charges over the hybrid fabric, there should be ample localized positive and negative charges at the fiber−fiber junctions, which can be leveraged for filtration purposes. Wool and polyester were selected as the constituent materials. Both types of fibers are utilized in commercial textiles, and they have opposite charging trends on the triboelectric series (Figure 1b). Yarns were acquired from a craft store and handwoven into a hybrid fabric (Figure 1c). Overall, the textile contained more of the warp yarn than weft yarn, containing ∼70% wool and 30% polyester. Fluffy fibers that are typically used for knitting were chosen because their voluminous nature helps to prevent pinhole formation at the fiber junctions when they are tightly woven together. The thickness of the hybrid fabric was ∼1 mm.

To verify the self-charging capability of the hybrid fabric, the induced surface voltages from the triboelectric charging of the constituent materials were evaluated. As displayed in Figure 2a, wool and polyester yarns were twisted together to mimic the heterojunctions present in the woven material. When the number of twists increased, the magnitude of the surface voltages on the wool and polyester yarns tended to increase, which is logical as there are more opportunities for frictional contact between the dissimilar fibers (Figure 2b,c). Considering the large number of heterojunctions in the actual fabrics, the increase in surface voltage with the number of twists bodes well for the performance of the bulk material. Note that when the positively charged wool is placed at a set distance from the device, the measured voltage is negative due to the charge that exists on the voltmeter's detector in response and the voltage it creates that opposes the direction of electron motion (see detailed analysis in Figure S2).[31]

One important metric for determining the suitability of filter material for a face mask is breathability, as the user needs to be able to breathe comfortably while wearing it. Pressure drop is commonly analyzed as a measure of this quality.[15] As shown in Figure 3a, the pressure drop across a filter fabric can be recorded with a manometer while the airflow speed, controlled by the vacuum at one end of the system, is monitored by a flowmeter. In addition to the wool/polyester hybrid fabric, three other types of filter materials were tested, including a tightly woven cotton fabric, a surgical mask, and a KN95 mask. Cotton was selected because it is commonly employed in nonmedical cloth face coverings, and it is neutral on the triboelectric series; therefore, it is the least likely fabric to generate triboelectric charges. The surgical mask and the KN95 mask were included as controls since they are well-tested commercial face masks with known performance characteristics. Surgical masks typically have one layer of melt-spun, nonwoven polypropylene fibers in the middle, while KN95 masks consist of 3−5 layers of spun-bound, nonwoven polypropylene material and have a similar theoretical performance to N95 masks.[21]

During normal exhalation, the average maximum airflow rate has been measured as 0.2 m/s, but the speed of the expired jets can be much higher for other respiratory emissions.[17,18] Face velocities near 0.2 m/s were also recently used in analyses of face mask performance, so pressure drops were measured at an airflow rate of 0.2 m/s.[17,18] The pressure drop of the hybrid fabric was found to be slightly higher than that of the surgical mask, which suggests that wearers of this type of face-covering materials would experience a similar comfort level (Figure 3b,c). Both the compliance to regulations requiring face mask usage and the duration of wearing are related to the discomfort that individuals experience when wearing the mask, so maximizing the comfort is important.[32] The tightly woven

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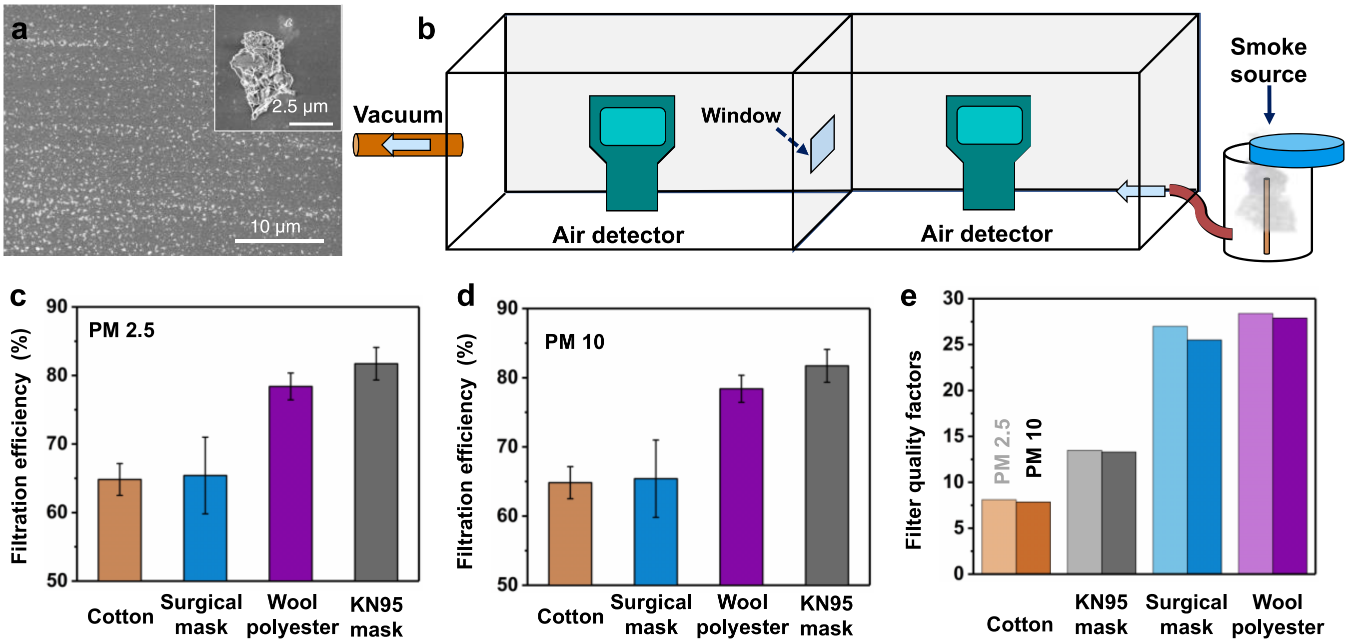

Figure 4. Evaluation of the air filtration efficiency of the fabrics. The key quality that determines the usefulness of a filter material is its ability to remove particulate matter. Particles released from burning incense were used as a surrogate for respiratory droplets or other ambient particulate matter to test the filtration capability of the samples. (a) SEM image of the particulate matter released from a burning incense stick collected on a silicon wafer, showing its size distribution. (b) In the experimental setup of the filtration test, smoke generated from a burning incense stick was fed to the chamber on the right, the flux of which could be tuned by the cover on the container. The smoke-laden air was pulled through the fabric toward the left chamber. Two particle counters, one in each chamber, were used to quantify the concentration of the particles in each chamber. Filtration efficiency was calculated by dividing the particulate matter concentration in the filtered air by that of unfiltered air. The average filtration efficiency of each sample for (c) $PM_{2.5}$ and (d) PM_{10} is plotted on these graphs, with the error bars indicating the standard deviations of the seven measurements. (e) Filter quality factors for the four materials take both their filtration efficiency (i.e., particle removal) and their pressure drop (i.e., breathability) into account to assess their potential for use in air filtration and face masks.

cotton fabric demonstrated a pressure drop as high as that of the KN95 mask, even though the cotton material was constructed as a single-layer filter. This is attributed to the tight knitting and thickness of the cotton yarn and the low porosity of the resulting fabric, which avoided generating leaky pinholes that air could pass through directly.

The ability of the hybrid fabric to filter particulate matter is the key factor for its potential use in face masks or other types of air filters. Ideally, a mask should be highly breathable while maintaining a high filtration efficiency of fine particulate pollutants to protect the wearer. As a proof of concept, smoke generated from burning incense was chosen as the source of particulate matter for our experiment to evaluate the filtration characteristics of the samples. As displayed in the scanning electron microscopy (SEM) image in Figure 4a, incense smoke particles are primarily less than a micron and typically even smaller, below 0.3 μm in diameter, which makes them a suitable surrogate for inhalable $PM_{2.5}$ and of respiratory aerosols.[33−35] A schematic illustrating our experimental setup, inspired by the design used in an earlier report by He et al.,[36] for determining the filtration efficiency, is shown in Figure 4b. Two clear acrylic chambers were constructed with a small window between them to allow air to flow through. During testing, the opening was blocked with the fabric samples. Incense smoke was generated in a separate connected vessel and guided through the system by vacuum, which maintained the airflow at a speed between 0.1 and 0.2 m/s. By closing or opening the container holding the combusting incense stick, the flux of smoke could be controlled.

Filtration efficiencies of the four samples analyzed are plotted in Figure 4c,d. As is expected, the KN95 mask was a much better filter than the surgical mask due to its higher number of nonwoven fiber layers and electrostatic charges. There was no significant difference between the cotton fabric and the surgical mask or between the wool/polyester hybrid fabric and the KN95 mask. Ordinary surgical masks and cotton are uncharged materials, and their poorer performance is expected because electrostatic interactions control the capture of small aerosols.[37] Without any fabric covering the window, 79% of $PM_{2.5}$ and 82% of PM_{10} could escape through the system, so both the surgical mask and the cotton fabric still offered a significant reduction in the number of particles entering the second chamber. The efficiencies for $PM_{2.5}$ and PM_{10} are effectively the same for each sample, which is logical, as most of the incense smoke is smaller than 2.5 μm in size.

The wool/polyester hybrid fabric demonstrated a higher filtration efficiency than the cotton-based control, which is attributed to the charges developed at the junctions between the dissimilar fibers. Significantly, since the cotton material has a higher pressure drop and therefore should have filtered better, it was still outperformed by the wool/polyester filter. The filter quality factor is often calculated to reconcile the contributions of filtration efficiency and pressure drop to a material's appropriateness for application in filtration media.[17,38,39] The following equation defines this quantity in terms of P, the fraction of particles that penetrate through the filter, and Δp, the pressure drop

$$q_f = \frac{\ln(1/P)}{\Delta p}$$

Figure 4e summarizes the filter quality factors of the face masks and fabrics analyzed in these experiments (Table S1). When taking the low pressure drop into account, the wool/polyester hybrid fabric outperforms the KN95 mask. It should be noted that this metric is not faultless, as low pressure drop is overemphasized through this calculation. Yet, the filter quality factor still signifies the great potential of a hybrid fabric like the one demonstrated here. By combining the dissimilar fibers in a single layer, the pressure drop across the fabric remains low while the charge generated at the heterojunctions allows for enhanced filtration capabilities over mono-material textiles. Additionally, the hybrid fabric does not rely on melt-blown textiles like the KN95 or N95 masks, and thus, the manufacturing limitations that led to the shortage of these masks would not apply to a commercial version of the wool/polyester material.

■ CONCLUSIONS

Here, we designed a self-charging hybrid fabric based on commonly available fibers, made from interwoven wool and polyester yarns, which exhibited a filtration efficiency comparable to that of KN95 masks but with lower pressure drop. Triboelectric charging at the heterojunctions within this fabric is suspected to be the origin of this improved performance over a homogeneous cloth mask material. Despite this encouraging proof of concept, more assessments are necessary. The experiments were performed with a flat piece of relatively small area fabric. Additional evaluations are needed for larger area fabrics to see if folding and bending cause leakage and compromise the filtration efficiency. The experimental samples were handwoven with one type of wool yarn and one type of polyester yarn. Since the fuzzy texture of the polyester yarn may have contributed to its enhanced behavior, it would be interesting to study whether other morphologies would perform equally as well. A more comprehensive analysis using yarns or threads with a variety of surface characteristics would help understand the role that the texture plays in determining the resultant material's filtration efficiency. The hybrid fabric's performance may have also been bolstered by the fact that $PM_{2.5}$ is typically negatively charged, and this material had a higher composition of wool, the positively charged fiber.[40,41] Subsequent research would need to be completed to determine how the fabric composition impacts the filtration capability and if there is an optimal composition. When the ways of using these fabrics are better defined in given applications, the issue of comfort needs to be addressed, too, just like other wearable materials and devices.[42] Triboelectric charge is also largely dependent on humidity. Since respiration is an event involving evolving moisture conditions, the filtration performance of the fabric is likely impacted by the humidity it experiences. Therefore, analysis regarding the self-charging and filtration at various values for relative humidity, and the best drying method to recover their performance, would also be beneficial for evaluating the performance of this material in a face mask and similar interwoven fabrics made from other fibers. The self-charging fabric could also be utilized in conjunction with other hydrophobic outer layers to improve its resistance.

■ MATERIALS AND METHODS

Materials. Fabrics were created using cotton (Lily Sugar 'n Cream Yarn, #10428255), polyester (Bernat Baby Velvet Yarn, #10602126), and wool (Patons Classic Wool DK Superwash) yarns of different surface textures that were purchased from a craft store (Figure S1). These samples were tightly plain-woven manually using a small handheld loom. The selected yarns were quite voluminous and flocculent, so they could be woven tightly without leaving pinholes at the fiber junctions. A control sample was made of just cotton yarn for the purpose of comparing a single-material fabric to the hybrid one. Cotton was also selected because it is commonly employed in nonmedical cloth face covering, and it is neutral on the triboelectric series. A surgical mask (VWR Maximum Protection Mask, 414004-670) and a KN95 mask (GB 2626-2006) were included as points of reference.

Analysis of Charges. A surface voltmeter is used to qualitatively compare electrostatic charging on different fibers, which measures the voltage over a large surface area at a set distance from the surface. Thus, when the material being analyzed is small in size, the resultant value is highly dependent on its substrate.[43] Steel was chosen as a substrate because its electrically conductive properties allowed it to be grounded prior to testing, which drains residual charges. Surface voltage was recorded using a surface voltmeter (AlphaLab, Inc. surface DC voltmeter SVM2). Wool and polyester yarns were twisted together a set number of times before they were pulled apart and individually placed on the steel surface, upon which the surface voltage was evaluated. Before measurement, the surface voltmeter was calibrated so that the steel had a surface voltage near zero. This was done to ensure the values measured would be indicative of the yarn's charge characteristics but not that of the substrates. Varying amounts of twisting were used in different trials of this experiment, and each trial was repeated three times.

Pressure Drops. Breathability was assessed via the pressure drop across the fabrics (Figure S1). As illustrated in Figure 3a, the pressure drops across the four materials were recorded using a manometer while the airflow rate, generated by the vacuum at one end of the system, was monitored by a flowmeter. The airflow speed was measured with a digital anemometer (Fisherbrand Traceable) in one chamber. The difference in pressure between that container and the one past the sample was determined by a manometer (Fisherbrand Traceable). Pressure drops were assessed at airflow rates of 0.2, 0.3, and 0.4 m/s. Three measurements were made at each airflow speed.

Evaluation of Filtration Capability. Filtration efficiency, which determines the ability of the material to block particles or droplets, was calculated using the ratio of the amount of particulate matter that passes through the mask to the amount of particulate matter measured before flowing through the filter material. Incense smoke was utilized as the source of $PM_{2.5}$ and PM_{10}, and by closing or opening the container holding the combusting incense stick, the amount of smoke could be controlled and varied within the range of 300−800 $\mu g/m^3$. An air detector (VSON intelligent air quality detector, IGERESS multifunction air detector) was located in each chamber to continuously monitor the $PM_{2.5}$ and PM_{10} concentrations on either side of the fabric. Once the concentrations in both chambers had equilibrated, the $PM_{2.5}$ and PM_{10} were recorded, and filtration efficiencies were determined. The experiment

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was conducted in the hood to avoid environmental influences and was repeated seven times. Burning products were also collected on a silicon wafer that was placed above a combusting stick for 2−3 min. SEM was employed to image and assess the size of the produced particles.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.1c03412.

Photos of the fabrics and a diagram explaining the surface voltmeter's working principle (Figures S1 and S2) and filter quality factors of the sample materials (Table S1) (PDF)

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Notes

The authors declare no competing financial interest.

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