Filtration performance of face masks and facepiece respirators used during COVID-19 pandemic

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ABSTRACT: The rapid spread of SARS-CoV-2 has created challenges for societies, healthcare settings, businesses, and institutions. To curb virus transmission, various measures like lockdown, social distancing, hand hygiene, and using appropriate personal protective equipment (PPEs), including face masks, have been recommended. Face masks and facepiece respirators are considered to act as barriers against microbial transmission from person to person.

In this study, we selected barrier materials used during the COVID-19 pandemic that included four non-medical face masks and three facepiece respirators. Facepiece respirators were distributed by the U.S. Administration through pharmacy outlets. Results showed that facepiece respirator R95 has the highest filtration efficiency (above 99%), which remains more or less the same over different particle sizes. The N95 respirator's filtration efficiency was lower than that of R95, but its barrier resistance was lower than that of the R95, indicating that it can be comfortably used over longer duration. Face masks were evaluated using ASTM F 3502-24 for their barrier performance. At 0.1 and 0.3 µm particle size, domestically manufactured masks met the standard for higher performance. Interestingly, the results indicate that quality of raw materials and manufacturing standards play important roles, as is evident in domestically manufactured face mask and facepiece respirators.

Application: Domestically manufactured face masks and facepiece respirators outperformed imported mask during COVID-19 Pandemic.

The Severe Acute Respiratory Syndrome (SARS-CoV-2) disease, commonly known as COVID-19, was first identified in hospitalized patients in Wuhan, China, between December 2019 and January 2020 [1]. The World Health Organization (WHO) declared it as a pandemic, because COVID-19 spread to 218 countries [2]. It has infected 776 million people worldwide and killed 7 million people (0.9% case fatality rate) [3]. Most COVID-19 patients develop mild symptoms like fever, cough, congestion, running nose, sore throat, fatigue, nausea, difficulty breathing, etc., while a few patients develop pneumonia, pulmonary edema, acute respiratory distress syndrome, or multiple organ failure [4,5]. The incubation period of this virus ranges from 5–6 days, but SARS-CoV-2 can be symptomized only after 14 days of exposure [6,7]. It has been reported that 17%–25% of people [8] and 14%–20% of people [9] remained asymptomatic throughout the period of infection. Pre-symptomatic individuals who have not developed symptoms still carry the SARS-CoV-2 virus that can be transmitted to other individuals [10]. Research suggests that infected people, whether symptomized or asymptomized, can transmit the virus, but the transmission is less likely by an asymptomized individual than by a symptomized patient, as it has higher viral loads at the onset of developing symptoms and during the 5–7 days of illness [11,12].

The principal modes of transmission of this virus are direct and close contact (human-to-human) and through respiratory droplets during sneezing, coughing, or speaking [13]. Indirect transmission through environmental matrices is less studied [14]. Respiratory virus transmission, as with SARS-CoV-2 transmission, is most likely through droplets (> 100 µm), coarse aerosols (> 5–100 µm), and fine-aerosol particles (< 5 µm). Most of the exhaled aerosols are < 5 µm in size [14,15]. The exhaled respiratory droplets that remain suspended in the still air under 5 s and may travel < 1 m from 1.5-m heights, while virus-enriched aerosol particles (≤ 5–100 µm) float in the air for hours and can travel ≥ 1 m from 1.5-m heights [14]. Particles < 10 µm penetrate below the glottis, and < 5 µm particles easily penetrate airways down to the alveolar space, while particles > 20 µm fall under the influence of gravity [16]. It is evident from literature that the size of SARS-CoV-2 virus ranges from 0.05–0.2 µm [5], while 0.1 µm can be considered as the common particle size of SARS-CoV-2 [17], with the droplets' size around 0.3 µm [2].

The degree of the transmission greatly depends on the amount of viable virus ejection by the infected person, the type of contact the person has with others, the settings (indoor vs. outdoor), and what infection prevention and control (IPC) measures were taken [18]. Environmental factors such as temperature and humidity play a vital role in the fate of aerosol droplets and potential transmission of the virus [2]. Other factors also influence the spread of the COVID-19 virus in the workplace, such as occupational factors, socio-demographic factors, working environments, etc. [18]. Healthcare personnel are mostly threatened with viral transmission, as they interact with patients (symptomatic or asymptomatic) daily and work closely with them [13]. Non-health care employees whose workspace includes person-to-person contact, poor ventilation, and shared work, eating, or travel accommodations are also potentially vulnerable to the threat. This includes professions such as retailers, housekeepers, food production workers, restaurant and hospitality workers, construction and transportation workers, social workers, counsellors, public safety officers, etc. However, people working remotely from home are far from this interaction and thus have lower risk of transmitting the virus [18].

The WHO provides complete guidelines to prevent and control the spread of SARS-CoV-2. They include appropriate use of face masks, physical or social distancing (≥ 1 m), hand hygiene, avoiding touching one's face, maintaining breathing protocol, acceptable airing in indoor locations, health examinations, contact tracing, quarantining, etc. [10]. Face mask usage reduces virus transmission from symptomatic, pre-symptomatic, or asymptomatic infected individuals [15,19-22]. Face mask mandates greatly reduced the virus transmission in the United States [23]. Face masks reduced the concentration of virus aerosol droplets from infected individuals as well as minimizing the travel distance [15,21,22]. A cluster-randomized trial done in Bangladesh during COVID-19 revealed that community masking significantly reduced the COVID-19 cases across the country [24].

The primary purpose of face masks is to provide protection against biological threats by establishing barriers, as well as providing breathable air and comfort to the wearer [2]. A surgical mask is a disposable material that forms a physical barrier between the wearer's mouth and nose and any potential pathogens in the surrounding area. These are commonly referred to as face masks (FMs), even though not all of them are classified as medical grade surgical masks. In comparison, a respirator is made to fit tightly over the face and filter airborne particles very effectively [25]. Personal protective equipment (PPE) includes surgical masks and respirators that are worn by employees in both healthcare and non-healthcare environments. Face masks are comprised of a three-layer polypropylene (PP) substrate, including a middle meltblown nonwoven (core material /filter layer) and outer spunbond nonwoven layers [26,27]. The fiber diameter of meltblown layer and spunbond layers are about 1–5 µm and 20 µm, respectively [27]. Filtering facepiece respirators (FFRs) like R95, N95, and KF94 are made of three to five layers, including one to two layers of meltblown nonwoven and outer spunbond nonwoven layers, as compared to the R95, which has an additional activated carbon layer. Facepiece respirators also contain micro/nanofiber layers, depending on the manufacturer and efficiency requirements. The meltblown filter layer plays a principal role in the overall filtration efficiency of surgical masks and filtering facepiece respirators [2]. Generally, adding filtration layers would increase filtration efficiency of the masks, but they may also cause discomfort to the mask wearers due to increased pressure drop between the surfaces of the mask resulting from high material thickness and mass in terms of grams per square meter (GSM). A critical analysis of protection vs. comfort characteristics is thus required to categorize FMs and FFRs.

In this study, we compared the effectiveness of commonly available FMs and FFRs that were used during COVID-19 in preventing SARS-CoV-2 transmission. An important aspect of this study has been that the work involved facepiece respirators distributed to the public by the U.S. Administration during the COVID-19 pandemic. Therefore, filtration data of these masks is useful information that will help in case of future outbreaks. We assessed their filtration performances, including filtration efficiency (FE), differential pressure (ΔP), air permeability, and moisture vapor transmission rate (MVTR). We hypothesized that FFRs would perform better than FMs since FFRs have more filtration layers, higher mass (GSM), and compactness compared to FMs. We also predict that filtration performances of face masks would change according to the diameter of the particles or particle size, as different diameter-sized particles have different ways of movement and thus their filtration efficiency may change accordingly. Our main objectives of this study were to: 1) observe the effect of particle size on the performance parameters of different FMs and FFRs, and 2) observe the effects of basic filter characteristics such as mass and thickness on the performance of FMs and FFRs.

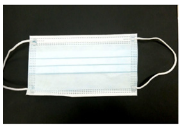
MATERIALS AND METHODS

Material collection

A total of four face masks (non-medical, three-layered nonwoven polypropylene) and three facepiece respirators (three- to five-layered) were obtained from pharmacies, hospitals, and retail outlets in Lubbock, TX, USA. The facepiece respirators were distributed by the U.S. Administration through pharmacy outlets. In the case of face masks, the outermost spunbond layers provide support and maintain the integrity of the mask and the inner meltblown layer provides resistance against particle penetration [28]. For higher filtration efficiency, additional filter substrates made from micro and nanofibers are needed. The filters' structural and physical details (GSM, fiber characteristics, product information) are given in **Table I**, along with their representative figures.

Filter substrate characterization

Material compositions of various masks were obtained from the manufacturers' labels and their details are de-

Type of Mask	Product Description	Country of Origin	Image	GSM, g/m²	Layer 1 (outermost)	Layer 2	Layer 3	Layer 4	Layer 5
FM1*	Non-medical mask	China		68 ± 1.13	PP spun bonded nonwoven	PP melt blown nonwoven	PP spun bonded nonwoven	-	-
FM2*	Non-medical mask	China		71.32 ± 1.86	PP spun bonded nonwoven	PP melt blown nonwoven	PP spun bonded nonwoven	-	-
FM3*	Non-medical mask	China		80.25 ± 2.43	PP spun bonded nonwoven	PP melt blown nonwoven	PP spun bonded nonwoven	-	-
FM4*	Non-medical mask	USA		67.29 ± 1.09	PP spun bonded nonwoven	PP melt blown nonwoven	PP spun bonded nonwoven	-	-
FFR1**	N95 (NIOSH; Honeywell DC300N95)	USA		236 ± 10.52	Bonded web	PP melt blown nonwoven (filter layer)	PP spun bonded nonwoven	-	-
FFR2**	KF94	South Korea		141.12 ± 6.65	PP spun bonded nonwoven	Bonded web	PP melt blown nonwoven (filter layer)	PP spun bonded nonwoven	-
FFR3**	R95 (NIOSH; 3M 4247)	USA		531.01 ± 29.22	PP spun bonded nonwoven	PP melt blown nonwoven (filter layer)	Activated carbon	PP melt blown nonwoven (filter layer)	Bonded web

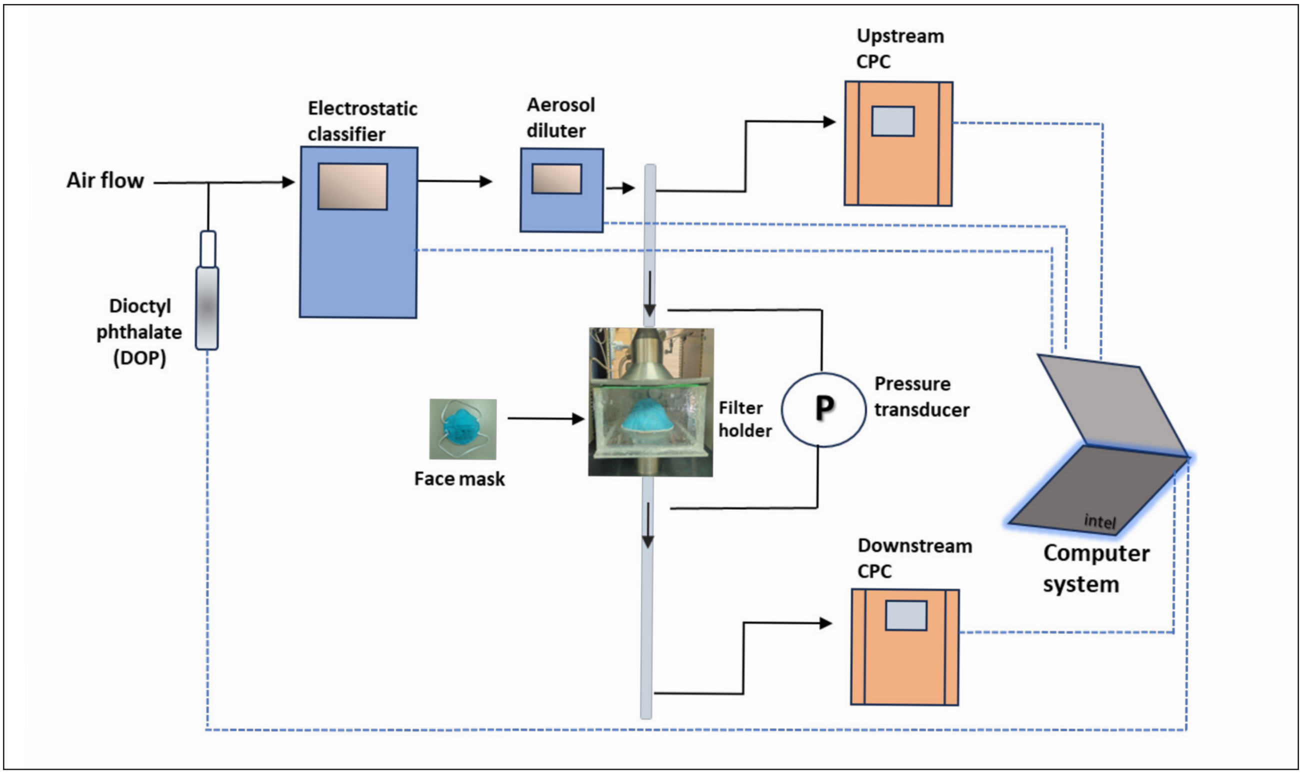
I. Specifications and details of face masks (*FMs) and facepiece respirators (**FFRs) used in this study (NIOSH: National Institute for Occupational Safety and Health; PP: polypropylene).

scribed in Table I. Thickness (mm) of the filter layers was measured under a specified pressure (8.6 oz/in²) using a thickness tester (Model No. 99-0697, AMES; Melrose, MA, USA) following the ASTM 1777-96 standard as described elsewhere [29].

Grams per square meter (GSM) is an indicator of a sample's mass and represented as g/m² of the samples. It can be an indicator of the filtration performance of nonwoven material since it is correlated with sample thickness and density of the packing material used [30]. The GSM of the selected mask substrates was measured by weighing cut sample (50 cm²) from the mask using Denver Instrument (Denver, CO, USA) laboratory analytical balance scale (Model P-603DMDS) and dividing them by their total area (length × breadth, m²).

Reagents used and particle generation

A Thermo Fisher Scientific (Waltham, MA, USA) ACS grade 2-propanol (isopropyl alcohol, catalogue no. A464-4) of ≥ 99.9% purity and a Sigma-Aldrich (St. Louis, MO, USA) dioctyl phthalate (DOP/Bis phthalate/2-ethylhexyl phthalate) oil (catalogue no. 18-610-258) of ≥ 99.5% purity were used to generate submicron-sized aerosolized particles of 0.03, 0.04, 0.05, 0.06, 0.08, 0.1, 0.15, 0.2, 0.25, and 0.3 µm in diameter. Particle size distribution was made to imitate the SARS-CoV-2 virus particle and droplet sizes, as described elsewhere [2,5,17], and guide for filter certification [31]. Two TSI (Shoreview, MN, USA) Model 3771 condensation particle counters (CPCs) for upstream and downstream and an aerosol neutralizer (TSI Model 3077) were attached with a TSI automated filter tester (Model 3160) and were utilized for measuring particle filtration efficiency.



1. Typical workflow of the TSI 3160 automated filter tester. Electrostatic classifier was used to generate monodisperse aerosolized particles (0.03–0.3 µm) from dioctyl phthalate (DOP) solution. The aerosol diluter dilutes particle concentration that the classifier generates by 100 times (1:100). A cup holder was used to place the mask for filtration testing against diluted aerosolized particles. A computer system was attached to both of the condensation particle counters (CPCs) to count the upstream and downstream concentration of diluted aerosolized particles. Filtration efficiency of the mask was measured by comparing the upstream and downstream concentration of aerosolized particles of interest. R^2 is coefficient of determination.

Figure 1 shows the typical workflow of the automated filter tester. The upstream CPC measured the upstream aerosol concentration, and the downstream CPC measured the downstream aerosol concentration. The CPCs were equipped with a differential mobility analyzer (TSI Model 308,100) that generates polydisperse aerosols of intended diameter, which were passed through the neutralizer. An aerosol diluter (TSI Model 3302) was used to lower particle concentration by mixing the generated aerosol particles with particle free air. The diluted aerosol particles went through the sample in a sample holder (7.98 cm diameter, 50.01 cm² area) [23]. Air flow was regulated by the combination of a vacuum pump and an adjustable flow control valve and measured by a TSI Model 4043 mass flow meter (L/min). The flow rate in this test (32.2 L/min) was set close to nominal values for normal human adult breathing at sea level in a moderate stress condition [32]. The TSI automated filter tester (Model 3160) ensured fractional filter efficiencies up to 99.999999% at 10 different monodisperse submicron particle sizes.

Filtration efficiency, pressure drop, and overall performance analysis

A 50 cm² cut sample was placed in a sample holder plate (7.98 cm diameter; 50.01 cm² area) during each test with a constant flow rate of 32 ± 0.5 L/min and face velocity (10 ± 0.5 cm/s) as specified in ASTM F3502-24 "Standard specification for barrier face coverings." Filtration efficiency of the sample was calculated by measuring particle transmission through each sample using the TSI automated filter tester (Model 3160) as described elsewhere [28]. This filter tester measures the fractional efficiency and pressure drop at different particle sizes (0.03–0.3 µm) to obtain most penetrating particles (MPPS) of the filter media. The overall size dependent number-based FE (ηN) was calculated using the following equation:

$$\eta N = 1\text{-}N_o/N_i \tag{1}$$

where N_i and N_o are the measured concentrations of aerosol at the upstream and downstream of the filter, respectively. The FE of each sample was calculated and presented as a percentage (%) and standard deviation (± SD).

The following equation was used to measure the overall performance (qF) of face mask filter and facepiece respirator filter substrates in this study, as described elsewhere [33]:

$$qF = \text{-}\ln P/\Delta p \tag{2}$$

where P is the penetration efficiency ($P = 1$ FE) of the sample, and Δp is the differential pressure between outer and inner surface of the filter substrates. Quality factor (qF) represents the overall performance of the filter substrates.

Air permeability test

Air permeability is defined as the speed of air flow through the material under differential pressure between the two fabric surfaces [34]. The air permeability test was performed using a Model M021S air permeability tester from SDL Atlas (Rock Hill, SC, USA) according to the method specified by ASTM D737-96 "Standard test method for air permeability of textile fabrics," as described elsewhere [35,36]. The 20 cm^2 samples were tightly placed between the top of the measuring chamber and the top clamp with the outer face of the filter substrates placed towards the air inlet orifice. The air flow was maintained by drawing air through the sample with a vacuum pump and was measured by selected flow meter covering a range of air flows (0.05 mL/s to 416 mL/s) regulated by valves. Air permeability results were expressed in mm/s at a specified pressure of 100 Pa.

Moisture vapor transmission rate analysis

The MVTR of the surgical masks and facepiece respirators was analyzed using an SDL Atlas Model M261 water vapor permeability tester following ASTM E96 "Standard test methods for water vapor transmission of materials," as described elsewhere [37]. A 50 cm^2-diameter-sized portion of the mask substrates was cut and tied onto a ringed dish with 50 mL of deionized (DI) water. Mask filter substrates were assembled on an electronically movable turntable at a steady rate (2 rpm). The MVTR was measured as an average weight loss of water as a means of evaporation through each cut sample. The weight loss of the sample was counted at 0 h of the rotation and also at 6 h, as described elsewhere [37]. The following equation was used to calculate the MVTR:

$$\mathrm{MVTR} = 24M/At \qquad (3)$$

where M represents the total weight loss (M_6 - M_0) of the assembly over time period (t = 6 h), and A is the area of the sample cut where the evaporation took place (A = 0.005413 m^2).

Statistical analysis

The MVTR, air permeability, filtration efficiency, pressure drop, and quality factor data were analyzed using one-way analysis of variance (ANOVA) followed by Tukey's multiple comparison test. A Student's t-test was also performed to compare all the means. Each of the face mask and face piece respirator substrates were tested, and in any case, a p-value less than 0.05 was considered statistically significant. All the analysis were performed using GraphPad Prism version 9.0 (GraphPad; San Diego, CA, USA) and Microsoft Excel 2010.

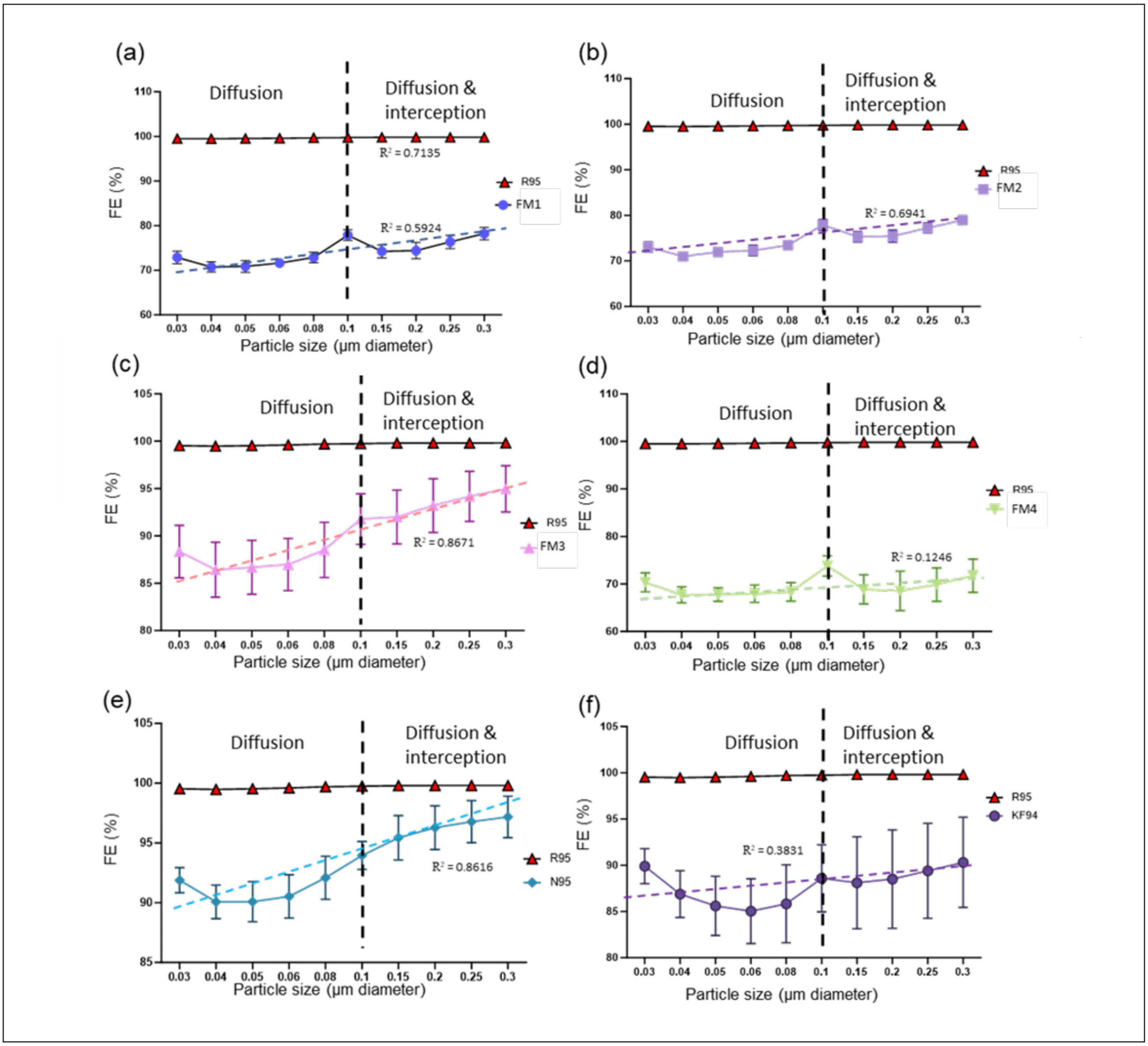
RESULTS AND DISCUSSION

The SARS virus is primarily transmitted through direct or indirect contact with the mucous membranes of the eyes, nose, or mouth with infected respiratory aerosol droplets [38,39]. Face masks provide a means of protection against virus transmission by providing a physical barrier between bodily parts and viruses. Surgical masks and respirators such as N95 are considered as nonpharmacological approaches in preventing or slowing down the transmission of various infectious diseases [40]. In this study, four non-medical surgical face masks (FM1–FM4) and three facepiece respirators (N95, KF94, R95) were selected. Their filtration efficiency, pressure drop, air permeability, MVTR, overall performance (qF) was evaluated against particle ranges of 0.03–0.3 µm. Their structural and manufacturing details (GSM, fabric characteristics, product information) are given in Table I.

Effects of particle size on FE of face masks and facepiece respirators

Filtration efficiency of face masks (FM1–FM4) and facepiece respirators (N95, KF94, R95) for different particle sizes (0.03, 0.04, 0.05, 0.06, 0.08, 0.1, 0.15, 0.2, 0.25, and 0.3 µm) was measured. A significant positive correlation was observed between particle size and FE in face masks ($p < 0.05$) (**Fig. 2a–2d**). The FE of face masks (FM1–FM4) seems to increase with the increasing particle size. Regression analysis showed that a moderate correlation is present between particle size and FE for FM1 and FM2 ($R^2 > 0.5$) (Fig. 2a and 2b). A strong correlation was found between particle size and FE for FM3 ($R^2 > 0.85$), while the relationship is not strong enough between particle size and FE for FM4 ($R^2 < 0.5$) (Fig. 2c and 2d). In general, the results show that there is a correlation between FE and particle size for non-medical masks.

For facepiece respirators, particle size has a positive influence on FE. For the N95 mask, FE started to increase after 0.04 µm particles and continued to increase until 0.3 µm particles. The R95 respirator shows the highest FE among all the masks tested here, and thus is included as a reference to compare with the FE of all face masks and other respirators in the study (Fig. 2a–2f). However, particle size has no significant influence on FE for R95, as FE remains the same over different particle sizes. This result shows that the R95 can provide better filtration efficiency irrespective of the size of the particles. However, here again, FE shows a slightly increasing trend with an increase in particle size. For N95 respirators, FE increased with the increasing particle sizes until 0.3 µm particles ($p < 0.05$). No distinct statistical relationship was observed between particle size and FE in the case of KF94 respirators. Lee et al. found similar results of no significant changes in FE when particle size changed from 0.1 to 0.25 µm (91.2 ± 9.0 to 95.1 ± 4.1% FE for 0.1 µm particles, and 91.3 ± 8.9 to 95.1 ± 4.0% FE for 0.25 µm particles) [41].

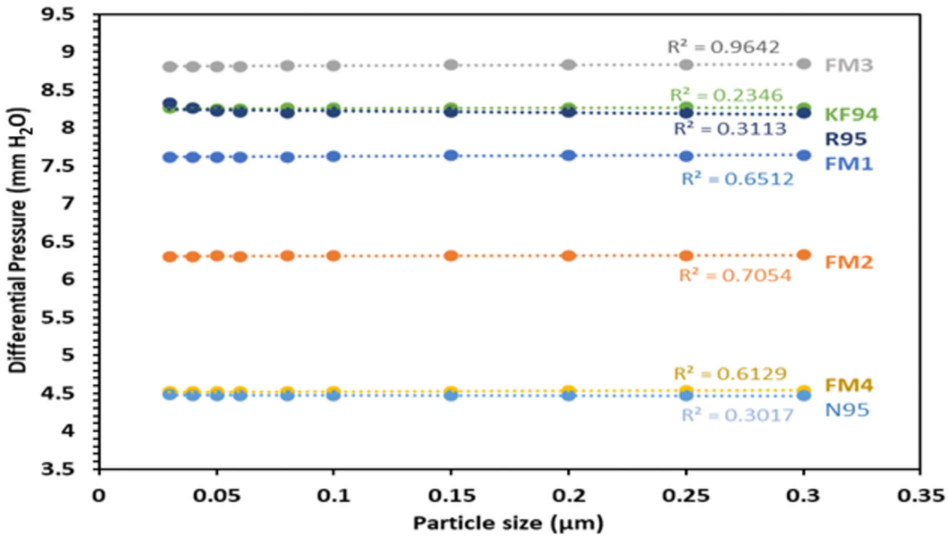


2. Particle size dependent filtration efficiency (FE) was evaluated for face masks: (a) FM1, (b) FM2, (c) FM3, and (d) FM4. The FE was also evaluated for facepiece respirators: (e) N95, and (f) KF94 and R95. The FE of each mask was compared against the FE of R95. Each value is represented as mean ± standard deviation (N= 5–10). For small particles less than 0.1 µm in diameter, the primary filtration mechanism is diffusion. Particles above 0.1 µm enter the region where diffusion and interception are the dominant mechanisms.

It is important to note that particle size 0.1 µm is considered as the most abundant SARS-CoV-2 particle size [17], and thus FE at this particle size determines the filtration performance of different filters against SARS-CoV-2. We found the highest filtration performances against SARS-CoV-2 sized particles in the case of R95 masks (99.75 ± 0.28), followed by N95 respirators, FM3, KF94 respirators, FM2, FM1, and FM4, respectively. Particles with the diameter in the range of 0.1 µm and below are captured by the filter substrates through diffusion, and hence the filter substrates are more efficient [42,43]. However, particles in the range of 0.1 µm to 0.3 µm diameter are captured by the filter substrates through both diffusion and interception, and filter substrates are more efficient [43,44]. On the other hand, we found that relatively lower filtration against particles ≤ 0.1 µm and relatively higher FE for particles ≥ 0.1 µm are possibly due to the presence of two different filtration mechanisms for the particles ≥ 0.1 µm to and ≤ 0.3µm. Overall, the results showed that filtration efficiency increases with the increasing particle sizes.

Effects of particle size on ΔP of face masks and facepiece respirators

Differential pressure is the difference between two pressures applied to the transducer. Particle size seems not to influence the pressure drop for all the face masks (FM1–



3. Differential pressure, ΔP mm H_2O, was evaluated against aerosol particles in the size ranges of 0.03–0.3 µm for face masks: (a) FM1, (b) FM2, (c) FM3, and (d) FM4. The same was done for facepiece respirators: (e) N95, and (f) KF94 and R95. Each value is represented as mean ± SD (N= 5–10). R^2 is coefficient of determination.

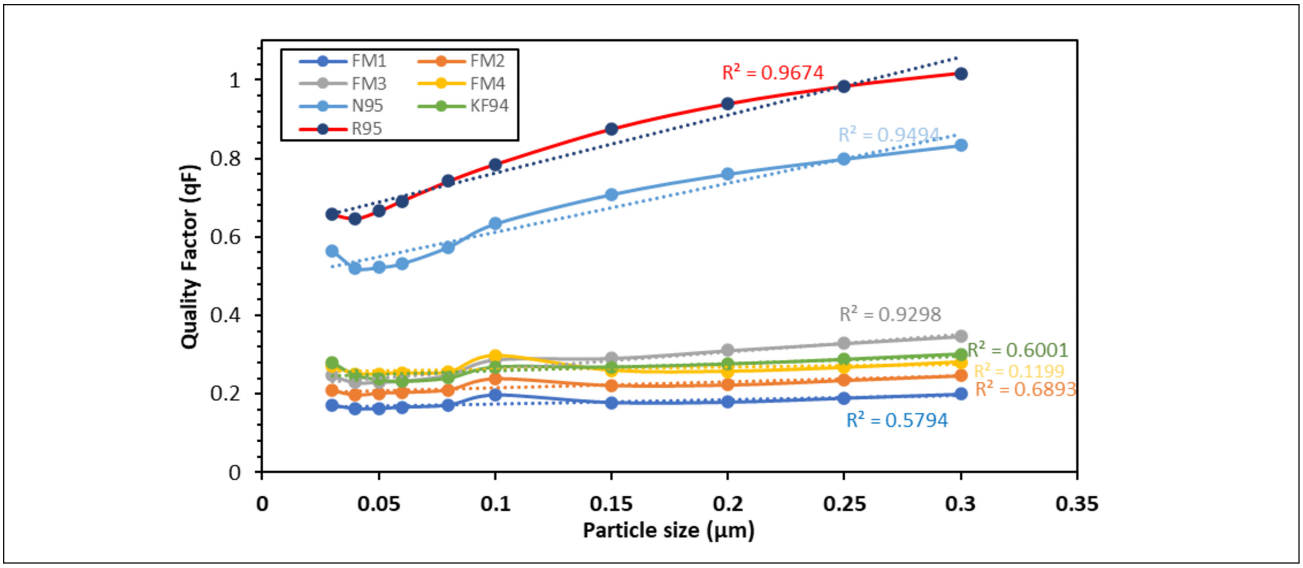
FM4) ($R^2 > 0.6$) (**Fig. 3**). For example, in FM1, no apparent increase in ΔP was observed for particle size 0.03, 0.1 µm, and 0.3 µm (ΔP = 7.62 ± 0.29, 7.63 ± 0.3, 7.64 ± 0.3, respectively), while their filtration efficiency slightly increased (FE% = 72.98 ± 1.42, 77.86 ± 1.21, 78.21 ± 1.41, respectively). The ΔP did not increase in facepiece respirators (FFRs) as well ($R^2 < 0.5$) (Fig. 3). The highest ΔP was observed in FM3 followed by KF94, R95, and the rest of the filter substrates, indicating the lower breathability offered by these filter substrates. The lowest ΔP was found for N95 masks, followed by FM4, indicating higher breathability offered by these filter substrates (Fig. 3). Overall, particle size has no significant influence on ΔP of filter substrates, meaning increasing particle size may not necessarily change the filter's breathability parameters, ensuring constant comfort to the wearers.

Effects of particle size on qF of face masks and facepiece respirators

The quality factor indicates the overall performance of face masks and facepiece respirators. The *qF* of three face masks (FM1–FM3) was positively correlated with the particle size ($p < 0.05$) ($R^2 > 0.5$) (**Fig. 4**). The highest *qF* was obtained at particle size 0.3 µm, while the lowest *qF* was observed at particle size 0.04 µm in the previously-mentioned masks. Particle size was also strongly positively correlated with the *qF* of N95 and R95 respirators ($R^2 > 0.85$), while particle size does not influence the *qF* of FM4 ($R^2 < 0.5$) (Fig. 4). The highest qF was obtained for R95 respirators, followed by N95 respirators. The *qF* of KF94 respirators and all the face masks (FM1–FM4) were substantially lower than that of R95 and were clustered together as shown in Fig. 3. It is important to note that *qF* is measured as a ratio between filtration efficiency and ΔP. Thus, we found a similar trend of increases in FE and *qF* against particle sizes given that ΔP did not influence the overall performance of the filter substrates. This result indicates that filtration efficiency influences more than pressure difference in deciding the overall quality of the filters. In general, particle size has a positive influence on overall performance of filter substrates.

Effects of MPPS on FE, ΔP, and qF of face masks and facepiece respirators

Most penetrating particle sizes represent the particles offering the least filtration efficiency and the lowest performance among the filters. The MPPS ranges from 0.03 to 0.05 µm for face masks and 0.03 to 0.06 µm for the respirators, except for the FM4, which has 0.2 µm MPPS. By combing both MPPS ranges, we reported 0.03 to 0.06 µm size particles as smaller and 0.2 µm size particles as larger. The highest FE was obtained in the case of R95 mask (99.42 ± 0.25%) at its MPPS, followed by the N95 mask, KF94 mask, FM3, and other face masks (FM1, FM2 and FM4) at their respective MPPS values. However, the FE decreased (63.81 ± 2.86) for FM4 for larger particles (0.2 µm) as MPPS shifted from (0.04–0.05 µm) to 0.2 µm. A similar decrease in FE was observed from shifting MPPS to larger sizes [45-48]. At MPPS 0.04–0.05 µm, FM4 masks met the ASTM F3502-24 "Standard specification for barrier face coverings" of higher performance, since it has ΔP less than 5 mm H_2O and FE of > 50%. However, other face masks have FE of > 50%, but their ΔP did not meet the above ASTM standard. The N95 clearly met the ASTM standard against 0.1 and 0.3 µm size particles, as it passes filtration efficiency of 95% and it has ΔP (ΔP < 5 mm H_2O) that achieves high performance barrier face covering following ASTM F3502-24



4. Quality factor (qF) was evaluated against aerosol particles in the size ranges of 0.03–0.3 µm for face masks: (a) FM1, (b) FM2, (c) FM3, and (d) FM4. The same was done for facepiece respirators: (e) N95, and (f) KF94 and R95. Each value is represented as mean ± SD (N= 5–10). R^2 is coefficient of determination.

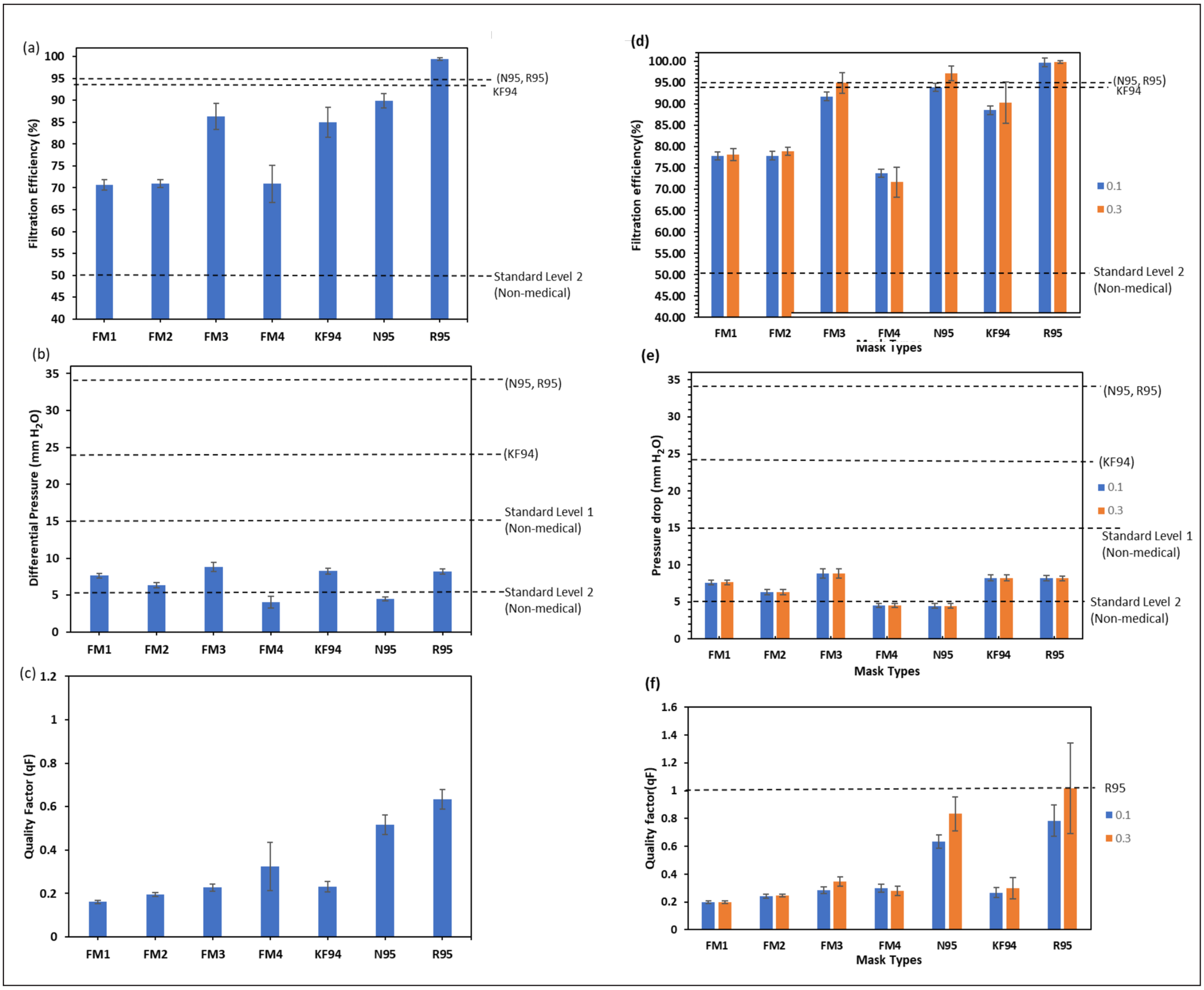
(**Fig. 5d–5e**). Both FM4 and N95 met the ASTM breathability for standard face coverings, possibly due to their similarity in meltblown filtration layer compositions like fiber diameter, fiber orientation, porosity, etc. The R95 has the highest FE (FE > 99%) at MPPS, but its ΔP failed to meet the above ASTM standard of high-performance face coverings following ASTM F3502-24 (Fig. 5a–5b). It should be noted that ASTM F3502-24 is for barrier face coverings, and facepiece respirators do not fall under this category. Facepiece respirators are required in situations to prevent the spread of aerosolized particles such as during intubation in hospitals. The R95 respirator has the highest overall performance (*qF*) at 0.3 µm particle size, which is considered as the droplet size of SARS-CoV-2 [2], given that it has the maximum filtration efficiency (99.81 ± 0.3%) at this particle size. The overall performance of the N95 respirator is next to the R95 respirator, and it has filtration efficiency close to the R95 at this particle size (97.17 ± 1.74%). None of the other masks studied here met the *qF* of R95 (Fig. 5c and Fig. 5f) at either particle size.

Effects of GSM on filtration efficiency of face masks and facepiece respirators

The grams per square meter (mass) of filter substrates in this study ranged between 67.29–80.25 g/m² for face masks and 141.12–531.01 g/m² for facepiece respirators. A significant positive correlation between GSM and FE was obtained for the particle sizes 0.03, 0.04, 0.05, and 0.06 µm ($p < 0.05$). The highest FE obtained (99.43%–99.6%) in these particle ranges was obtained in the case of R95 respirators, as their compact structure and highest GSM (531.01 ± 29.22) enables efficient barrier to particles. The FE of N95 respirators (90.07%–91.89%) for particle sizes ranging between 0.03 and 0.06 µm and with GSM (236 ± 10.52) was next to that of R95 respirators. However, for KF94 mask, GSM did not seem to influence the FE, possibly due to the different structural compositions of the filter layers of KF94, like fiber diameter, fiber orientation, and porosity. The FE of KF94 was slightly lower than that of FM3; however, the GSM of KF94 is higher than that of FM3. All the face masks (FM1–FM4) included in this study have low GSM (67.29 ± 1.09; -80.25 ± 2.43), and thus their FE varied accordingly. Alternatively, we did not find significant relationship between GSM and FE among face masks and respirators for larger particle sizes (0.08–0.3 µm). Smaller particles (0.03–0.06 µm) penetrate more through the filter layers of the face mask and respirators, which is possibly due to the single diffusion method dominating while moving smaller particles. With masks of increasing GSM, the penetration of these particles is slowed down. The penetration of larger particles is not slowed down in masks of increasing GSM, possibly due to larger particles moving in a variety of ways, such as diffusion and interception or impaction. Regression analysis showed that GSM has a moderate correlation with the FE of the mask filter substrates ($R^2 > 0.5$) (**Fig. 6b**). However, there is an increasing trend in the filtration efficiency values with the increase in GSM and thickness. The GSM is also strongly correlated with the thickness of the mask materials ($R^2 > 0.85$) (Fig. 6a). We found low thickness for face masks (0.42–0.63 mm) with low GSM (67.29–80.25 g/m²) and high thickness for the respirators (1.04–3.7 mm) with high GSM (141.11–531.01 g/m²).

Effects of GSM on pressure ΔP of face masks and facepiece respirators

Pressure drop is expressed as ΔP (mm H_2O) between the two surfaces of the filter substrates and indicates the breathability and/or resistance of the substrates. The higher the pres-

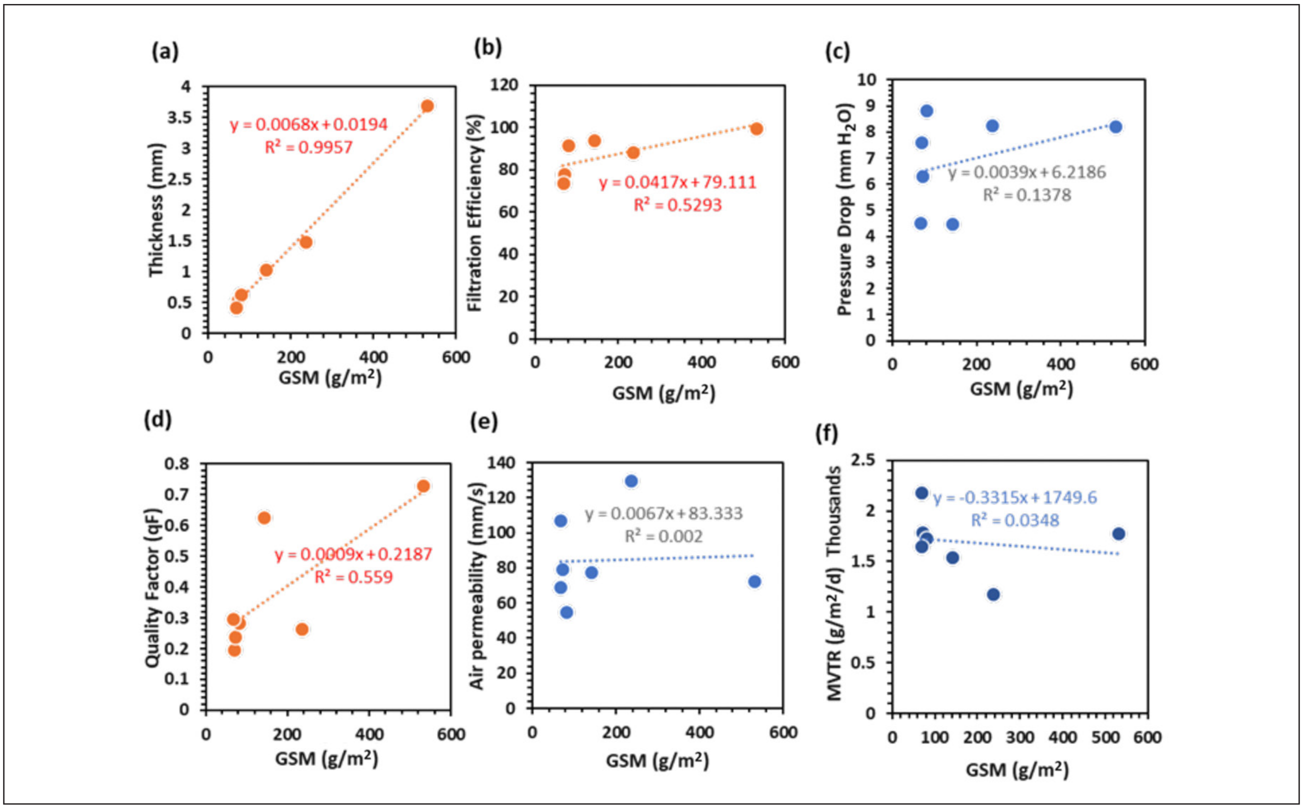


5. Comparing filtration efficiency (FE%), pressure drop (mm H_2O), and quality factor (qF) of filter substrates at most penetrating particle sizes (MPPS) of: (a-c) 0.03–0.06 μm, and (d-f) at 0.1 and 0.3 μm sizes. Dashed lines indicate standard for FE%, ΔP, and qF for non-medical masks and facepiece respirators following ASTM F3502-24 "Standard specification for barrier face coverings."

sure drop, the lower the breathability of the filter substrates. The lowest ΔP was obtained for the N95 respirators (4.47–4.48 mm H_2O), and the highest ΔP was obtained for FM3 (8.81–8.83 mm H_2O). The ΔP of FM4 was close to the ΔP of N95 respirators (4.52–4.54 mm H_2O for FM4, and 4.47–4.48 mm H_2O for N95). However, their GSM varies greatly (67.29 ± 1.09 for FM4, and 236 ± 10.52 for N95 respirators) (Table I). The ΔP of KF94 (8.25–8.26 mmH_2O) is the second highest among the filter substrates next to ΔP of FM3. The ΔP of R95 respirators (8.2–8.22 mmH_2O) was similar to that of KF94 respirators, while the GSM of R95 respirators was 3.76-fold higher than the GSM of KF94 respirators; R95 respirators contain an additional filter layer and an activated carbon layer. Regression analysis showed that a weak correlation was observed between ΔP and GSM (R^2 = 0.1374) for the particle size 0.1 μm (Fig. 6c), indicating GSM has a lower effect on ΔP of filter substrates. However, with increasing GSM, the trend seems to be in an increasing direction with ΔP values.

Effects of GSM on qF of face masks and facepiece respirators

The quality factor indicates the overall performance of filter substrates. In this study, a positive correlation was obtained between GSM and *qF* of the filter substrates (face masks and facepiece respirators) across all particle sizes (0.03–0.3μm) (R^2 = 0.559, p <0.05) (Fig. 6d). The highest *qF* was found for R95 masks (0.643–0.764) and has been considered as a standard to which compare the *qF* of all other masks studied here. The *qF* of N95 respirators is the second highest (0.56–0.83) among the filter substrates next to *qF* of R95 (0.66–1). The *qF* of N95 mask are 0.63 and 0.83 at 0.1 μm and 0.3 μm particle size, respectively, while the *qF* of R95 respirators are 0.78 and 0.1, respectively for those particle sizes (Fig. 4). The *qF* of KF94 (0.23–0.28) and all the face masks (0.16–0.34) in this study were much lower than both R95 and N95 and thus are clustered separately than both N95 and R95 in Fig. 4.



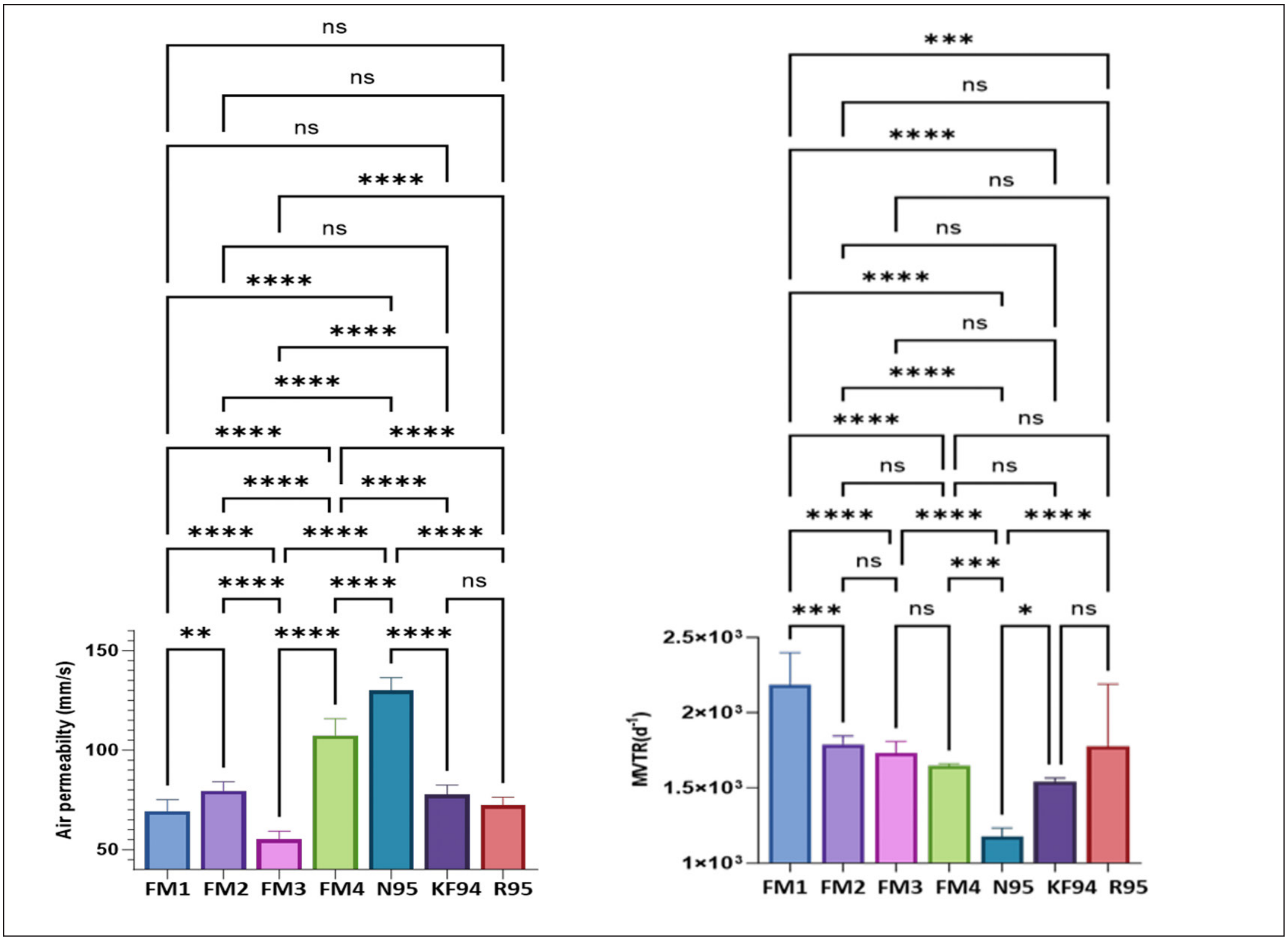
6. Correlation analysis between the variables showing coefficient of determination (R^2) values and the equations of the correlations: (a) GSM and thickness; (b) GSM and FE%; (c) GSM and pressure drop; (d) GSM and qF; (e) GSM and air permeability; and (f) GSM and MVTR. The R^2 values ≥ 0.85 indicate strong correlation between the variables, and R^2 values of ≥ 0.5 indicate that moderate correlation exists between the variables. Values ≤ 0.5 indicate weak correlation exists between them.

Effects of mass GSM on air permeability of face masks and facepiece respirators

Since the fibers in nonwoven filter substrates are ubiquitously distributed and provide a porous structure, air flows through the minute pores in the structure. As thickness and GSM of the fabric substrates increase depending on the fiber arrangement, the space between the fibers is reduced and the porosity decreases, resulting in lower air permeation through the gap between the fibers [49]. In this study, the highest air permeability (130 ± 6.5 mm/s) was obtained for N95 respirators. The air permeability of FM4 is next to the air permeability of N95 but significantly lower than that of N95 respirator. Similarly, the GSM of FM4 (67.29 ± 1.09 g/m²) is much lower than that of N95 (236 ± 10.52 g/m²) (**Fig. 7a**). The air permeabilities of FM1 and FM2, KF94, and R95 are close to each other (Fig. 7a). The air permeability of FM3 was the lowest (55.17 ± 4.14 mm/s) among the filter substrates, even though GSM of FM3 (80.25 ± 2.83) is much higher than GSM of other face masks. Regression analysis showed that a very weak relationship is present between GSM and air permeability of the filter substrates (R^2 = 0.002) (Fig. 6e). From this, we come to a conjecture that GSM does not have any significant influence on air permeability of face masks and respirators. However, Zhu et al. found a positive influence of fabric thickness on the air permeability of nonwoven polyester fabrics [50]. Our results show the structure of the filter substrates, arrangement of fibers in the structure, and the assembly of the overall filter influence the air permeability.

Effects of GSM on MVTR of face masks and facepiece respirators

Moisture vapor transportation rate denotes the rate at which water vapor escapes from the microclimate between the skin and the fabric and plays an important role in determining the comfort of the material [37]. The key factor affecting comfort, particularly in sweaty environments, is the moisture vapor transmission [51]. Among all the face masks, the highest MVTR was found for the FM1 face mask. The MVTR of FM2 and FM4 were much lower compared to that of FM1, while the GSM of FM2 and FM4 did not differ significantly from FM1. On the other hand, there was no significant difference in MVTR among FM2, FM3, and FM4, although their GSM varies greatly (Fig. 7b). From these, we can conclude that MVTR is independent of GSM and thickness for face masks. We found the lowest MVTR for N95 respirator, which has a GSM higher than the GSM of all the face masks, while MVTR of both KF94 and R95 respirators are not significantly different from each other (Fig. 7b), even though their GSM varies greatly (141.12 ±



7. (a) Air permeability (mm/s), and (b) MVTR (d^{-1}) of face masks (FM1–FM4), and facepiece respirators (N95, KF94, and R95). Significant difference of the values between the two masks represented by P value (* P < 0.05, ** P < 0.01, *** P < 0.001, **** P < 0.0001).

6.65 for KF94; and 531 ± 29.22 for R95). The MVTR of the R95 respirator is also comparable to FM2–FM4, as shown in Fig. 7b, even though the GSM of R95 is higher than that of the face masks. The MVTR of the N95 respirator is much lower than that of R95. Regression analysis showed that there was a very weak relationship present between GSM and MVTR of the filter substrates (R^2 = 0.0348) (Fig. 6f). Considering all the previously-noted analysis, we conclude that GSM does not have significant influence on MVTR of filter substrates (face mask and respirators). Here again, the overall structure of the mask and the arrangement of fibers influence the transport of vapor and hence affect the comfort as measured by MVTR.

CONCLUSIONS

This study investigated the filtration efficacy of face masks and facepiece respirators that were used during COVID-19 in mitigating the transmission of SARS-CoV-2 and assessed their comfort related properties. Microbial transmission from infected individuals to healthy individuals remains prevalent, especially in healthcare settings. As aerosol transmission is considered the major route for SARS-CoV-2 infection, we designed the study to examine the filtration efficacy of facemasks and facepiece respirators that act as barriers for aerosol transmission of the pathogenic virus.

Results showed that the particle size has a positive influence on the filtration efficiency and quality factor in all the filter substrates, while particle size has no influence on ΔP of filter substrates. On the other hand, GSM influences FE and qF of filter substrates, while there is no strong relationship found between GSM and other performance parameters (ΔP, air permeability) of the filter substrates. Results show that with an increase in the mass of filter substrates, there is a decreasing trend with MVTR values. We found that all non-medical face masks and respirators, like N95 and R95 respirators in this study, reach the Level 1 standard for barrier face coverings (FE > 20%, ΔP < 15 mm H_2O) according to ASTM F3502-24 for FE and ΔP. Out of four face masks, only FM4, which was made and distributed by the United States, passed the Level 2 standard for barrier face coverings (FE > 50%, ΔP < 5 mm H_2O), indicating that strictly maintained manufacturing standards and quality of raw materials play important roles in the performance of filters. The R95 has the highest filtration efficiency and overall performance, followed by N95 masks. Thus, R95 gives enough protection against microbial transmission. The R95 has the highest MVTR among all the facepiece respirators studied here. However, it has a relatively higher pressure drop and thus cannot act as an effective filter substrate for longer use from a comfort point of view. However, there are situations such as toxic aerosol transmission under limited duration, where filtration efficiency occupies primary partition and hence the need for R95. The N95 may act as an effective filter substrate, since it has lower ΔP compared to R95, which provides sufficient comfort to mask wearers for prolonged duration, while its filtration efficiency and overall performance is close to R95 masks. Face masks with necessary fit could be an alternative since they are readily accessible and meet the standard of high-category masks for barrier face coverings. In case of situations where N95 masks are in shortage, properly fitting face masks can be used. However, their performance will be less than those of facepiece respirators like N95. Results show that domestically manufactured filters outperform imported masks, pressing the importance of quality standards. In summary, R95 provides the highest filtration efficiency and N95 provides the necessary balance of filtration efficiency and resistance, making them ideal filters for aerosol barrier in situations such as viral outbreaks.

Given the severity of pandemics and their global impact, appropriate PPE, including face masks, are crucial for curbing transmission. Future research should explore factors such as demographics and sociological aspects like lack of healthcare access and lack of availability of cost-effective PPE to better understand the types of masks needed and their effectiveness in reducing virus transmission. **TJ**

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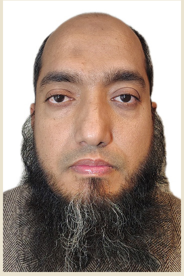
ABOUT THE AUTHORS

We studied this topic because commonly available face masks and respirators used during the COVID-19 pandemic needed evaluation against SARS-CoV-2 transmission. This research includes analysis of non-medical face masks and respirators, while previous studies focused only on different barrier face coverings.

Sample collection was not easy at the beginning of this study, but with collaboration, we were able to solve the issue. We discovered that domestically manufactured masks outperform imported masks and that, surprisingly, N95 masks can be used for longer periods.

Some of those in the mask manufacturing industry might benefit from considering masks made in the United States as a standard for mass production. As a next step, performance of surgical masks may be analyzed in future research.



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