Filtration efficiency and breathability of selected face masks

RACHEAL T. AFOLABI AND SESHADRI RAMKUMAR

ABSTRACT: Face masks have been used as physical barriers to stop respiratory infections for many years. Due to insufficient and low supply of certified masks, alternative face covers such as face shields, neck gaiters, and fabric reusable masks gained attention during the COVID-19 pandemic. However, for these alternate face masks to fulfill their intended function, they must be effective. Additionally, the level of breathability provided by the makeshift masks must be at a certain level.

The work reported in this paper was carried out to determine the relationship between filtration efficiency (FE), breathability, and important physical characteristics of mask substrates. The fiber diameter of the core filter layer was determined using a scanning electron microscope. Five types of face masks (two types of N95, two types of surgical masks, and a 100% knitted cotton fabric) were tested for their FE and breathability using moisture vapor transmission rate (MVTR). The cotton knitted mask had the lowest FE (5.10%–26.47%), while the National Institute for Occupational Safety and Health (NIOSH)-certified N95 mask had the highest FE values (92.10%–99.65%). However, the cotton mask outperformed the N95 in terms of the pressure drop, meaning higher comfort. In general, the N95 face mask provided the best protection against aerosolized particles.

According to the regression analysis, the fiber diameter of the mask filter substrate serves as an important predictor of FE of mask substrates. In this study, it was confirmed that fiber diameter is inversely related to the filtration ability. Results show that compact structure with finer fibers will enable higher filtration efficiency. The study lends itself to developing layered face masks to obtain optimum filters with good filtration, better fit, and acceptable comfort for the wearer.

Application: This paper is highly timely and focuses on important applications for nonwovens as facemasks.

Although masks have been worn over the face as a defense against odor, it was not until the 16th century that their medical application began. Face masks evolved from beak-shaped perforated devices to bulky industrial masks, dust masks, and flat, three-layered surgical masks readily available today [1-4]. Microorganisms, including SARS-CoV-2, are likely to stay in the air for extended periods of time, increasing the chance that a vulnerable host may inhale them and become infected. These types of inhalable microorganism-containing particles are known as “bioaerosols” [5,6]. Infection occurs from inhaling pathogenic airborne cells or organisms [5]. The longer a molecule stays in the atmosphere, the faster the spread of infection occurs [4]. Viral particles spread quickly when inhaled up close in an unventilated or inadequately ventilated environment with contaminated aerosols [7]. Since the coronavirus is mostly transmitted through aerosol droplets in the atmosphere, a person with no covering would contract it [1]. One of the preventative measures to stop the disease’s spread has been the introduction of face masks as a preventive measure [8]. The results of Lindsley et al. [9] showed that face masks are superior to face shields for reducing the spread of the SARS-CoV-2. Face masks have historically been used to prevent airborne illnesses, primarily those that damage the respiratory system. Face coverings guard the user and others from dangerous respiratory illnesses by curbing the spread of airborne pathogens [1]. Surgical face masks have even been found to be at least 79% effective [5,8,10].

Considering the paucity of understanding regarding the amount and concentration of SARS-CoV-2 aerosol necessary to transmit the disease, physical isolation and public use of well-fitting masks have been employed, which effectively decreased the transmission of SARS-CoV-2 [1,11]. Therefore, using face masks to inhibit the spread of pathogens has been found to be a successful strategy. Additionally, face masks are useful for protection against environmental pollutants and poisons during industrial operations in addition to avoiding the spread of pathogens [12,13]. High efficiency masks such as N95 were hard to come by during the pandemic due to lack of supply [14]. Apart from that, it was not economically favorable for the masses to purchase such masks. [15]. Thus, face masks made of clothing materials and other filter substrates were identified as alternatives [4,8]. It is important that the mask materials must be proven to be suitable for use as coverings that prevent the penetration of potentially pathogenic aerosols [1]. The qualifications of a recommendable material would be needed to accomplish this goal. For instance, to prevent air leakage, there should be no space between the mask and the face.

Air leakage is not a problem with N95 face masks, although it is the case with face coverings and three-ply masks [8].

Face covers were considered as a simple alternative means of defending against airborne pandemics, in addition to the face masks advised by the United States government through the National Institute of Occupational Health and Safety (NIOSH; Washington, DC, USA) [2]. However, there is currently a dearth of data on the efficacy of textile materials used as face covers. All N95 masks, including respirators and surgical masks, adhere to established certification standards set forth by NIOSH. Compared to respirators and medical masks, handcrafted face covers have a longer potential usage period and can be reused, but they perform poorly at filtering infectious aerosols [16]. Their low filtration efficiency (FE) is a result of the open structure that is natural for textile substrates like wovens and knits compared to wetland and spunmelt nonwovens [17].

Surgical masks are expected to protect the user from the environment, whereas N95s are designed to insulate the wearer from it [18]. Certain surgical masks may allow a high proportion of airborne viruses to pass through, providing very poor protection against infectious organisms that are aerosolized and have particle sizes between 10 and 80 nm [18].

The filtration efficiency (FE) of face masks, which is controlled by the mask's pore size, particle size, and charge [19], is crucial for assessing how well the masks work to prevent aerosol inhalation. When it comes to cloth masks, various fabric materials function differently in terms of air permeability and filtration [4,20]. The effectiveness of cloth face covers as workable personal protective equipment (PPE) for reducing the transmission of infectious respiratory aerosol has been reported in several research papers [1,4,11,21-24]. Model experiments and artificially produced water droplets have been used to assess the filtration efficiency of face masks under various airflow conditions [4,21-24]. A high FE rate was caused by the test samples' (facemasks') considerable reduction in aerosol transmission. Because the FE rate and particle size are directly inversely correlated, FE must likewise drop as particle size decreases. The filtering method relies on the size of the droplet particles, and the mechanism of particle filtration through the masks may be by diffusion, interception, or inertial impaction [4,25].

In addition to filtration, comfort to the wearer and fit also play important roles. Among different attributes of comfort, it will be logical to understand the moisture vapor transmission rate (MVTR) of filter substrates, which is termed as breathability. The MVTR is used to gauge permeability of filter materials and to gauge how comfortable they would be to the wearers. The MVTR is based on the physical, chemical, and quality of structural characteristics of the mask making materials [26]. This in turn affects the material's breathability, because the material is thought to be more breathable when water vapor can pass through it without much resistance. Calculating the pressure difference throughout the mask allows for the breathability to be determined [4]. Understanding the parameters that affect the filtration performance of textile materials used as face covers is essential. Hao et al. [27] investigated the factors affecting the filtration performance of 18 typical household items, including towels, polyester, and medical masks. The density and structure of the material allowed for filtration efficiencies of 5% to 50%. Moreover, the MVTR analysis was not performed for this study. Investigating the variables that affect the filtration performance of textile materials used as face covers is thus required to enhance performance, which was the aim of the current study. Five different face masks were tested in this work for their filtering efficiency and their MVTR. The objective was to identify the factors influencing the effectiveness of N95 particulate respirators, medical masks, and 100% cotton masks and to assess the connection between physical characteristics, MVTR, and filtering effectiveness.

MATERIALS AND METHODS

Five different face mask samples were used in this experiment, and the tests were carried out at the Institute of Environmental and Human Health (TIEHH) at Texas Tech University (TTU) in Lubbock, TX, USA. We obtained two different kinds of N95 masks from CVS pharmacies in Lubbock. Additionally, two kinds of surgical masks and one kind of mask made entirely from cotton were chosen for this study. The two surgical masks were chosen because they were the most popular and easily accessible of the various surgical masks that were available during the COVID-19 pandemic. Due to cotton fabric affordability and availability in all homes, a 100% cotton mask was chosen, as it is the most well-known face cover.

Thickness and weight

Samples were cut into 1-in. x 1-in. squares and converted into meters to measure the g/m² (GSM). Following the ASTM D1777 "Standard test method for thickness of textile materials," using a precise laboratory scale, each sample was then further weighed. The g/m² denoted by GSM was then calculated for each sample, and for each sample this was repeated five times and the mean values and standard deviation (SD) were computed. Each sample, which had already been cut into squares, had its thickness measured using a thickness gauge (AMES Model 99-0697, Ames Instrument; Canajoharie, NY, USA), and the thickness was noted in millimeters (mm).

Morphology and characterization

The fiber size was assessed using the scanning electron microscope (SEM, Hitachi S/N 4300; Hitachi, Tokyo), which provides insight into the size distribution of fibers and can be used to assess thickness [28]. Samples were cut from the middle layer of the masks. A thin coating of iridium was

Sample	Layers	Average Thickness, mm	GSM, g/m²	Average Fiber Diameter in the Middle Layer, µm
N95-I (3M Aura™9205+)	5	1.72 (0.07)	337.6 (15.60)	1.52 (0.57)
N95-II (Honeywell DC300N95)	3	1.99 (0.16)	346.56 (21.96)	1.88 (0.52)
SM-I (surgical mask)	3	0.596 (0.02)	110.72 (7.87)	1.88 (0.45)
SM-II (surgical mask)	3	0.632 (0.02)	120 (11.03)	1.88 (0.44)
Cotton t-shirt	1	0.556 (0.01)	212 (9.30)	18.00 (1.73)
Note: Values within parentheses are the standard deviations. Average values indicate the mean of 5 repeats.				

I. Physical properties of different face masks.

used to impart conductivity to these layers after mounting them onto sample mounts with double-sided carbon tape. All SEM photos were captured using a side mount secondary electron (SE) detector (S/N 4300) at an aperture of about 80. Images acquired at high magnification, ranging from 300 to 1200, were used to measure the size of fibers.

Filtration efficiency test

The particle sizes measured in this study ranged from 0.03 µm to 0.40 µm, specifically including the following values: 0.03, 0.04, 0.05, 0.06, 0.08, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, and 0.40 µm. The procedure outlined by Ayodeji et al. [1] was used in the test to measure the sample's level of filtration efficiency. The TSI Model 3160 automated filter tester (TSI Inc.; Shoreview, MN, USA) was the instrument employed. It has two chambers, upstream and downstream, where the air is forced to flow during the experiment. The choice of particle size was made based on previously reported tested size ranges and the SARS-CoV-2 size distribution. Test procedures from ASTM F3502-21 "Standard specification for barrier face coverings" was used to evaluate the particle-size-dependent FE of face covers that are not NIOSH certified, with just two exceptions (samples were preconditioned at 38 ± 2.5°C, and 85 ± 5% relative humidity for 25 ± 1 h) [1,29].

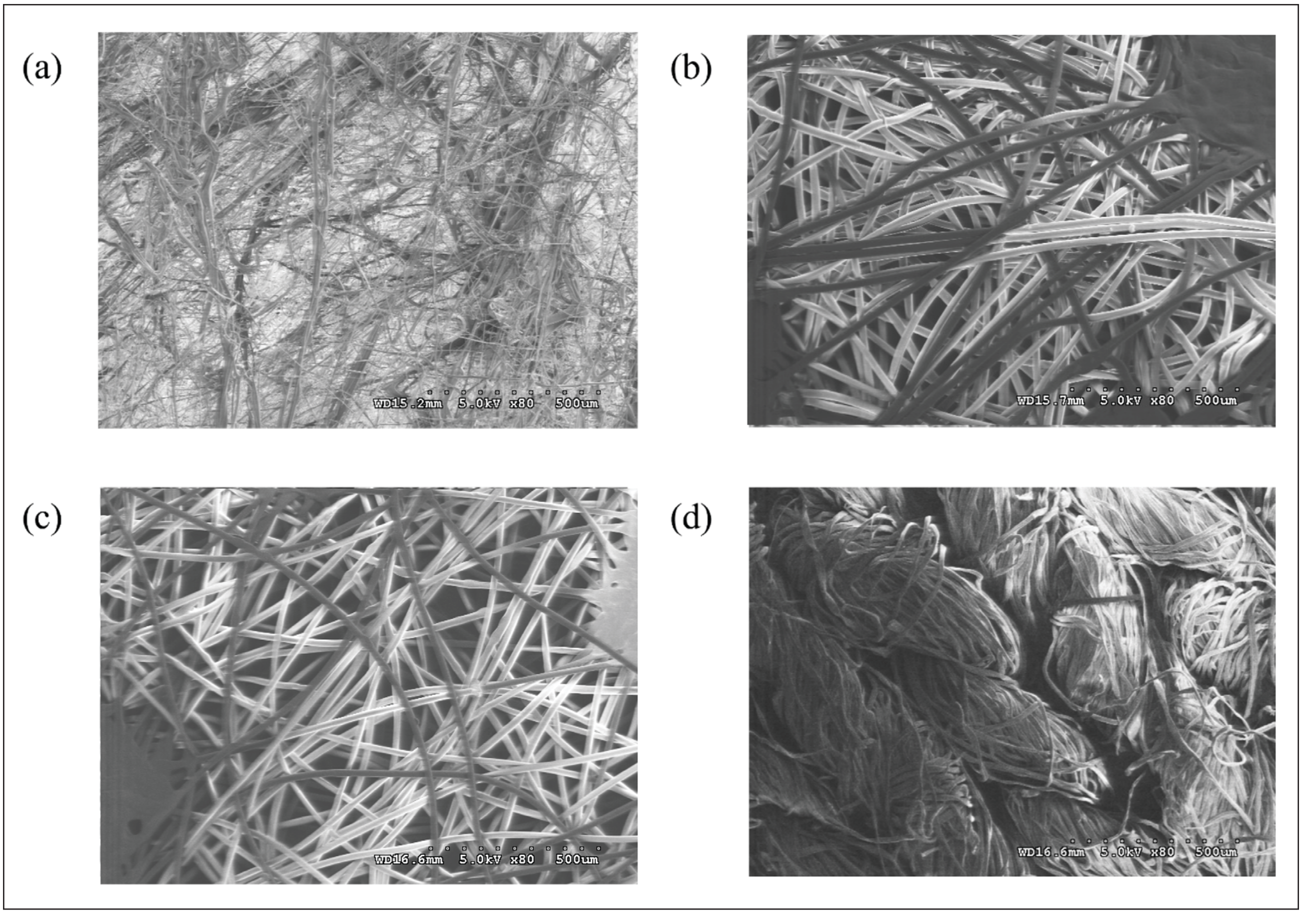
Dioctylphthalate (DOP) oil was utilized to create the aerosolized particles, with sizes ranging from 0.03 µm to 0.40 µm in the current study, following the experimental procedure given by Ayodeji et al. and Cho et al. [1,29]. The TSI fractional filtration efficiency tester (TSI Inc.) with two Model 3771 condensation particle counters (CPCs) outfitted with differential mobility analyzers (DMAs; Model 308,100) and aerosol neutralizers (Model 3077) with Krypton-85 was used to measure particle transmission through each sample to determine the FE of the samples. Using DOP atomizers, an electrostatic classifier (Model 3080), and a silica gel desiccant as an air supply dryer, aerosol particles (d = 0.03–0.4 µm) were produced using DOP oil. An adjustable valve and vacuum pump were used to control the airflow, and a mass flow meter (Model 4043) in L/min was used to measure it. Polydisperse aerosols of the desired diameter were generated using a DMA and subsequently passed through an additional neutralizer. Aerosol particles pass through the sample in a sample holder plate with a diameter of 6.4 cm and an area of 32.17 cm² after dilution with an aerosol diluter (Model 3302) with particle-free air and mixing. The first and second CPCs in the filter tester were used to measure the concentration of aerosols across the upstream and downstream of the sample holder, respectively. A TSI Green Line Paper (HE–1071) of a known particle penetration and efficiency at a certain pressure was tested to track analytical accuracy as part of the quality assurance/quality control (QA/QC) methodology.

Moisture vapor transmission rate test

The approach utilized to conduct this test was selected based on the study by Ramkumar et al. [26]. The selected method, known as the Evaporative Dish method, adheres to the British Standard BS 7209 "Specification for water vapour permeable apparel fabrics." The samples were stored for an initial duration of 24 h under standard temperature of 20 ± 2°C and relative humidity of 65 ± 5%. Each sample was placed in a test dish that had been pre-filled with distilled water and adjusted to maintain a temperature of 20°C and a relative humidity of 65%. The sample was then sealed.

This was allowed to stand for 60 min to reach an equilibrium of the water vapor pressure gradient, after which the dish was weighed, and the rate of water vapor penetration was determined.

Five test specimens with diameters slightly greater than the dish rings (inner diameter of the ring was 8.2 cm) were cut for each sample. A burette was used to measure 46 mL of distilled water, which was then added to the dish. Each specimen was positioned on the rim of the evaporation dish using an adhesive coating. Additionally, this was put on the turntable, which was designed to promote equilibrium through an hour of continuous rotation. Each assembly was then weighed to the nearest 0.001 g. A similar procedure was followed after 5 h of rotation.



1. Scanning electron microscope (SEM) images of the middle layer of (a) N95-I, (b) N95-II, (c) surgical mask, and (d) cotton t-shirt.

The MVTR, expressed in g/m²/day, was computed as follows:

$$MVTR = \frac{24M}{At}$$

where M is the mass in grams of the assembly with samples that was lost during the period t (5 h); the number of hours between each assembly weigh-in is denoted by the symbol t; and apparent area of the sample is denoted as A (A = 0.005413 m²).

Data analysis

Microsoft Excel (Microsoft; Redmond, WA, USA) was used to enter the quantitative data from this study. The results were then imported into the Statistical Package for Social Sciences (SPSS) 20 Edition (IBM; Armonk, NY, USA) for data analysis. Descriptive statistics, analysis of variance (ANOVA), correlation, and regression analysis were used to analyze the data.

RESULTS

This study was carried out to evaluate the filtration efficiencies and breathability of five different types of face masks that were widely used during the COVID-19 pandemic. The N95 facemask brands tested in this study were distributed by the United States government to the public through pharmacy outlets. Tests were carried out for five different masks to determine their physical properties, such as the filter substrate structure (SEM), thickness, and GSM. The values for thickness and GSM of each fabric can be found in **Table I**. The bulkiest fabric was Honeywell N95 (N95-II; Honeywell, Charlotte, NC, USA) with an average thickness of 1.99 mm, and this was closely followed by NIOSH N95 (N95-I). Furthermore, the fabric with the highest GSM was N95-II, again closely followed by N95-I.

SEM characterization

An SEM was used to understand the structural characteristics of the core middle layer of face masks. Images from the middle layer of each kind of fabric filter are shown in **Fig. 1**. The fiber arrangements in the core layer of N95-I, N95-II, SM-I, SM-II, and cotton t-shirt are depicted in Figs. 1a–1d, respectively. Upon observation, it is evident that Fig. 1a (N95-I) exhibits the finest fiber arrangement among the samples in this study due to its fiber diameter of 1.52 µm. The N95-II, SM-I, and SM-II masks have the same fiber diameter of 1.88 µm, while the cotton t-shirt has the highest value at 18 µm.

Basic physical characteristics

The thickness of each mask was measured in millimeters, while their GSM was measured in g/m^2. The results for each sample are given in Table I. The values in parentheses indicate the standard deviation for each sample.

Moisture vapor transmission (breathability)

Moisture vapor transmission rate is one indicator of a material's ability to breathe as measured by the movement of water vapor through fabric samples. The MVTR is measured in grams per square meter per day ($g/m^2/day$) and is the rate at which water vapor permeates a material over a predetermined time period (one of the components that determines breathability) [30]. High MVTR value indicates the material's increased water vapor transfer and breathability, as well as the wearer's comfort [31]. However, while comparing facemasks with varying weight, it would be logical to normalize the MVTR values with the weight (GSM). The normalized MVTR is calculated as:

$$Normalized\ MVTR\ (day^{-1}) = \frac{MVTR}{GSM}$$

Table II shows the MVTR along with the corresponding normalized MVTR values. The values in parentheses denote the standard deviation. The N95-I mask has the highest MVTR value of 2500.65 $g/m^2/day$, making it the most physiologically comfortable to wear and providing enough ventilation [26]. The least comfortable mask to wear was the SM-II mask, which had the lowest MVTR value of 1876.96 $g/m^2/day$. The MVTR values are mostly influenced by the amount of resistance provided by the fabric's pore spaces [4]. With p-values significantly higher than 0.05 at α =0.05, it is evident from **Table III** that the MVTR does not statistically significantly correlate with physical characteristics such as GSM, fiber diameter, and thickness for the sample tested. There is a negative relationship between MVTR and fiber diameter, indicating that higher fiber size results in lower transfer of water vapor and showing that large diameter fibers serve as barriers to transfer of vapor. The results emphasize the importance of structural integrity and the arrangement of fibers within the structure. In addition, a material's surface features and chemistry also impact transport characteristics, as is evident from polypropylene based surgical mask (SM-II) that has the lowest MVTR value. However, there is a need for a thorough study on the influence of a nonwoven fabric substrate's physical and structural characteristics on MVTR.

According to Ramkumar et al. [26], the breathability test measures how quickly water vapor flows across the substrate. As a result, it provides a measurement of how well vapor is exchanged when the mask is worn. The correlation between FE and pressure drop at each particle size is shown in **Table IV**. The data shows *p*-value less than 0.05 at $\alpha = 0.05$ for all particle sizes, indicating a strong relationship between the two variables. It is understood that the material filtration effectiveness is directly proportional to the pressure drop. The pressure difference during airflow is an important representation of the comfort of the masks and is measured in mmH_2O. The cotton material had the least pressure drop of 1.19–1.20 mmH_2O, while the N95-II had the highest pressure drop of 12.21–12.25 mmH_2O due to its structural coherence and compactness, which is evident in its high filtration efficiency as given in **Table V**.

Type	Average MVTR, $g/m^2/day$	Normalized MVTR, day^{-1}
N95-I (3M Aura™9205+)	2500.65 (98.67)	7.41 (0.29)
N95-II (Honeywell DC300N95)	2137.08 (30.20)	6.17 (0.09)
SM-I (surgical mask)	2379.46 (428.60)	21.04 (3.87)
SM-II (surgical mask)	1876.96 (438.64)	15.64 (3.66)
Cotton t-shirt	1919.82 (145.97)	9.06 (0.69)
Note: Values within parentheses are the standard deviations. Average values indicate the mean of 5 repeats.		

II. Moisture vapor transmission rate (MVTR) for different face masks.

Physical Properties	*p*-value ($\alpha = 0.05$)	Correlation Coefficient (*r*)
Thickness, mm	0.450	0.447
Fiber diameter, µm	0.406	-0.486
GSM, g/m^2	0.569	0.346

III. Correlation between MVTR and material properties.

Size, µm	p-value (α = 0.05)	Correlation Coefficient (r)
0.030	0.037	0.900
0.040	0.039	0.895
0.050	0.044	0.888
0.060	0.045	0.886
0.080	0.045	0.886
0.100	0.047	0.883
0.150	0.045	0.887
0.200	0.044	0.888
0.250	0.041	0.894
0.300	0.039	0.897
0.350	0.037	0.901
0.400	0.035	0.904

IV. Correlation between filtration efficiency (FE) and pressure drop (Δp) at different particle sizes at α = 0.05.

	FE, % Min–Max	Δp, mmH_2O Min–Max
N95-I (3M Aura™9205+)	92.10–99.65 (1.68)–(0.27)	12.21–12.25 (0.83)–(0.82)
N95-II (Honeywell Dc300N95)	83.57–92.89 (1.46)–(3.14)	9.98–10.00 (1.94)–(1.96)
SM-I (Surgical Mask)	81.76–91.03 (1.51)–(1.09)	15.94–16.02 (1.19)–(1.21)
SM-II (Surgical Mask)	62.94–74.61 (1.98)–(1.89)	8.84–8.87 (0.47) – (0.45)
Cotton T-Shirt	5.14–26.47 (0.21)–(2.07)	1.19–1.20 (0.11)–(0.12)

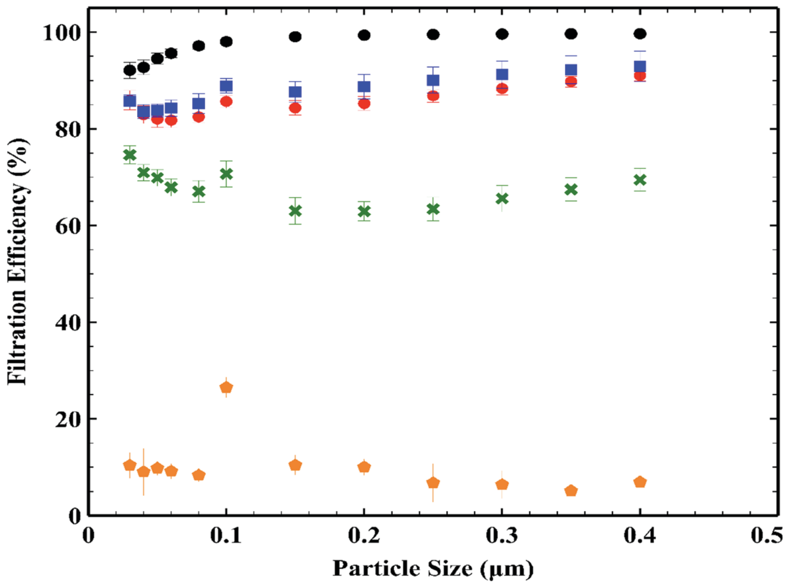
FE = filtration efficiency; Δp = pressure drop.
Note: Values within parentheses are the standard deviations. Average values indicate the mean of 5 repeats.

V. Filtration performance characteristics.

However, overall filtration is not only influenced by filtration efficiency but also by how well it fits, preventing leakage of aerosolized particles.

Table V shows the minimum and maximum filtration efficiency, as well as the pressure drop (Δp) value, for each fabric sample across all particle sizes. The standard deviation of each sample is denoted within parentheses. The cotton face mask had the lowest pressure drop value of 1.19–1.20 mmH_2O. These findings align with previous studies by Lee et al. [15] and Morais et al. [17], which establish an inverse relationship between mask thickness and pressure drop. Our results for MVTR in this study show that not only thickness, but also other structural factors such as GSM, finishing treatments, and surface characteristics like hydrophilicity or hydrophobicity impact the transport of vapor, which is also an indicator of comfort. The N95 and surgical masks generally have higher FE than the cotton masks. It is, however, expected that surgical masks would have better filtration efficiency than the cotton mask or any other fabricated masks. The cotton fabric used in this study exhibited FE values below 30%, indicating a lower filtration efficiency. This is attributed to the fabric's looser fit and open structure that results in inadequate filtration of aerosols or particulates [4]. This observation aligns with the findings of Mello et al. [10], who demonstrated that the lack of a proper fit negatively impacts the effectiveness of these masks.

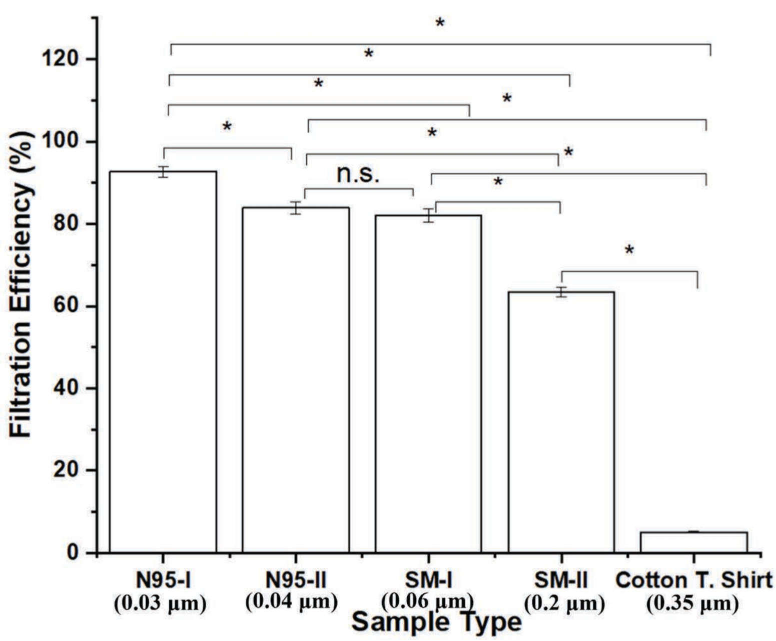
Figure 2 shows the variation of size-dependent filtration efficiencies of the different face mask materials. Aerosols of size less than 5 µm were used in the procedure, as they represent the size of the major bioaerosols that transmit the coronavirus disease [4]. The results obtained in this study for FE shows that with N95-I, N95-II, and SM-I, there is an unsteady increase from particle size of 0.03 µm–0.4 µm. For the SM-II masks, there is a gradual decrease and a peak at 0.1 µm, followed by another gradual increase. For cotton, however, there is an increase from 0.03 µm–0.1 µm. For N95-I, N95-II, and SM-I, a sudden peak of the filtration efficiency at 0.1 µm followed by a decrease to 0.3 µm and



2. Filtration efficiency of N95-I (black circle), N95-II (blue square), SM-I (red circle), SM-II (green cross), and cotton fabric (mustard hexagon)

an increase at 0.4 µm was observed. This result corroborates with the findings that different materials have varying filtration efficiencies depending on the particle size and nature of fabric characteristics [10,32].

Most penetrating particle size (MPPS) refers to the particle size at which the FE of a face mask is the lowest. It is an important factor in evaluating the filtration performance of masks and understanding their effectiveness against different particle sizes. The most penetrating particle sizes for N95-I, N95-II, SM-I, SM-II, and cotton t-shirt are 0.03 µm, 0.04 µm, 0.06 µm, 0.2 µm, and 0.35 µm, respectively. Filtration efficiency usually depends on certain factors, such as the nature of aerosols, pore size of the face mask material, number of layers of the face mask, internal structural ar-



*3. Filtration efficiency at most penetrating particle size (MPPS) for different samples. The crossbars in this figure represent the standard errors of the mean. In the chart, * ($p < 0.05$) shows that there is a significant difference between the samples, while n.s. indicates that there is no significant difference.*

Size, μm	*p*-value ($\alpha = 0.05$)	Correlation Coefficient (*r*)
0.030	0.873	0.10
0.040	0.391	0.50
0.050	0.391	0.50
0.060	0.391	0.50
0.080	0.391	0.50
0.100	0.391	0.50
0.150	0.285	0.60
0.200	0.285	0.60
0.250	0.285	0.60
0.300	0.285	0.60
0.350	0.285	0.60
0.400	0.285	0.60

VI. Correlation between GSM and FE at different particle sizes at $\alpha = 0.05$.

rangement of the material, and other environmental factors such as temperature and relative humidity of the environment [13,26,33]. The FE of N95-II ranges from 83.57%–92.89%, while the FE of SM-I ranges from 81.76%–91.03%. The SM-I has a better filtration performance when compared with the other surgical mask. The cotton mask recorded the least FE values, ranging from 5.10% to 26.47%. The NIOSH-certified N95-I mask recorded the highest FE values at 92.10%–99.65%, with its lowest values at 0.03 μm and highest value at 0.04 μm, which is shown in Fig. 2. It is important to mention that the single-layer knitted cotton t-shirt, due to its open structure compared to compact structures of meltblown, wetland substrates, is not normally used in filter development. However, this fabric was included in the study to emphasize the influence of structure, fiber arrangement, and other structural factors, such as density, on the barrier properties. Filtration efficiency is dependent on these aspects, including filtration, fit, and form (comfort) [34]. The influence of proper fit and structural compactness on FE has been highlighted by Konda et al. [4] and Mello et al. [10].

To compare the MPPS filtration efficiency across samples, ANOVA analysis was used, which shows that at least two sample means differ. Tukey's HSD test was later used for multiple comparisons of means. The confidence interval was 0.95. The results of these comparisons are shown in **Fig. 3**. The MPPS values are presented in parentheses below each sample. There is no statistically significant difference between sample N95-II and SM-I, while others showed significant differences. The order of the MPPS filtration efficiency was N95-I > N95-II & SM-I > SM-II > cotton fabric.

Table VI shows the *p* values for the correlation between FE and GSM at different particle sizes. The *p* value at all particle sizes is greater than the α value. This shows that there is no statistically significant relationship between the FE and GSM of the fabric. The filtration efficiency of the masks used in this study did not show any trend as the GSM increases. This observation was also supported by Drewnick et al. [35]. This result shows that FE is more influenced by the fiber fineness and structural characteristics of filtration layers.

Regression analysis

Regression analysis can be used to compare the relationship between the physical properties of the face masks and their FE [13]. A regression analysis was conducted to assess the predictive ability of fiber diameter, pressure drop, and GSM on the filtration efficiency. For this analysis, a stepwise regression technique was employed. Only fiber diameter was included in the final model, as pressure drop and GSM were not found statistically significant and thus excluded from the final model. The regression model was significant, explaining 94% of the variation in FE of the different materials ($p = 0.03$). The regression equation is given as:

$$FE = -4.608\,(\text{Fiber diameter}) + 93.467$$

This suggests an inversely proportional relationship between fiber diameter and filtration efficiency. Materials with higher fiber diameters tend to have larger pore sizes that can reduce their filtration efficiency. This result is evident from higher FE of masks with finer fibers compared to cotton fabric made from coarser yarn.

Regression analysis was also employed to assess the relationship between MVTR and the physical properties of the materials. The regression model was statistically nonsignificant ($p = 0.801$). Therefore, the result indicates that the physical properties investigated in this study do not serve as predictors of MVTR.

The results obtained from this study provided insight into how structural differences among the selected face masks affected their effectiveness in terms of breathability, which give room for future recommendations.

CONCLUSIONS

Based on the findings of this study, N95 respirators demonstrated the highest particle filtration efficiency due to their finer fiber arrangement and compact fit. Fiber diameter emerged as a strong predictor of FE. Among the samples, the cotton mask was the most comfortable based on the lowest pressure drop values, despite having the lowest filtration efficiency. To enhance the filtration efficiency of cotton masks, increasing the number of layers and adopting additional high surface area substrates in the mask material could be considered. The study also revealed no significant variation in MVTR among N95, surgical masks, and cotton masks. However, the measured physical properties were unable to explain the underlying reasons for this phenomenon. It is suggested that future studies explore additional physical properties that can elucidate the variations in MVTR and their relationship with filtration characteristics. These results are expected to provide valuable insights for the design of future face masks, enabling the fabrication of highly efficient protective masks. **TJ**

ACKNOWLEDGEMENTS

The authors would like to acknowledge Mirza Khyum and Kenneth Kikanme for helping with sample collection and manuscript preparation. The authors would like to thank Dr. Bo Zhao at Texas Tech University for her assistance with the SEM work.

LITERATURE CITED

1. Ayodeji, O.J., Hilliard, T.A., and Ramkumar, S., *Int. J. Environ. Res.* 16(1): 1(2022). https://doi.org/10.1007/s41742-021-00390-6.
2. Diaz, K.T. and Smaldone, G.C., *Am. J. Infect. Control* 38(7): 501(2010). https://doi.org/10.1016/j.ajic.2010.06.002.
3. Goh, K.J., Choong, M.C., Cheong, E.H., et al., *Ann. Acad. Med. Singap.* 49(3): 108(2020). https://doi.org/10.47102/annals-acadmedsg.202057.
4. Konda, A., Prakash, A., Moss, G.A., et al., *ACS Nano* 14(5): 6339(2020). https://doi.org/10.1021/acsnano.0c03252.
5. Abboah-Offei, M., Salifu, Y., Adewale, B., et al., *Int. J. Adv. Nurs. Stud.* 3: 100013(2021). https://doi.org/10.1016/j.ijnsa.2020.100013.
6. Kim, K.-H., Kabir, E., and Jahan, S.A., *J. Environ. Sci.* 67: 23(2018). https://doi.org/10.1016/j.jes.2017.08.027.
7. WHO, "Coronavirus disease (COVID-19): How is it transmitted?", World Health Organization, Geneva, Switzerland, 23 December 2021. Available [Online] https://www.who.int/news-room/questions-and-answers/item/coronavirus-disease-covid-19-how-is-it-transmitted <1July2023>.
8. Howard, J., Huang, A., Li, Z., et al., *Proc. Natl. Acad. Sci. U.S.A.* 118(4): 1(2021). https://doi.org/10.1073/pnas.2014564118.
9. Lindsley, W.G., Blachere, F.M., Law, B.F., et al., *Aerosol Sci. Technol.* 55(4): 449(2021). https://doi.org/10.1080/02786826.2020.1862409.
10. Mello, V.M., Eller, C.M., Salvio, A.L., et al., *PLoS One* 17(2): e0264389(2022). https://doi.org/10.1371/journal.pone.0264389.
11. Narasimhan, S., Balakrishnan, M., Ayodeji, O.J., et al., *TAPPI J.* 21(1): 23(2022). https://doi.org/10.32964/TJ21.1.23.
12. Kumar, A., Bhattacharjee, B., Sangeetha, D., et al., *J. Ind. Text.* 51(2_suppl): 3430S(2022). https://doi.org/10.1177/15280837211028794.
13. Shokri , A., Golbabaei, F., Seddigh-Zadeh, A., et al., *Int. J. Occup. Hyg.* 7(1): 10(2015).
14. Aragaw, T.A., *Mar. Pollut. Bull.* 159: 111517(2020). https://doi.org/10.1016/j.marpolbul.2020.111517.
15. Lee, L.Y.-k, Lam, E.P.-w, Chan, C.-k., et al., *BMC Public Health* 20(1): 1(2020). https://doi.org/10.1186/s12889-020-09087-5.
16. Sharma, A., Omidvarborna, H., and Kumar, P., *J. Hazard. Mater.* 422: 126783(2022). https://doi.org/10.1016/j.jhazmat.2021.126783.
17. Morais, F.G., Sakano, V.K., Lima, L.N.d., et al., *Aerosol Sci. Technol.* 55(9): 1028(2021). https://doi.org/10.1080/02786826.2021.1915466.
18. Bałazy, A., Toivola, M., Adhikari, A., et al., *Am. J. Infect. Control* 34(2): 51(2006). https://doi.org/10.1016/j.ajic.2005.08.018.
19. Tcharkhtchi, A., Abbasnezhad, N., Seydani, M.Z., et al., *Bioact. Mater.* 6(1): 106(2021). https://doi.org/10.1016/j.bioactmat.2020.08.002.

ABOUT THE AUTHORS

Afolabi

Ramkumar

Face masks have become an important first line of defense in terms of airborne diseases, and there is a need to understand the filtration capabilities of many widely used masks. This study evaluates the N95 and other masks that were distributed during the COVID-19 pandemic.

The most difficult aspect of this study was comparing filtration and other comfort related properties of the masks. We discovered that filtration and comfort have to be balanced. We also found that not all masks are the same — even within the same category.

Manufacturers of masks and their various components can use this information to create products that are both comfortable and effective in terms of filtration. Our next step is to look into functional aspects, such as coatings, etc., on filtration and comfort characteristics.

Afolabi is a graduate student and Ramkumar is professor in the Department of Environmental Toxicology at Texas Tech University in Lubbock, TX, USA. Email Ramkumar at s.ramkumar@ttu.edu.

ABOUT THIS PAPER

Cite this article as:
Afolabi, R.T., and Ramkumar, S., *TAPPI J.* 22(9): 574(2023). https://doi.org/10.32964/TJ22.9.574

DOI: https://doi.org/10.32964/TJ22.9.574

ISSN: 0734-1415

Publisher: TAPPI Press

[About this journal]

20. Wilson, A.M., Abney, S.E., King, M.-F., et al., *J. Hosp. Infect.* 105(4): 640(2020). https://doi.org/10.1016/j.jhin.2020.05.036.
21. Öhman, J., Gren, P., Sjödahl, M., et al., *J. Appl. Phys.* 131(4): 044702(2022). https://doi.org/10.1063/5.0077710.
22. Pan, J., Harb, C., Leng, W., et al., *Aerosol Sci. Technol.* 55(6): 718(2021). https://doi.org/10.1080/02786826.2021.1890687.
23. Wang, D., You, Y., Zhou, X., et al., *PLoS One* 15(10): e0240285(2020). https://doi.org/10.1371/journal.pone.0240285.
24. Zhao, M., Liao, L., Xiao, W., et al., *Nano Lett.* 20(7): 5544(2020). https://doi.org/10.1021/acs.nanolett.0c02211.
25. Patra, S.S., Nath, J., Panda, S., et al., *J. Air Waste Manage. Assoc.* 72(1): 3(2022). https://doi.org/10.1080/10962247.2021.1948459.
26. Ramkumar, S.S., Purushothaman, A., Hake, K.D., et al., *J. Eng. Fibers Fabr.* 2(4): 155892500700200403(2007). https://doi.org/10.1177/155892500700200403.
27. Hao, W., Xu, G., and Wang, Y., *J. Occup. Environ. Hyg.* 18(3): 128(2021). https://doi.org/10.1080/15459624.2020.1868482.
28. Kannan, M., in *A Textbook on Fundamentals and Applications of Nanotechnology* (K.S. Subramanian, Ed.), Daya, Delhi, India, 2018, pp. 81-92.
29. Cho, H.-W., Yoon, C.-S, Lee, J.-H, et al., *Ann. Occup. Hyg.* 55(6): 666(2011). https://doi.org/10.1093/annhyg/mer032.
30. Kapoor, A., Baronia, A.K., Azim, A., et al., *Indian J. Crit. Care Med.* 25(1): 12(2021). https://doi.org/10.5005/jp-journals-10071-23598.
31. Jinka, S., Behrens, R., Korzeniewski, C., et al., *J. Ind. Text.* 42(4): 501(2013). https://doi.org/10.1177/1528083712464257.
32. Joo, T., Takeuchi, M., Liu, F., et al., *Aerosol Sci. Technol.* 55(8): 930(2021). https://doi.org/10.1080/02786826.2021.1905149.
33. Zangmeister, C.D., Radney, J.D., Vicenzi, E.P, et al., *ACS Nano* 14(7): 9188(2020). https://doi.org/10.1021/acsnano.0c05025.
34. Ramkumar, S., "The basics and the alternatives: A multidisciplinary approach to innovations in PPE could support needed development," *Textile Technology Source*, 25 May 2020. Available [Online] https://textiletechsource.com/2020/05/25/the-basics-and-the-alternatives/ <1July2023>.
35. Drewnick, F., Pikmann, J., Fachinger, F., et al., *Aerosol Sci. Technol.* 55(1): 63(2021). https://doi.org/10.1080/02786826.2020.1817846.