Filtration performances of non-medical materials as candidates for homemade face mask filters

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Abstract:

The recent outbreak of the coronavirus disease (COVID-19) is causing a shortage of personal protective equipment (PPE) in different countries of the world. Because the coronavirus can transmit through droplets and aerosols, face masks, especially N95 respirators that require complex certification, are urgently needed. Given the situation, the U.S. Centers for Disease Control and Prevention (CDC) recommends that "in settings where face masks are not available, healthcare personnel might use homemade masks (e.g., bandana, scarf) for the care of patients with COVID-19 as a last resort." Although aerosols and droplets can be removed through the fibers of these fabrics through a series of filtration mechanisms, their filtration performances have not been evaluated in detail. Moreover, there are a series of non-medical materials available on the market, such as household air filters, coffee filters, and different types of fabrics, which may be useful when medical mask filters are not available. In this study, we comprehensively evaluated the overall and size-dependent filtration performances of non-medical materials. The experiments were conducted under different face velocities to consider the influence of the filtering area used by the wearer. The flow resistance across these filter materials is collected as an indicator of the breathability of the materials. Based on the results, multiple layers of household air filters are able to achieve similar filtration efficiencies compared to the N95 material without causing a significant increase of flow resistance. Considering that these air filters may shed micrometer fibers during the cutting and folding processes, it is recommended that these filters should be inserted in multiple layers of fabrics when manufacturing homemade face masks.

Keywords: homemade face masks, filter materials, household air filter, filtration efficiency, aerosols

Introduction

Due to the 2019 coronavirus disease (COVID-19) outbreak, the global demand for personal protective equipment (PPE) has surged and created a severe shortage across the world (U.S. News, 2020). It is especially the case for face masks, as more evidence shows that the coronavirus can be transmitted by aerosols (Leung et al., 2020; WHO, 2020). Facemasks are crucial for protecting healthcare personnel (HCP) and immune-compromised people from the virus (Adhikari et al., 2020; Bowdle and Munoz-Price, 2020; Milton et al., 2013). Given the situation, the Centers for Disease Control and Prevention (CDC) recommends a few strategies for optimizing the supply of face masks. Specifically, under the circumstance when no face masks are available, the mitigating options include using high-efficiency particulate air (HEPA) filters to generate particle-free air, or manufacturing homemade masks as a last resort (CDC, 2020). The homemade masks can be made of non-medical materials, including "bandana and scarf," which are mentioned in the strategies. The CDC further noted that "however, homemade masks are not considered PPE, since their capability to protect HCP is unknown."

Among existing approaches to manufacturing homemade face masks, 3D printing has the potential to produce face masks with high repeatability and quality control and may be used to alleviate the shortage of PPE in remote communities (as demonstrated in Fig. 1). The 3D-printed face mask requires a filter material to be inserted at its front to remove droplets and aerosols in the ambient air. Given the shortage of certified medical filter supplies, the filter materials need to be selected from non-medical sources that are easily accessible through the market. More importantly, as a core component of the face mask, the filter materials need to achieve a high efficiency in particle removal and a low flow resistance to ensure breathability. Candidate non-

medical materials may include household air filters, coffee filters, activated carbon filters, and various types of fabrics, such as bandana, scarf, and bedsheets. However, few existing studies have comprehensively assessed the effectiveness of these non-medical materials in particle filtration, creating uncertainties in the choice of filter materials. The dataset on the filtration performance of non-medical materials is also urgently needed, so that mitigation strategies can be used when medical supplies are unavailable.

The performance of the filter material is characterized by its filtration efficiency, i.e., the percentage of particles filtered by the material (Hinds, 1999). The flow resistance across the filter material will also affect the performance of the filter because, for a face mask, the flow resistance determines breathability. Darcy's equation calculates the pressure drop across a filter for fluid flow through porous media, where it linearly increases with the thickness of the filter material and the superficial filtering velocity (Cooper and Alley, 2010). Airborne particles are removed by filtration through mechanisms of impaction, interception, diffusion, and electrostatic interaction (Hinds, 1999). Impaction and interception are effective for removing particles with larger sizes (> 1 μm), while diffusion is most effective for removing particles with smaller sizes (<100 nm) (Friedlander, 2000). This feature results in an "escape window" where particles with hundreds of nanometers can penetrate through the filter, resulting in lower efficiencies. The overall filtration efficiency of a filter is calculated by dividing the concentration of particles collected via filter media by that of total particles. Therefore, the overall efficiency may depend on the size distribution of the introduced aerosols and does not differentiate the performance of the filter for particles with different sizes. However, as the virus may be carried by aerosols with different sizes, the size-dependent filtration efficiency of the filter materials needs to be carefully

examined. For example, the widely used "N95" respirator is required to provide a filtration efficiency of at least 95% for 0.3 μm particles when subjected to careful testing (FDA, 2019; NIOSH, 1995). To demonstrate the capabilities of non-medical filter materials in removing ambient aerosols and potentially virus particles, we need to examine both the size-dependent and overall filtration efficiencies.

Due to its extensive usage in building air purification, household air filters have been comprehensively examined by manufacturers and existing literature (Alderman et al., 2008; Fazli et al., 2019; Payet et al., 1992; Wallace, 2006; Wallace and Howard-Reed, 2002; Wallace et al., 2004). Different rating systems, such as microparticle performance rating (MPR), minimum efficiency reporting value (MERV), and filter performance rating (FPR) are created to consider the filtration performance for particles in different size ranges. The certification of these filters may be done by the manufacturer and by a professional as a part of a complete system test according to guidelines (ASHRAE, 1996). However, these air filters are not designed for homemade face masks, and the face velocities through the filters may significantly vary when they are used as face mask filtering materials. One issue associated with these household air filter materials is their biocompatibility, where fiber fragments may be generated after a long period of usage and inhaled by wearers. However, in the designed 3D-printed face mask, two fabric layers can be placed above and below the filter material to avoid the spreading of these large debris, allowing the usage of these non-medical filter materials as medical filters.

Household fabrics were evaluated in a few existing studies, although the specifications of the fabrics were not provided in detail. Jung et al. (2014) compared the filtering efficiencies of

masks and handkerchiefs commonly used by the general public to protect against particulate air pollution, and found that the average filtration efficiency per mask type ranged from 99% for quarantine masks to 2% for handkerchiefs. In a similar study, Mueller et al. (2018) discovered that the filtration efficiency for folded bandana range from 18 to 40%, while that of handkerchief is around 23% (Mueller et al., 2018). To consider this particle leakage associated with different mask-wearing configurations, studies also used a mannequin head for testing. Filtration efficiencies of 33 to 78% for surgical masks, 65% for cloth masks, 10 to 60% for household fabrics were reported (Bowen, 2010; Rengasamy and Eimer, 2011; Shakya et al., 2017). The issue associated with these studies on fabrics as homemade face mask filter material is that the specifications of the fabrics are not directly comparable. According to the mechanism of filtration, the fiber diameter, fiber material, and filter permeability determine the interactions between the fibers and particles. To isolate the influence of different fabric specifications on their filtration performance, we used the thread count, i.e., the number of horizontal and vertical threads per square inch, as the parameter to study the filtration performance of the fabrics.

In this study, we comprehensively measured the size-dependent and overall filtration efficiency of non-medical filter materials under a range of face velocities. The flow resistances across the filter materials as a function of the number of filter layers and face velocities were examined. The filtration performances of the non-medical materials were compared against medical counterparts such as N95, KN95 (equivalent of N95 in China, GB2626-2006), and earloop face mask filter materials. The derived results will help communities where certified face masks are urgently needed and in severe shortage.

2. Methods

2.1. Experimental setup

Figure 2 shows a schematic diagram of the experimental setup. The test aerosols are generated by a constant output atomizer (Model 3076, TSI Inc.) nebulizing a NaCl-water solution with a mass concentration of 0.1%. The atomizer generates aerosols at a flow rate of 3.0 liters per minute (lpm). The aerosols are first diluted by an inline diluter and then dried by a homemade diffusion dryer. Afterward, the aerosols, together with a stream of filtered make-up air, are introduced to a mixing chamber. The fully suspended aerosols are then directed into a filter holder (Air Sampling Cassette, Zefon International Inc.), where the disc-shaped filter material is firmly pressed onto mesh support and sealed at the edge. The filter material is cut to discs with a diameter of 37 mm. The face mask designed at Missouri S&T (Fig. 1) has a filter diameter of 74 mm, meaning that under an average inhaling flow rate of 60 lpm (Hinds, 1999), the face velocity will be 23.2 cm s^{-1}. Therefore, to evaluate the filter material under the same face velocity, the flow rate extracted from the 37 mm filter holder is set at 15 lpm. However, considering that face masks with larger filter areas may be used, we also evaluated the performance of the filter materials under flow rates of 10 and 6 lpm, corresponding to face velocities of 15.3, and 9.2 cm s^{-1}. A scanning mobility particle sizer (SMPS, Model 3936, TSI Inc.) measures the size distributions of aerosols upstream and downstream of the filter holder. The SMPS samples aerosols at a flow rate of 1 lpm, so the rest of the flow (14, 9, or 5 lpm) through the filter holder is maintained by a critical orifice. As a make-up flow, filtered dilution air is introduced to the system downstream of the diffusion dryer.

The SMPS system is equipped with a differential mobility analyzer (DMA, Model 3081, TSI Inc.) that classifies particles in the range between 10 to 600 nm, and a condensation particle counter (CPC, Model 3750) that measures the concentration of the mobility-classified particles. The size distribution of aerosols ($n(D_\mathrm{p})$) is obtained by scanning the voltage that is applied on the DMA. Similar to a previous work (Li et al., 2018), the size-dependent filtration efficiency ($\eta(D_\mathrm{p})$) is calculated by

$$\eta(D_\mathrm{p}) = 1 - \frac{n_\mathrm{o}(D_\mathrm{p})}{n_\mathrm{i}(D_\mathrm{p})} \quad \text{Eq. (1)}$$

where $n_\mathrm{o}(D_\mathrm{p})$ and $n_\mathrm{i}(D_\mathrm{p})$ are the size distributions measured at the outlet (downstream) and inlet (upstream) of the filter holder. Based on the size distributions, we can also evaluate the overall number-based filtration efficiencies. The particle size distributions are first integrated over the measured size range to calculate the total number (N), where

$$N = \int n(D_\mathrm{p}) d(D_\mathrm{p}) \quad \text{Eq. (2)}$$

The overall number-based filtration efficiencies (η_N) is calculated by

$$\eta_N = 1 - \frac{N_\mathrm{o}}{N_\mathrm{i}} \quad \text{Eq. (3)}$$

where N_o and N_i are the total number concentrations of aerosols at the outlet and inlet of the filter holder. The SMPS system also monitors the pressures upstream and downstream of the filter, which can be used to calculate the pressure drop across the filter materials.

2.2. Filter materials

In this study, four types of medical filter materials and thirteen types of non-medical filter materials are evaluated. Some materials are assessed in multiple layers to study the influence of

the number of layers (or filter thickness) on filtration efficiency and flow resistance. A total number of 43 combinations of filter materials were examined under the three different face velocities (23.2, 15.3, and 9.2 cm s^{-1}). Table 1 lists the information of the filter materials and the tests that have been performed.

In this study, the N95 filter material was used as a reference for filter performance. Two KN95 filter materials and a surgical mask filter material were evaluated and compared against N95 material. We also examined three types of household air filters, each with a different microparticle performance rating (MPR). The rating system was developed by 3M to quantify the air filter's ability to capture aerosols from 0.3 to 1 μm in size from the air passing through the filter. The activated carbon filter (fine ground and coarse ground) was combined with one layer of the HEPA 2500 MPR filter. The two types of coffee filters, each combined into three layers, and one layer of the vacuum bag are used for evaluation. In the testing of the fabrics, we evaluated the filtration performance of a cotton bandana, a woolen yarn scarf, and several pillowcases. The pillowcases are manufactured by the same company, but with different thread counts (TC) to study how the quality of the fabrics affects the filtration performance. Certain materials were tested with varying layers to promote filtration efficiency.

According to the classification of filter materials (Hinds, 1999), N95, KN95, surgical mask, and HEPA filters belong to fibrous filters, which can filter particles because of electrostatic interactions in addition to the general filtration mechanisms of impaction, interception, and Brownian diffusion. These materials have the potential to filter particles more efficiently while maintaining a relatively low pressure drop. The rest of the materials can be classified as fabric

filters, which mainly rely on low permeabilities of the materials to collect aerosols via general mechanisms of impaction, interception, and Brownian diffusion. For simplicity, Table 1 also lists the acronyms of the tested materials, showing both the type of the material and the layers being tested. All of the materials were evaluated at face velocities of 23.2, 15.3, and 9.2 cm s^{-1}, corresponding to flow rates of 15, 10, and 6 lpm through the filter materials.

The performance of the filter material is a function of the filtration efficiency and the flow resistance through the filter. Better filter materials have a higher filtration efficiency (lower penetration efficiency) and a lower pressure drop. Following the convention of Hinds (1999), the filter quality, q_F, is calculated for each type of the filter, using the equation

$$q_F = \frac{\ln(1/P)}{\Delta P} \quad \text{Eq. (4)}$$

where P is the penetration efficiency of particles ($P = 1 - \eta$), and ΔP is the pressure drop across the filter. Based on this definition, filters with better performances, i.e., higher filtration efficiency and lower pressure drop, will have higher values of q_F.

3. Results and Discussion

3.1. Comparison of different filter materials

We first examined the performance of the medical and non-medical materials in their filtration efficiencies for 0.3 μm particles and their overall efficiencies. Figs. 3a, 3c, and 3d show the efficiencies and flow resistances collected at face velocities of 23.2, 15.3, and 9.2 cm s^{-1}, respectively. Filters with better performances generate data points at the bottom right corners of the figures. Fig. 3b further shows the overall filtration efficiencies and flow resistances measured at the face velocity of 23.2 cm s^{-1}. A comparison between Figs. 3a and 3b did not demonstrate

significant changes of the data point locations, meaning that different methods for calculating the filtration efficiencies will not significantly influence the performance of the filter materials. However, according to Eq. (2), the overall filtration efficiency is dependent on the size distribution of the test aerosols. The evaluation of filter performance based on overall number-based filtration efficiency may be biased for filters with higher filtration efficiencies in the size range where the test aerosols are most concentrated. Therefore, we follow the convention of using the filtration efficiency at 0.3 μm as an indicator for the filter performance.

At a face velocity of 23.3 cm s^{-1}, N95 material has filtration efficiencies of 94.4% for 0.3 μm particles and 93.3% for the test aerosols overall, while the pressure drop is 1.0 kPa. KN95 materials have similar performances compared to the N95 material, but the surgical mask material provides a filtration efficiency of 73.4% for 0.3 μm particles. Using N95 material as a reference, we can identify several non-medical materials that have similar performance. For example, four layers of HEPA (2500 MPR), two layers of HEPA (1900 MPR), and eight layers of air filters (3000 MPR) provide filtration efficiencies of 99.0%, 92.0%, and 94.4% for 0.3 μm particles at pressure drops of 1.1, 1.0, and 0.9 kPa. Finer activated carbon filter and vacuum bag produce filtration efficiencies of 90.2% and 93.0% for 0.3 μm particles, similar to that of N95, but the pressure drop is significantly larger (2.5 and 2.1 kPa). Coffee filters provide moderate filtration efficiencies of around 50% for 0.3 μm particles, but the pressure drop is significantly higher than most of the other materials.

Compared to the commercialized medical and household air filters, all of the tested fabrics showed filtration efficiencies below 60%. A scarf or bandana is not able to remove aerosols

efficiently, even after multiple layers are stacked. For example, four layers of a scarf or a bandana only provide filtration efficiencies of 28.1% or 7.1% for 0.3 μm particles. This filtration efficiency is not acceptable for removing airborne particles, even if face shields are equipped by HCP. It should be noted that different fabrics may have different specifications, such as fiber diameter, thickness, permeability, and fiber material, resulting in different filtration performance. In this study, we use the thread count as the parameter to relate the fabric property to the filtration performance. Our results suggest that fabrics with denser weaving patterns are able to provide a higher filtration efficiency. For example, four layers of 1000, 600, and 400-thread count pillowcases generate filtration efficiencies of 55.0%, 44.6%, and 19.9%, respectively. We should also note that particles can also be removed by fabrics through electrostatic interaction with fabric fibers. Therefore, fabrics made of polyester, glass, and silk materials may remove aerosols more efficiently than cotton fabrics (Perumalraj, 2016). The measurement also shows that the filtration efficiency and flow resistance increase with the number of layers used for testing. However, the slope of the correlations between the flow resistance and the number of layers in the filter is different for materials, which is a result of different filter permeabilities.

At reduced face velocities of 15.3 cm s^{-1} (Fig. 3c) and 9.2 cm s^{-1} (Fig. 3d), the flow resistance across the filters reduced significantly, in agreement with Darcy's equation. There is a general trend that the filtration efficiencies at 0.3 μm increase with decreasing face velocity, which may be resulted from the longer residence time of particles in the filter. However, as shown in Section 3.3, there is not a simple correlation between face velocity and filtration efficiency, because the removal of particles under different face velocities are strongly size-dependent.

Fig. 3 shows that fibrous and fabric filters naturally separate into two regimes in flow resistance-filtration efficiency plot. This separation is labeled with dashed lines in the figure, where data to the left of the dashed line correspond to fabric filters, and data to the right correspond to fibrous filters. Using Eq. (3), we calculated the filter quality of the test materials, and the results are listed in Table 1. Note that our calculation shows that for filter materials with multiple layers, the filter quality increases with the number of layers used in the material. Therefore, Table 1 lists the highest filter quality values only. Fibrous filters generally have better filter quality, due to the removal of aerosols through the additional electrostatic interactions. Fabrics with a higher thread count generally have a better filter quality. Using the filter quality as a metric, we can observe that household air filters are potential candidates for homemade mask filter materials. Among the fabric filter materials, the vacuum bag also showed good filter quality. However, the large flow resistance associated with the flow through the vacuum bag limits its application in homemade masks due to the significantly enhanced flow resistance and reduced breathability.

3.2. Size-dependent filtration efficiency

Fig. 4 shows the size-dependent filtration efficiencies of the selected non-medical materials and comparison against the N95 material. These filters yield satisfactory filtration efficiencies for droplets and larger particles. Almost all the test materials show an “escape window” between 100 and 400 nm. Because common virus (e.g. flu virus, zika virus, and corona virus) has a size between 20 and 400 nm (Almeida and Tyrrell, 1967; Lakdawala et al., 2011; Shangguan et al., 1998; Zhu et al., 2020), it is possible that the virus-containing aerosols can penetrate through this “escape window” and further transmit through the human respiratory system.

Household air filters typically have better filtration performances, as shown in Fig. 4a. At a face velocity of 23 cm s^{-1}, the filtration efficiencies are above 70% at all sizes. Eight layers of air filter (F-8) have almost the identical size-dependent filtration efficiency as that of N95, while its pressure drop (0.9 kPa) is lower than that of N95 (1.0 kPa). Four layers of HEPA (H-4, 2500 MPR) has superior filtration efficiency than N95 material at all different sizes, but its pressure drop (1.1 kPa) is slightly higher than N95. Vacuum bag (VB) also has a similar filtration efficiency compared to N95, but its pressure drop, 2.1 kPa, is much higher. Coffee filters and activated carbon filters have lower size-dependent filtration efficiencies compared to that of N95 (Fig. 4b). The coffee filters (NB and BR) further require more significant flow resistances to maintain the face velocity of 23.2 cm s^{-1}. The activated carbon filters have relatively high filtration efficiencies for submicron aerosols, and finer activated carbon particles (FC) provide a better filtration performance.

As for the fabrics (Fig. 4c), the size-dependent filtration efficiencies are significantly lower than that of N95, again demonstrating the insufficiency of using fabrics as homemade masks. The bandana, scarf, and 400 thread count pillowcase have size-dependent filtration efficiency values below 40%. This low capturing efficiency will not be compensated by wearing face shields, as face shields mainly rely on impaction and interception to remove larger aerosols and droplets. However, if the fabrics are the only resources of non-medical materials for homemade face masks, we should choose more densely woven fabrics that have higher thread counts (see P6-4 vs P4-4), or use multiple layers of fabrics.

Fig. 4d shows the size-dependent filtration efficiency of the household air filter (3000 MPR, H30) with different number of layers. Comparing Fig. 4d with Fig. 4c, it can be seen that a single layer of air filter is already much more efficient in removing aerosols than most of the fabrics. Therefore, given the high filtration efficiency of multi-layer air filter and low pressure drops of both the air filter and fabrics, a layer-by-layer stacking combination of fabrics and household air filter may achieve both high filtration performance (i.e. filtration efficiency and breathability) and good biocompatibility, where the debris from the air filter will be collected by the fabrics. Fig. 4 also shows that a filter that has a higher filtration efficiency at 0.3 μm performs consistently better at all sizes within the test range. This is likely because the filter with better performance has larger filter thickness and lower permeability, which is beneficial for removing both smaller particles by Brownian diffusion and larger particles by impaction and interception.

3.3. Influence of face velocity

In this study, we tested the filter materials under three different face velocities (23.2, 15.3, and 9.2 cm s^{-1}) (Fig. 5). At an inhaling flow rate of 60 lpm, the face velocities correspond to filtering areas of 111, 67, and 43 cm^2, respectively. Fibrous and fabric filters showed different patterns in their dependence on face velocity. For fibrous filters, such as N95 and air filters (3000 MPR), the filtration efficiency decreases with increasing face velocity. This decrease in filtration efficiency appeared at all tested sizes. However, for fabric filters, such as BR coffee filter and folded pillowcase (600 thread count, 4 layers), the enhanced face velocity led to decreased filtration efficiency for particles with smaller sizes (e.g., below 100 nm) and increased filtration efficiency for particles with larger sizes (e.g., above 200 nm).

These different dependence of filtration performances on face velocity are likely a result of the interaction between the residence time of particles in the filter and particle filtration mechanisms. Most of the fibrous filter materials are made of electrets, which retain electrostatic charges to enhance the collection of particles through electrostatic force and induced dipole effects. It should be noted that these fibrous filters often have a relatively smaller flow resistance, meaning that the residence time of particles in the filter is mainly determined by the face velocities. Under this situation, a reduced residence time of particles will lead to less particle collection, because there is insufficient time for smaller particles to diffuse to the filter fibers through Brownian motion and for larger particles to be collected by fibers via impaction and interception. As for fabric filters, the significantly enhanced flow resistance is a result of the low permeability of the filter materials. This low permeability leads to a considerably enhanced velocity of particles through the pores of the materials, leading to further reduction of particle residence time. However, the removal of larger particles likely benefited from this enhanced velocity, promoting the impaction and interception of particles on the filter fibers. As for particles with smaller sizes, the filtration efficiency will further decrease because the particle residence time is not long enough for particle collection via Brownian motion.

Therefore, the materials of the filter will largely determine the filtration efficiencies. A larger flow resistance does not necessarily lead to a higher filtration efficiency. Fibrous filters are able to achieve both a lower flow resistance that facilitates the flow through the materials, and a high collection efficiency of particles through the Brownian motion, interception, impaction, and electrostatic interaction. The increase of the flow resistance through these fibrous filters, resulting from the enhanced face velocities, will lead to a reduced residence time of particles in

the filter and a reduction of filtration efficiency. Whereas for fabric filters, the increase of flow resistance will lead to an enhanced filtration efficiency of larger particles due to the enhanced impaction and interception, while the filtration efficiency of smaller particles will decrease.

We further examined the microscopic structures of the tested filter materials examined in Fig. 5, and the images are shown in Fig. 6. It confirms that fibrous filters typically have higher permeability and thinner fiber. Fabric filter materials, on the other hand, are less permeable and composed of wider fibers. Similar features were also observed in an earlier study on cloth masks (Neupane et al., 2019). The lower permeability of the fabric filters leads to drastic changes in the particle velocity in the filter and different size-dependent filtration features under different face velocities.

3.4. Non-medical materials for homemade masks

Our study shows that fabrics, such as scarfs, bandanas, and pillowcases, are insufficient to remove aerosols in the size range where coronavirus may be attached onto. Although folding the fabrics can enhance the filtration efficiencies, the values are still not comparable to those of commercialized household air filters and medical materials. Furthermore, the significantly enhanced flow resistance after folding or stacking will lead to difficulty in breathing and the leakage of airflow from the sides of the homemade masks.

Household air filters can remove aerosols efficiently at a relatively low flow resistance. The issues associated with using these filter materials is that they may shed fibers during the cutting and bending of the materials. These fibers, typically in size range of 0.5 to 2 μm, can be inhaled

if the materials are in direct contact with the wearer, and may further cause respiratory diseases (Shannon et al., 2005). However, our study shows that folded fabric materials can be relatively efficient in collecting particles above 0.5 μm through impaction and interception (Fig. 5b). Therefore, a "sandwich" structure of the fabric and fibrous filters, with fibrous filters inserted inside the layers of fabric materials, may serve as an approach for the general public to manufacture homemade masks when medical supplies are urgently needed but in severe shortage.

We should also note that the certification of medical face masks requires that these devices should satisfy requirements in flow resistance, filtration efficiency (particle filtration and bacterial filtration), flammability (Rengasamy et al., 2018), and biocompatibility (FDA, 2020). In this study, we evaluated the flow resistance and particle filtration only. The remaining aspects will be examined in our future studies.

4. Conclusions

In this study, we examined the performance of a wide range of non-medical materials as candidates for medical filters. By evaluating four types of medical materials and thirteen types of non-medical materials (43 combinations of filter configurations), each under three different face velocities, we found that fibrous filters, such as household air filters, can achieve a filtration efficiency and flow resistance similar to that of N95 mask materials. Fabrics, such as a scarf, bandana, and pillowcases with different thread counts, are relatively inefficient for collecting aerosols while inducing a large pressure drop, which may lead to difficulty in breathing. Moreover, we observed a positive relationship between the thread count of the fabrics and the

filtration efficiencies. The difference between the fibrous and fabric materials is that fibrous materials could further remove aerosols with electrostatic mechanisms. This additional mechanism allows an adequate removal of aerosols at a relatively large permeability of the filter materials. Based on the results, we recommend manufacturing homemade face masks with a combination of fibrous and fabric materials to guarantee the sufficient removal of aerosols and avoid the inhaling of fiber fragments generated during the cutting and folding of the fibrous filters. If fibrous materials are unavailable, fabric materials need to be folded with multiple layers to enhance filtration efficiency. However, the wearer needs to ensure the sealing between the mask and face, as the flow resistance associated with these folded fabrics are relatively high.

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Table and Figure captions:

Table 1. Information on the non-medical materials and the tests conducted.

Fig. 1. The 3D-printed face mask designed by the student team at Missouri University of Science and Technology (Missouri S&T). The filter material is a disc that can be inserted to the front of the face mask, where the seal is formed by threads on the cap and the face mask body.

Fig. 2. A schematic diagram of the experimental setup of this study.

Fig. 3. Filtration efficiency at 0.3 μm, overall number-based filtration efficiency, and corresponding pressure drops of the tested medical and non-medical filter materials. (a) Filter pressure drop and filtration efficiency for 0.3 μm particles measured at a face velocity of 23.2 cm s^{-1}; (b) Filter pressure drop and overall filtration efficiency measured at a face velocity of 23.2 cm s^{-1}; (c) Filter pressure drop and filtration efficiency for 0.3 μm particles measured at a face velocity of 15.3 cm s^{-1}; (d) Filter pressure drop and filtration efficiency for 0.3 μm particles measured at a face velocity of 9.2 cm s^{-1}. Dashed lines mark the approximate boundary between fibrous and fabric filters.

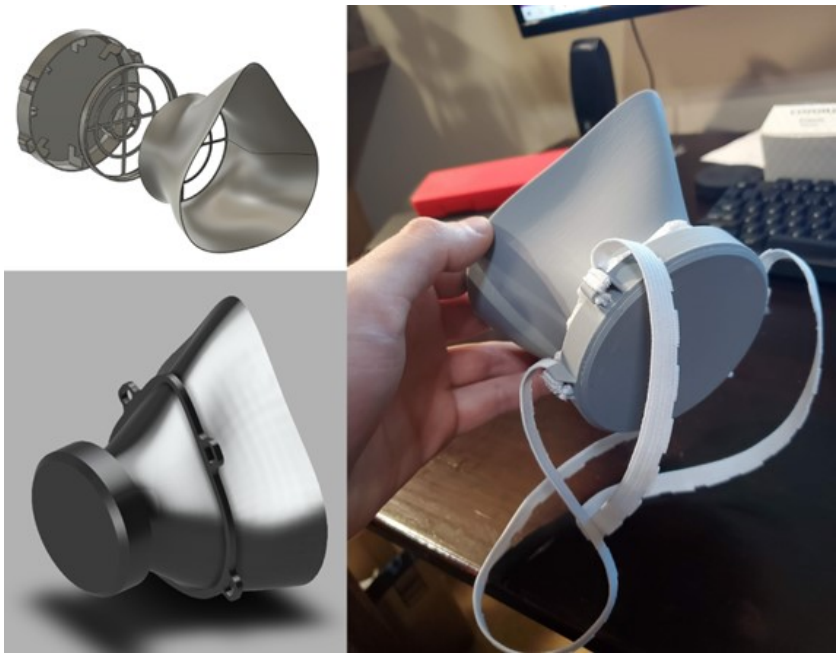
Fig. 4. (a-c) Size-dependent filtration efficiencies of non-medical materials and comparison against N95 material. (d) The influence of air filter (3000 MPR) layer number on the size-dependent filtration efficiency. Measurements were made under a face velocity of 25.2 cm s^{-1}.

Fig. 5. Influence of face velocity on the size-dependent filtration performances of the filter materials: (a) N95 and Brew rite coffee filters (3 layers) and (b) household air filter (3000 MPR, 4 layers) and 600 thread count pillowcases (4 layers). L, M, and H correspond to face velocities of 9.2, 15.3, and 25.2 cm s^{-1}.

Fig. 6. Microscope images of filter materials: (a) N95; (b) household air filter (3000 MPR); (c) Brew Rite coffee filter; and (d) 600 thread count pillowcase.

Table 1. Information on the non-medical materials and the tests conducted.

Filter type	Brand	Model	Layers	Acronym	q_F
N95	3M	8210	1	N95	2.88
KN95	NIDI	N/A	1	KN95-N	2.31
KN95	Jinjiang	N/A	1	KN95-J	3.21
Surgical (earloop)	Walgreens	N/A	1	Sg	1.29
Household air filter	3M	1900 MPR	1 – 2	H19	1.82
Houlshold air filter	3M	2500 MPR	1 – 4	H25	3.51
Houlshold air filter	BestAir	3000 MPR	1 – 8	H30	3.20
Vacuum Bag	Hoover	N/A	1	VB	2.45
Coffee Filter	Natural Brew	N/A	3	NB-3	0.23
Coffee Filter	Brew Rite	N/A	3	BR-3	0.27
Activated Carbon	API	Coarse	1	CC	0.96
Activated Carbon	API	Fine	1	FC	0.84
Bandana	Levi	Men's Cotton	1 – 4	B	0.12
Scarf	Wander Agio	Warm Long	1 – 4	S	0.41
Pillowcase	Cal Design Den	400 TC	1 – 4	P4	0.22
Pillowcase	Cal Design Den	600 TC	1 – 4	P6	0.30
Pillowcase	Cal Design Den	1000 TC	1 – 4	P10	0.38



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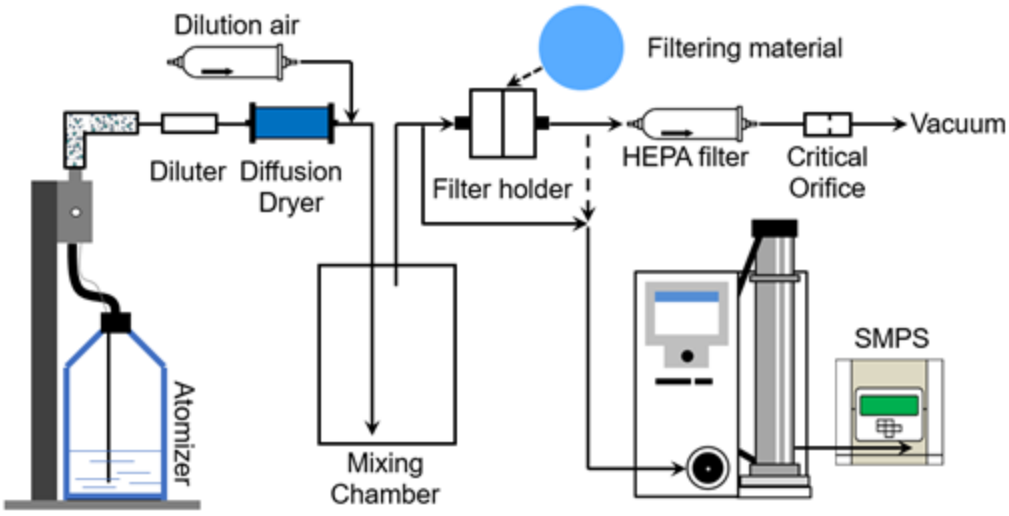

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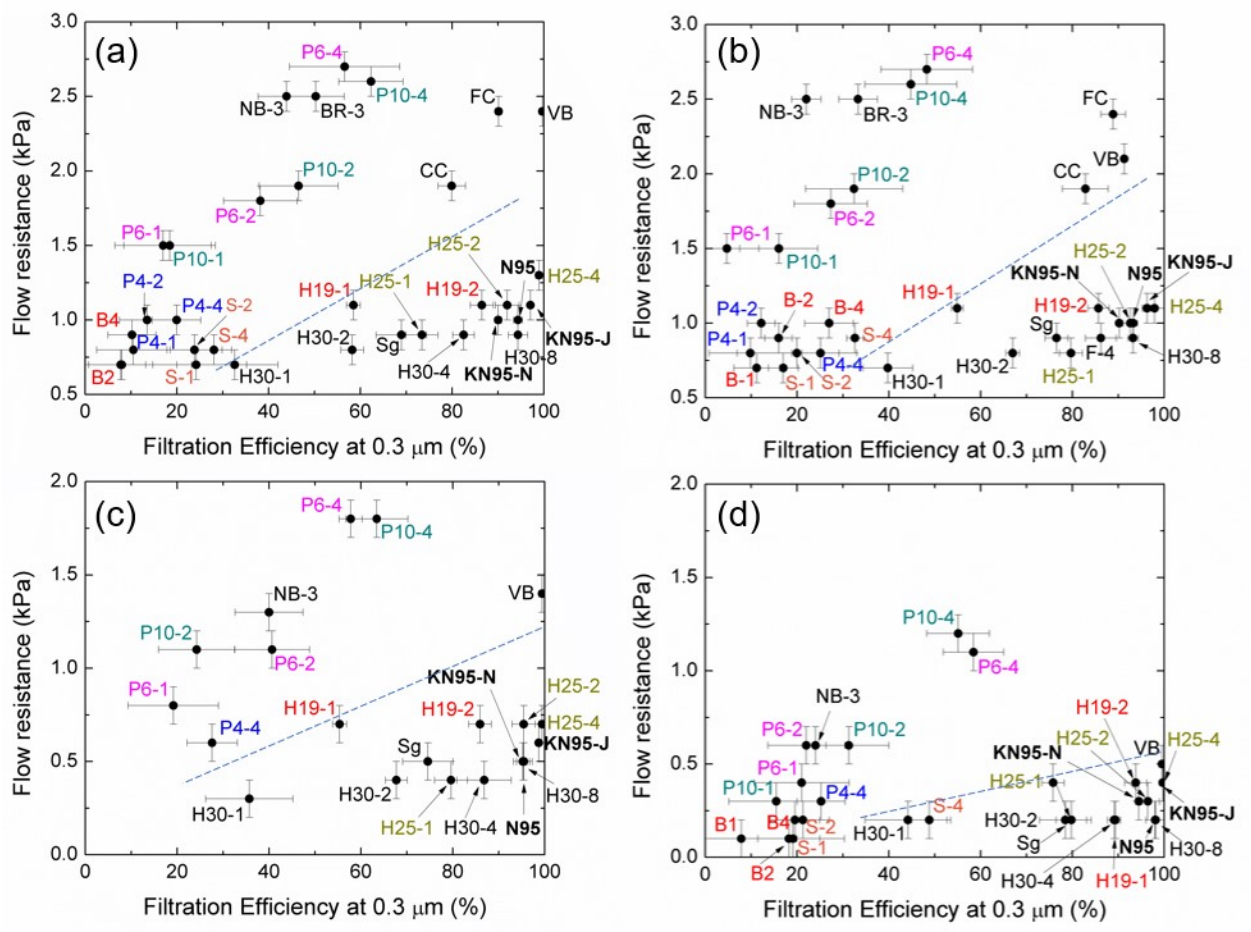

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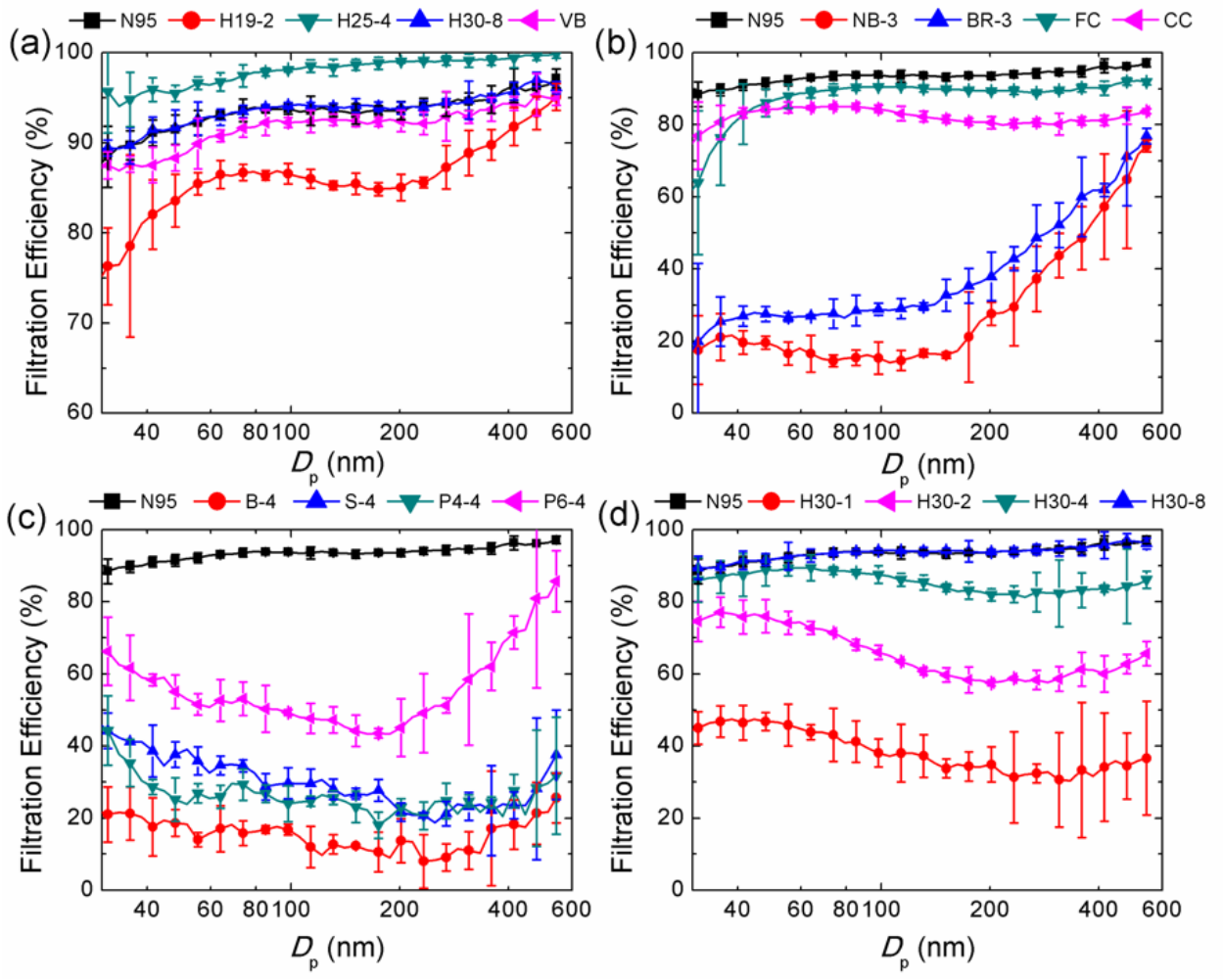

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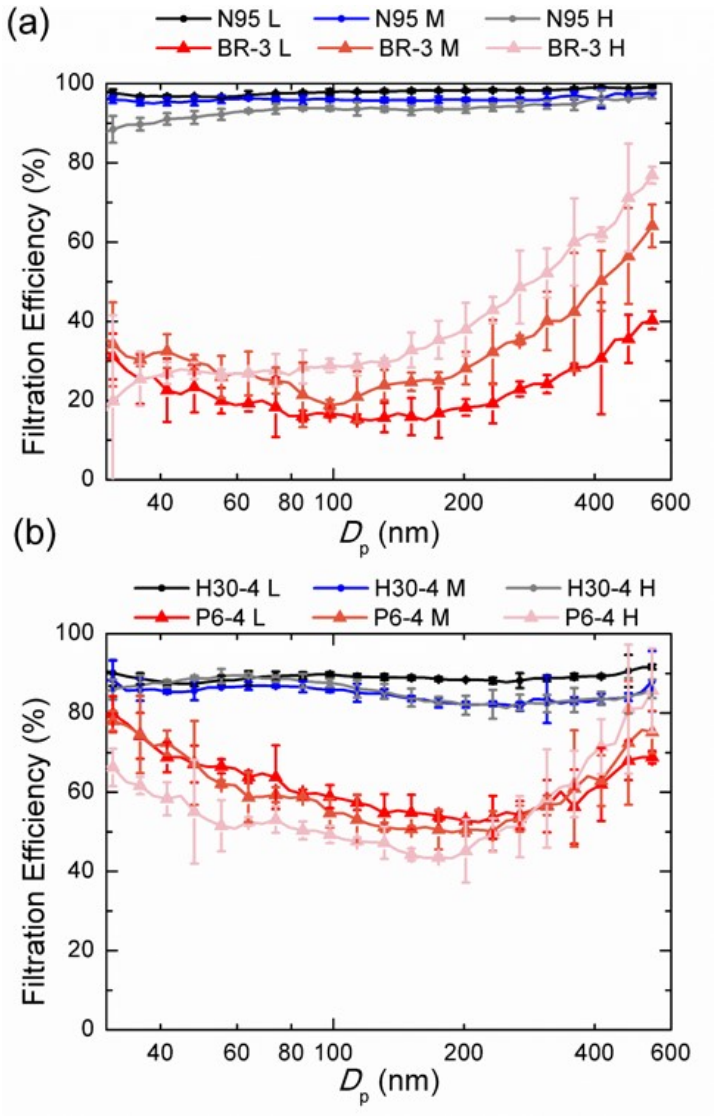

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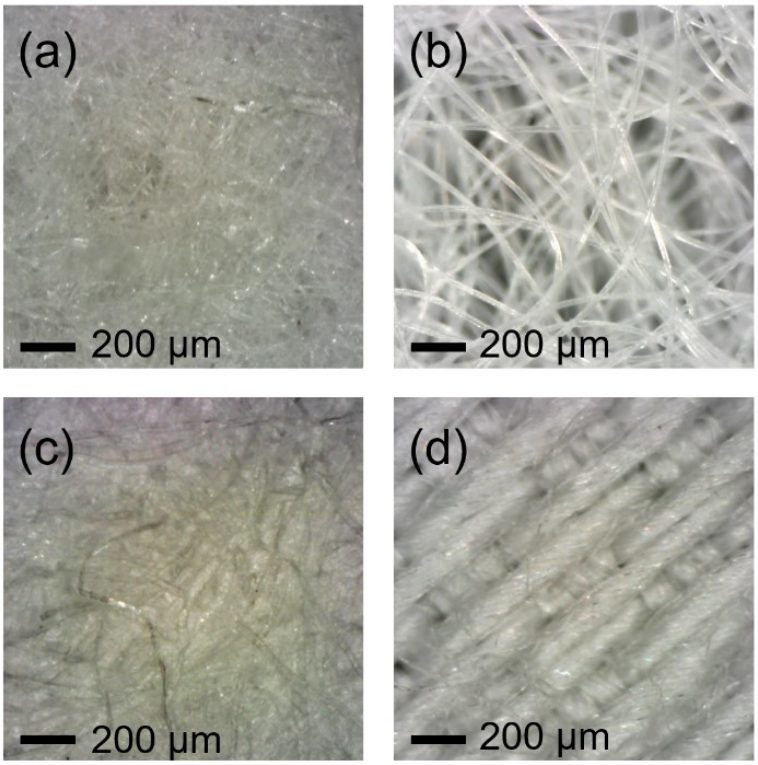

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