Cloth Mask Breathability and Filtration Efficiency Technical Report

1. Executive Summary

The present scientific evidence indicates that mask-wearing by the public is an effective measure for reducing transmission of SARS-CoV-2 due to a combination of droplet (>5 um) and aerosol protection (<5 um). Given that many varieties of cloth mask are effective at reducing transmission via large droplets, **any mask is better than no mask. Mask use should be strongly encouraged to be used in conjunction with measures such as physical distancing.** This report focuses primarily on the material considerations for designing cloth masks which protect against transmission via smaller droplets and aerosols in addition to protecting against transmission via larger droplets. Better understanding the respective risks of aerosol transmission compared to large droplet transmission for SARS-CoV-2 is an area of developing study.

In this report, we compare studies of different materials that could be used to make homemade masks, with the goal of (1) summarizing both qualitative findings for what materials may provide a greater degree of aerosol protection for homemade masks and (2) identifying gaps in the scientific literature for future study. We consider all literature that evaluated the breathability and filtration efficiency of materials that could be used for homemade masks.

It should be noted that the studies reviewed only evaluated the material and did not study leakage that can occur at the side of the mask once it is on a person's face. Mask fit is a critical element in the overall effectiveness of any mask and masks should be designed to minimize leakage around the sides and by the nose. Mask fit and design will be addressed in a separate report.

Key conclusions from this technical report:

1. Non-woven and microfiber materials (e.g., Filti, Halyard) tend to have >80% filtration efficiency which is higher than woven or knit materials (Figure 4). However, some non-woven (e.g. Oly-Fun) and microfiber materials have filtration efficiency <20%. The integrity of non-woven materials may degrade after washing; after washing, the filtration efficiency of Filti declined by 50% (TSI-MaskFAQ).
2. Hydrophobic materials may be useful for blocking droplets (Aydin et al. 2020)
3. Many fabrics have a lower filtration efficiency than microfiber and non-woven materials. Natural fiber and synthetic knit have poor filtration efficiency of particles 300 nm in diameter. The 300 nm-particle filtration efficiency of woven materials is highly dependent on the characteristics of the weave (Figure 3). Quilt batting in general also has poor filtration efficiency of 300 nm particles and should be avoided.
4. Using multiple layers of the same material can improve filtration but each layer also increases the pressure differential and reduces breathability (Figure S2).
5. Fabrics (but not non-woven materials) should be washed in hot water and heat dried before making a mask in order to remove additives used to prepare or market the fabric

(such as starch) and prevent distorting the shape of the mask if shrinkage occurs after washing. Washing and/or hot-air drying may or may not alter material characteristics, so the filtration efficiency and pressure differential should be assessed after materials have been washed ~10 times. Non-woven materials should not be washed with soap and water because washing reduces their filtration efficiency.

6. While it is possible to electrostatically charge materials by rubbing them with latex, the efficiency gained from the induced charge dissipates substantially within 30-120 min (Zhao et al., 2020). Meltblown polypropylene, often used in N95 filtering facepiece respirator and surgical masks, do not maintain their charge after washing with soap and water, and, therefore, lose filtration efficiency (Viscusi et al., 2007).
7. Damp quilting cotton, cotton flannel, and dense, polyester craft felt did not have significantly different filtration efficiency than dry materials (but damp materials may have higher resistance, which was not tested) (O'Kelly et al., 2020).
8. Some materials contain or are treated with chemical or mechanical toxins or irritants and should not be used for mask materials.

Given the wide variability in approaches in the current literature, we strongly advise future work in this space focus on reproducible, replicable research, with clear and precise descriptions of both materials assessed and methods used for assessments. Specifically:

1. Studies should report sufficient details of fabrics tested and how they were acquired. Without these details, other researchers and cloth mask makers cannot obtain and test comparable fabrics. Details that should be included are
   - Material composition
   - Brand, product, and batch
   - Whether the material is knit, woven, or non-woven
   - If a woven fabric, thread count and weave
   - Close up photograph with scale
2. Methods and apparatuses used for evaluating material characteristics (filtration efficiency, pressure differential, etc.) should be described clearly and completely, with, if possible pictures or diagrams to assist replication.
3. Studies should use the same method of measuring filtration efficiency to allow direct comparison of results from multiple studies. The NIOSH method for testing N95 masks can be adapted for fabric/material samples; the method uses a TSI 8130 or TSI 8130a machine with a face velocity of 9-10 cm/s.
4. Consider using standardized test materials, e.g., reference media sheets, to evaluate filtration efficiency on the system. These sheets are available in filtration efficiency of 85%, 95% or 99% using a test process with the NaCl particles specified in the NIOSH standard. Use those same conditions and particles for the materials to be evaluated.
5. Critical factors to standardize and report in test methods include

- face velocity (or air flow and cross-sectional area of materials tested) mimicking light breathing, heavy working, coughing, and sneezing
- characteristics of particles used for filtration efficiency tests (e.g., mono- vs poly dispersed; size; type (NaCl vs polystyrene); charged vs. uncharged)
- sufficient details on the fabrics/materials tested that someone else could order the same fabric/material.

6. Washing and hot-air drying may or may not alter material characteristics, so the filtration efficiency and pressure differential should be assessed after materials have been washed ~10 times. Washing canvas material does not degrade filtration efficiency (TSI). Other materials have not been tested after washing.

2. Introduction

The global COVID-19 pandemic has led to increased need for universal face masking, to protect both the wearer and the public. Given the shortage of surgical masks and N95 filtering facepiece respirators, the general public has been advised to wear homemade or purchased cloth masks. Many types of masks can block large droplets, and a recent meta-analysis indicates that mask-wearing by members of the public is effective at reducing transmission rates for SARS-CoV-2 (Chu et al., 2020). Beyond reduction in droplet-based transmission, a second concern is the ability of cloth masks to filter smaller droplets and aerosols, which is the topic of this report. A mask's ability to protect against aerosols is dependent on the choice of mask fabric and the mask's design. A number of recent published and pre-print studies have evaluated the filtration efficiency and differential pressure (an indicator of breathability) of various materials. In this report, we provide a synthesis of those studies, make recommendations for mask material selection for small particle filtration, and also provide guidance for researchers.

One of the major limitations of the current studies is that the materials tested are often not specified with enough detail so that the experiment could be reproduced or that someone making masks could purchase the material. For example, a variety of materials called "cotton T-shirt" fabric have a wide range of thread counts, densities, and textures. The lack of characterization of the material also limits opportunities to understand which material properties are most important or to extrapolate from published results to similar materials.

To allow for experiment replicability, fabric characterization should include, at a minimum, **the composition of materials** (i.e. 100% cotton), **thickness** (grams per square meter), **fabrication technique** (woven, knit, or non-woven) and if applicable, **threads per inch.** Additional details on thread thickness and pitch would also be beneficial to ensure that appropriate comparisons are made. Since we do not fully understand which material properties most affect filtration efficiency and pressure differentials, there may be additional fabric characteristics that are important to report so that experiments can be repeated and experimental results can be effectively utilized.

Measurement methods vary across different studies. Methods used to assess the filtration efficiency of common materials vary widely in key parameters, including the type of particles used to assess efficiency, the rate at which air is pulled through the mask, etc. Additionally, many papers do not report all necessary parameters or techniques used to assess filtration efficiency. Without better understanding of the expected relationship between face velocity and pressure differential or filtration efficiency, it is a challenge to compare one study to another. Moreover, the specifications that could be used to compare one measurement to another (such as face velocity or area of the material under test) are not always reported.

Box 1: Definition of Terms

ΔP = pressure differential: pressure across a tested material under air flow at a specified face velocity perpendicular to the plane of the tested material
BFE = bacterial filtration efficiency
CMD = count median (geometric) diameter: the median diameter of particles in a distribution
FE = filtration efficiency
MMAD = mass median aerodynamic diameter
MPS = mean particle size
PFE = particle filtration efficiency
$\mathbf{P_{filter}}$ = filter penetration, given as a percent (typically 0–5%)
SD = standard deviation
VFE = viral filtration efficiency

- Common units of *pressure* are: Pa, mbar, and mm H_2O. Relevant unit conversion factors are 1.0 Pa = 0.001 kPa = 0.01 mbar = 0.102 mm H_2O.
- Common units of *volumetric flow* are L/min, L/s, cm^3/s, or CFM (cubic feet/min). Relevant unit conversion factors are 1.0 cm^3/s = 0.06 L/min = 0.0021 CFM.
- Common units for *face velocity* (also called "volumetric flow per unit area" or "flow velocity") are cm/s or m/s.

3. Fabric characterization

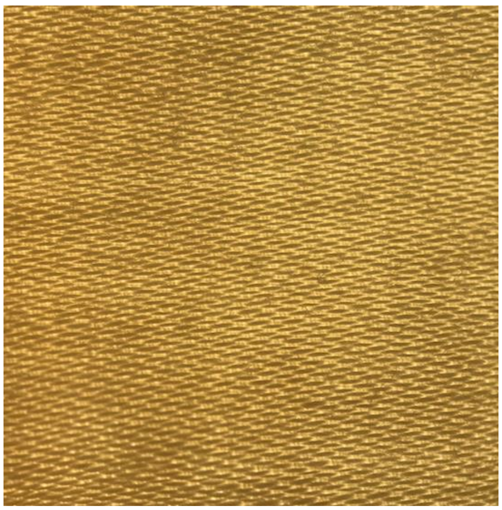
To understand how the pressure differential and filtration efficiency of fabrics can differ, it is helpful to understand the physical properties of fabrics, which can vary widely. Fabrics can be made from one or more natural or synthetic materials. Cotton, linen, silk, and wool are examples of natural materials. Nylon, polyester, polyurethane, and polypropyl acetate are examples of synthetic materials. Fabric density is typically described by threads per square inch (TPI) or grams per square meter. The thread diameter and pitch are also useful in distinguishing one fabric from another, but are rarely specified for a fabric. Whether or not a thread is twisted may also influence filtration efficiency. Twisting a thread reduces the effective surface area of the thread by hiding some fibers behind other fibers, making them less likely to interact with the air flowing through the fabric. Material is also characterized by whether the threads are knitted or woven together or composed of non-woven fibers. Knit fabrics may stretch over time, such that their pores will increase in size and their ability to filter particles will decrease (Zhao et al., 2020). Within manufacturing methods, some patterns can be more effective at filtering than others. For example, one study found that twill weave filters particles more effectively than satin weave (Sharma et al., 1998). Even after the threads are attached to each other, the fabric can be altered through post-processing, for example by cutting loops (e.g. velvet and corduroy) or leaving them intact (e.g. terrycloth and fleece). Together, thread diameter and pitch and manufacturing method influence filtration efficiency because they impact the average size of pores within the material. Nonwoven bonded fabrics have high filtration efficiencies. Nonwoven polypropylene and polyethylene are typical components of N95 filtering facepiece respirators and surgical masks.

Fabric may be hydrophobic (fabrics that repel water) or hydrophilic (fabrics that absorb water), depending upon the material or the presence of a fabric treatment. A hydrophobic fabric resists water penetration, while a hydrophilic fabric draws water into the fabric. Polyester is naturally hydrophobic, while cotton is naturally hydrophilic. The outer layers of surgical masks are hydrophobic. More hydrophobic materials in a mask will increase the relative humidity in the breathing space. For example, walking briskly with a hydrophobic surgical mask for 1 hr was found to increase the relative humidity and temperature in the mask dead space from approximately 55% to 90% and from 32 to 33.5 °C, respectively (Roberge et al., 2012); in the same study, 7% of participants reported significant facial warmth and 11% reported moisture buildup on the inside of the mask. The selection of material for a mask may influence the buildup of humidity on the inside of a mask; there is no published literature on the topic.

Fabric may also be naturally electrically charged or hold an artificially induced charge that improves filtration. Filters used in respirators, including N95 filtering facepiece respirators and most surgical masks, contain a layer of charged/electrostatic fabric that greatly enhances particle filtration (Rengasamy & Eimer, 2013). It has been suggested that some fabrics can temporarily hold an electrostatic charge, and can be recharged by mask wearer (e.g., by rubbing mask with latex glove) periodically (Zhao et al., 2020). But whether this is practical has not been determined. When a filter material is stripped of its electrical charge the filtration efficiency will decline. Electrostatic materials, such as meltblown polypropylene that is often used in N95 filtering facepiece respirators and surgical masks, do not maintain their charge and lose filtration efficiency after washing with soap and water (Viscusi et al., 2007); therefore the use of electrostatic materials should be considered carefully before including in a mask.

However, dipping N95 filtering facepiece respirators in tap water does not affect the filtration efficiency (Viscusi et al., 2007).

For a single layer of non-electrostatic material, small pore size may be associated with higher filtration efficiency (Zhao et al. 2020). Crudely, relative pore size of two materials can be determined by holding the material directly over the eye and up to a bright light (Image 1). For multiple layers of non-electrostatic material, the pore size of a single layer does not necessarily indicate the pore size of the stacked layers because the pores may be aligned or misaligned (Image 2).



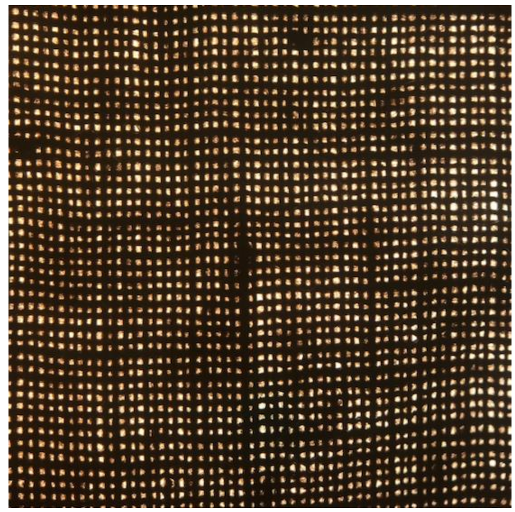
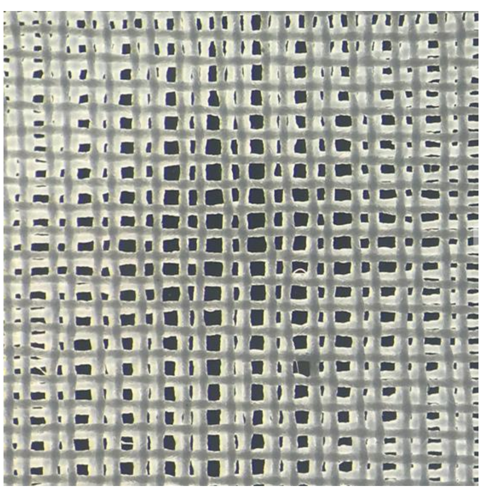


Image 1: Light visibility through a more dense fabric (left; 200 threads per inch (tpi) cotton pillow case), and less-dense fabric (right; 60 tpi open-weave cotton)



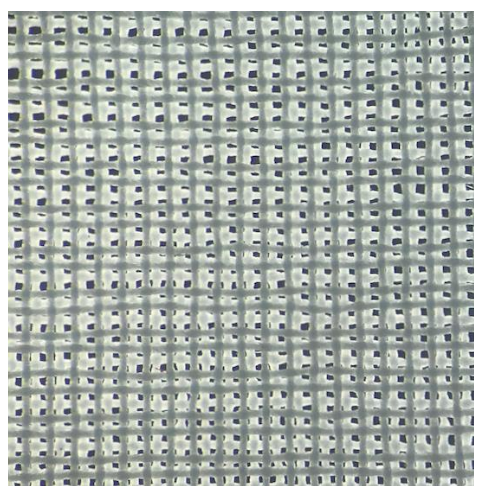


Image 2: Pores in 2 layers of 75 tpi polyester chiffon that are (left) aligned and (right) misaligned. These two microscopy photos were backlit using crossed-polarized illumination; this results in the holes being black and the fibers being brightly lit and helps eliminate the ambiguity between what is a bright hole and what is a bright fiber.

Cloth masks are meant to be washed before reuse. However, only a few materials have been evaluated before and after washing and little is known about the effects of soap, detergent, water and drying temperature on material integrity and associated filtration efficiency.

4. Pressure differential

Measurements of pressure differential

To be effective, a mask needs to both filter out particles and allow a person to breathe easily. The ease of breathing through a respirator, surgical mask, or cloth mask is typically measured by the pressure differential between the two sides of a mask as air flows through it at a rate similar to that during breathing. For materials that are homogenous (non-directional), the pressure differential measured when passing air from side A to side B is the same as the pressure differential measured when air flows from side B to side A. For a mask that is asymmetric or made of heterogeneous layers, the air pressure differential could be directionally-dependent (air pressure from side A to side B different than from side B to side A).

The pressure differential across a fabric or mask under a given face velocity is an indicator of how much the material impedes air flow. This is directly related to the breathability of a section of material: higher values of pressure differential indicate that the fabric or mask is harder to breathe through and lower values mean that it is more breathable.

Darcy's Law states that the difference between the pressure on the upstream side of a porous medium (the side that is first impacted by particles in the flow) and the pressure on the downstream side (the reverse side) is proportional to the face velocity of air through the medium (Xia et al., 2018). Darcy's law serves as a basis for the following general relationships:

- For a fixed volumetric flow rate, an increase in area of the tested material will decrease the face velocity and pressure differential. A near-linear relationship has been experimentally demonstrated for microfiber cloth (Xia et al., 2018).
- For a fixed face velocity, a larger area of a given material is not expected to substantially change the pressure differential, as both face velocity and pressure are already normalized by area (pressure is force per unit area). Inhomogeneities in flow and in the material could make small differences in the pressure differential when the area under test changes. Moreover, as there is always a boundary layer, the face velocity, even under laminar, unidirectional flow, is not exactly the same across the tested area and this will create a small difference in pressure differential when the tested area is varied.
- For a fixed face velocity, it is expected that pressure differential will increase with multiple layers of the same material because molecules will have to move through more of the material that has a given impedance and the pores of one layer are not expected to align perfectly with the streamlines and the pores in another layer.

However, the linear relationship between pressure differential and face velocity assumed by Darcy's law does not always hold, so measurements of pressure differentials obtained in experiments that used different face velocities should not be directly compared.

Standards for measuring pressure differential

There are a number of standards that define measurement methods and performance criteria for N95 filtering facepiece respirators and surgical masks. Some of these methods have been adapted to measure pressure across fabrics. There is also a new EU standard for fabrics (CWA 17553 (similar to AFNOR)). In general, testing methods specify the cross-sectional area of fabric to be tested and the volumetric flow rate across the fabric (or the face velocity), as well as the method for measuring pressure differential. The use of a standard face velocity is required to make the measured pressure differential comparable across different materials and different areas under test. Below are the maximum pressure differentials specified in the standards.

Table 1. Maximum pressure differentials specified by various standards. Note that the measurement methods vary among the standards.

Standard	N95 / FFP1-3			Surgical masks		Fabrics for masks
	Face velocity	Inhalation	Exhalation	Flow rate	Inhalation and Exhalation	
EU[1]	Inhalation: 95 L/min over 150 cm^2 = 10.6 cm/s Exhalation: 160 L/min over 150 cm^2 = 17.8 cm/s	[4] 210/240/300 Pa	210 Pa	8 L/min over 4.9 cm^2 = 27.2 cm/s	[5]40/40/60 Pa/cm^2 over 4.9 cm^2 (196/196/294 Pa)	70 Pa/cm^2
NIOSH[2]	85 L/min over 150 cm^2 = 9.4 cm/s	343 Pa	245 Pa	---	---	---
ASTM[3]	---	---	---	8 L/min over 4.9 cm^2 = 27.2 cm/s	[6] 50/60/60 Pa/cm^2 over 4.9 cm^2 (245/294/294 Pa)	---

1. EU = European Union
2. NIOSH = U.S. National Institute for Occupational Safety and Health
3. ASTM International (formerly the American Society for Testing and Materials)
4. For FFP1, FFP2, and FFP3, respectively
5. For surgical masks type I, II, and IIR, respectively. Note: Pressure per area does not have clear physical meaning and the theory behind these units is not clear.
6. For surgical mask barrier levels of 1, 2, and 3, respectively

5. Filtration Efficiency

Measurement of Filtration Efficiency

The filtration efficiency (FE) is a measure of the proportion of particles intercepted by the fabric or filter. The general approach to determining the filtration efficiency of a fabric or filter is to challenge the fabric with particles carried in air moving at a specific velocity, and to measure the particle concentration upstream from (before) the fabric and downstream from (after) the fabric. The difference between these two concentrations is used to determine the penetration rate (P_{filter}) or filtration efficiency (FE (%) = 100 - P_{filter}). filtration efficiency depends on the material/fabric but also on particle size and shape, particle charge, air velocity, (e.g., face velocity) and how the particles are counted (e.g., mass vs count). This same measure can be used for a whole mask or a sample of material. Filtration efficiency is considered to be the same no matter which direction the particles are through the fabric or filter. An FE = 95% means that 95% of particles (of a specified size) are intercepted by the filter, and would not be either inhaled by the wearer or expelled by the wearer into the air outside the mask.

Face velocity is inversely associated with filtration efficiency (Leung et al., 2010; Sanchez et al., 2013). One reason for this may be that at higher flow rates, a particle has less time to diffuse away from the path of convection that would cause it to hit a fiber (Leung et al., 2010). Another reason may be that a higher flow rate results in enlargement of pores in a material, which allows more particles to pass through the material. Inhomogeneities in the air flow (at any face velocity) or inhomogeneities in quality of the tested material result in a range of filtration efficiencies. The effect of these inhomogeneities may be larger for smaller test areas (because the entire sample, rather than a portion of the sample, is of lower quality). Thus, filtration efficiency measurements are expected to be more accurate if multiple samples of each material, each with a test area similar in size to the area of a face mask are tested.

Filtration efficiency is also dependent on the size of the particles used to challenge the material. Aerosols (<5000 nm) and droplets (>5000 nm) (Tellier, 2009) are blocked by filters according to different mechanisms, such as straining, inertial impaction, interception, diffusion and electrostatic attraction (Konda et al., 2020a). N95 filtering facepiece respirators and surgical masks rely on electrostatic attraction for their high filtration efficiencies. Materials that have been charged can lose their electrostatic properties and become unable to capture particles through electrostatic attraction and uncharged fabrics can be physically charged so that they are able to capture particles through electrostatic attraction. Given all of these processes, particles with a diameter of 300 nm are the most difficult to capture (Zhao et al., 2020): smaller particles are readily captured through diffusion and larger particles through interception and inertia. This aligns with the 300 nm particle diameter used in the most conservative (protective) filtration efficiency tests (NIOSH).

While the SARS-CoV-2 virus is 60–150 nm in diameter (Cai et al., 2020), respiratory viruses are emitted from the respiratory tract as free viruses; instead, they are released as droplets in respiratory secretions (Nicas et al. 2005). Thus, SARS-CoV-2, like other respiratory viruses, is present in particles with a variety of size ranges (Liu et al., 2020).

For details on national standards on methods for measuring filtration efficiency and differential pressure, please refer to the forthcoming N95DECON.org Technical Report on *Standards for Surgical N95 Filtering Facepiece Respirators and Surgical Masks*.

6. Literature review on fabric breathability and filtration efficiency

Methods for Literature Review

Pubmed and Google Scholar were searched for studies evaluating filtration efficiency and differential pressure for fabrics and other materials that might be used to make cloth masks. Keywords for search were:
((“fabric” OR “cloth”) AND “mask”) AND “filtration efficiency” AND (“breathability” OR “pressure drop” OR “pressure differential”). Article abstracts were reviewed and excluded if they mentioned materials that could not be easily procured by a typical US resident (such as activated carbon, nano-tubes, particles, fibers) or required an input of energy (such as a nanogenerator). One paper was excluded because it examined coating cloth with mangosteen extract, which is not widely available (Ekabutr et al., 2019). Only articles published in English were included in this review; one article in Korean (Jang & Kim, 2015) appears to be appropriate for inclusion other than the language requirement.

Factors considered in evaluation of the quality of the studies and their limitations were: whether the study was published in peer-reviewed scientific journal, whether standard methods were used for evaluation of filtration efficiency and pressure differential, whether methods for fabric evaluation were described in enough detail so that the study could be replicated, whether the fabric was described in adequate detail so that it could be acquired by others in order to replicate the study, and whether multiple samples were tested. We used the evaluation results to rank the studies and determine whether or not they should be included in the data analyzed in the discussion.

We report results from literature in terms of face velocity and pressure, both of which already have the relevant quantities (force and volumetric flux) normalized by the area that is being measured. In this way, measurements can be more easily compared across experiments that use different areas of materials. Such a comparison, when the face velocity is the same across experiments, assumes that measurements are made with flow that is laminar and perpendicular to the plane of the material under test with negligible edge effects, flow imperfections, and material inhomogeneities.

Results

The methods used in each study is described along with the primary findings and the limitations of the study; studies are arranged in order of quality (see Supplemental Information). Two-dimensional graphs of the findings from each study on filtration efficiency (%) by differential pressure (Pa) were prepared for a single layer of fabric (Figure 1A) and multi-layered fabrics/fabric combinations (Figure 1B). The scales are the same for all graphs to allow for comparisons. Filtration efficiency and pressure differential results within and across studies were highly variable, even for what are listed as the same materials. Graphs were not prepared for those studies that had a very limited number of data points or presented findings that could not be translated into standard measures of filtration efficiency (%) or differential pressure (Pa).

Several studies are not included in the results because of their essential aspects of their methods were undefined (i.e. Konda et al., 2020a), highly inaccurate (i.e. pressure differentials from Wang Y 2020), entirely incomparable to other studies because of very high face velocities used for testing (i.e. Aydin et al., 2020, Lustig et al. 2020, O'Kelly et al., 2020) or particles/organisms tested (i.e. Amour et al., 2020) (Tables 2-3).

Detailed summary of each study

TSI, 2020

TSI, the manufacturer of the machines used to test N95 filtering facepiece respirator filtration efficiency and pressure differential following the NIOSH method, tested more than 100 fabrics and fabric combinations that were selected, prepared, and sent to TSI for testing by a community mask-maker. TSI conducted the fabric tests using TSI 8130a and generally followed the NIOSH procedure (42 CFR part 84) using polydisperse uncharged NaCl particles to challenge the material. They maintained a flow rate of 60 L/min across 100 cm^2 to produce a face velocity of 10 cm/s, similar to the NIOSH flow rate of 85 L/min over 150 cm^2 (face velocity = 9.4 cm/s). Many of the fabrics tested were described in adequate detail for replication. Multiple samples of some fabrics were also tested. [https://www.maskfaq.com/test-results].

A primary study finding was that some non-woven materials had high filtration efficiencies. One layer of Filti material had a filtration efficiency of ~87% and was still relatively breathable (ΔP = 83 Pa); and ~98% for two layers, but the pressure differential was high (143 Pa). Similarly, one layer (the blue sheet) of Halyard H600 surgical instrument wrap had a filtration efficiency of ~63% while the blue and white layers together had a filtration efficiency of ~85%. One layer of Evolon had 58% filtration efficiency and one layer of Pellon 360 had ~35% filtration efficiency while two layers had ~66% filtration efficiency. Materials with poor filtration efficiency included Jo-Ann Stores' stretch chiffon as well as samples of spandex, sports nylon, and quilter's cotton. One material, silky solid charmeuse, exceeded the NIOSH standard for pressure differential (245 Pa), indicating that it would be too difficult to breathe through to serve as mask material. Multilayer and mixed fabrics were also tested.

An important finding was the effect of washing (front-loading washer, standard temperature setting, laundry detergent only, standard dryer heat setting (Schempf 2020) on fabric filtration efficiency and pressure differential. Washing DuckCanvas had little effect on filtration efficiency (147 to 15%) or pressure differential (90 to 101 Pa). However, washing two layers of Filti reduced filtration efficiency from 98% to 46% and the pressure differential dropped from 142 to 40 Pa. The effect of washing and drying the Pellon and Evolon was not examined.

The primary limitation of the study was that only one sample of each fabric type/condition was tested. This high-quality study used NIOSH methods and a thorough description of materials.

Rengasamy *et al.* 2010

Rengasamy et al. (Rengasamy et al., 2010), in a peer-reviewed paper, evaluated various combinations of cotton/polyester sweatshirts, T-shirts, towels, and scarfs, as well as N95 filtering facepiece respirator filter media and three brands of purchased cloth masks. The pressure differential across materials was only evaluated at 5.5 cm/s (33 L/min). This lower flow rate is approximately the same as what was used in Zhao 2020, et al. (Zhao et al., 2020). Filtration efficiency was tested using polydispersed and monodispersed NaCl using a TSI 8130, which provides a test area of 100 cm^2, and flow rates of 5.5 cm/s and 16.5 cm/s.

The primary study finding was that all the knitted or woven fabrics perform substantially worse than the N95 filtering facepiece respirator filter material when tested with polydispersed particles. Efficiencies ranged from 10–60%, with three brands of towels and one brand of sweatshirt with the best filtration efficiency and T-shirts and scarfs demonstrating a much lower filtration efficiency. For the monodispersed particle trials, filtration efficiency was slightly lower when face velocity increased from 5.5 cm/s to 16.5 cm/s. As expected, filtration efficiency for particles 300 nm MMAD is slightly lower than for larger particles and much lower than for smaller particles. For polydispersed particles, increasing face velocity did not affect filtration efficiency. There was a wide variation in performance between different cotton/polyester blends and it is unclear how much of that is due to composition or some other unspecified factor.

The primary limitation of the study was that the characteristics of materials were not presented in adequate detail to allow for the experiment to be replicated or for consumers to identify/purchase the most effective fabrics/materials.

Wang D. *et al.* 2020

In this non-peer-reviewed preprint, Wang et al (Wang et al., 2020) evaluated 17 materials and 15 combinations of materials for pressure difference, resistance to surface wetting, particle filtration efficiency, and bacterial filtration efficiency. They followed the China standard for surgical masks (YY0469-2011) which requires a pressure differential of ≤49 Pa, resistance to surface wetting of ≥3 [unitless], particle filtration efficiency (PFE) of ≥30%, and bacterial filtration efficiency (bacterial filtration efficiency) of ≥95%. The 17 individual materials included materials from various clothing and household items, including a diaper, tea towels, medical non-woven material, and a non-woven shopping bag. They report the brand (e.g. UNIQLO) and composition (e.g. 100% cotton) of candidate materials. The particle filtration efficiency test process was similar to the NIOSH method but used a flow rate of 30 L/min instead of 85 L/min.

Pressure differential was evaluated first in order to exclude materials from further study with a pressure difference > 49 Pa under a flow rate of 8 L/min through 4.9 cm^2 of material as measured with a Qingdao SRP ZR-1200. This corresponds to a face velocity of 27.2 cm/s. particle filtration efficiency was evaluated using the TSI 8130 Automated Filter Tester at 30

L/min through a cross-sectional area of 100 cm^2 using a NaCl aerosol (median diameter of particle count 75 ± 20 nm). Bacterial filtration efficiency was measured using *Staphylococcus aureus* in an airflow of 28.3 L/min.

Eleven of the 17 single-layer materials met the pressure differential criterion of ≤49 Pa. Some of the materials that failed the pressure differential test were jeans, a diaper, and two pillowcases. Of the 11 that met the pressure differential criterion, only the medical non-woven material met the particle filtration efficiency of >30% (42 ± 2%). The other materials, such as the T-shirt, fleece, tea towel and non-woven shopping bag, had particle filtration efficiency ranging from 6 to 14%. None of the materials met the high standard for bacterial filtration efficiency (≥95%). Of the 15 double-layer materials evaluated, 12 passed the pressure differential criterion and 7 of those 12 had a filtration efficiency >30%. The particle filtration efficiency of the fleece sweater plus hairy tea towel was 56 ± 1%, roughly equivalent to that of the double-layer non-woven material (54 ± 1%).

This was the only study that conducted both particle filtration efficiency and bacterial filtration efficiency tests on the same material combinations; particle filtration efficiency tests the filtration of particles <300 nm while bacterial filtration efficiency tests the filtration of bacteria of 3 um in size. There was no consistent relationship between particle filtration efficiency and bacterial filtration efficiency. For four material combinations particle filtration efficiency ranged from 35 to 56% while bacterial filtration efficiency was less than half with values from 16 to 24%. For three other material combinations particle filtration efficiency ranged from 40 to 54% while the bacterial filtration efficiency ranged from 88 to 93%.

Wang Y. *et al.,* unpublished 2020

Wang Y. and colleagues evaluated the filtration efficiency and pressure differential of a wide range of materials and reported the results in a publicly available dataset (https://yangwangpmtl.wordpress.com/). For the first 169 samples, the pressure differential was measured by a scanning mobility particle sizer (TSI SMPS) with a resolution of 0.1 kPa and an assumed accuracy of +/- 0.5 kPa; for the later tests a digital manometer with a 0.001 psi (6.9 Pa) resolution and accuracy of +/-0.3% accuracy was used (personal communication with Wang Y, 14 June 2020). Test aerosols (NaCl) were generated by a constant output atomizer (TSI 3076) and filtration efficiency was measured at 300 nm with a scanning mobility particle sizer (SMPS, TSI 3936). The filtration efficiency and pressure differential were tested at face velocities of 9 cm/s (60.0 L/min through 111 cm^2), 15 cm/s (60.3 L/min through 67 cm^2), 23 cm/s (60.3 L/min through 43 cm^2).

Air filters had the highest filtration efficiencies and relatively low pressure differentials compared to the other materials tested in this study. Microfiber materials had filtration efficiencies >50% but relatively high pressure differentials. The filtration efficiency of knit and woven cottons was less than 40%.

The primary limitation of this study is the low resolution of the pressure differential measurement, 100 Pa. As a result, the average pressure differentials reported were an order of magnitude higher than in other studies, for the same material. Given the unreliability of the measurement, no pressure differentials are reported for this study.

Zhao *et al.* 2020

Zhao et al. (Zhao et al., 2020), in a peer-reviewed report, evaluated different materials for pressure differential and filtration efficiency using a modified NIOSH method. The modification was the use of 32 L/min volumetric flow rate over a surface area of 100 cm^2, yielding a face velocity of 5.3 cm/s. Materials were imaged using a scanning electron microscope. The materials were also tested for filtration efficiency after electrically charging them by rubbing them with latex or nitrile gloves.

The primary finding of this study was that materials with an electrostatic charge have higher filtration efficiency than uncharged materials. After rubbing the materials to create an electrostatic charge, all materials except for cotton showed increased filtration efficiency. However, this gain in filtration efficiency decayed rapidly. Polyester and silk lost almost all of the efficiency associated with the induced charge 30 minutes after the charge was induced; polypropylene lost >60% of the induced efficiency after 60 minutes and nylon lost >90% of the induced efficiency after 120 minutes. Data from this study was featured in WHO's guidance on community mask wearing (WHO 2020; When and how to use masks).

The filtration efficiency of meltblown polypropylene used in two surgical-style masks and an N95 filtering facepiece respirator were 19, 33 and 96%, respectively. The type of spunbond polypropylene tested in this study had a low pressure differential and a filtration efficiency of only 6%. Cotton, polyester, nylon and silk had filtration efficiency of 5–25% and polypropylene spunbond had filtration efficiency of 6–10%. The differences in filtration efficiency for cotton materials of different weights, based on this imaging, was attributed to pore size. Polyester had similar properties as cotton. With regard to pressure differential, nylon exhibited a pressure differential of 244 Pa, an order of magnitude or two higher than the other materials and higher than the tested surgical-style masks and filtering facepiece respirator material.

The primary limitation of this study was that the characteristics of materials were not presented in enough detail to allow for the experiments to be replicated or for consumers to identify/purchase the most effective fabrics/materials.

Jung *et al.* 2014

In this peer-reviewed study, Jung et al (Jung et al., 2014) evaluated the particle filtration efficiency of 44 different models of masks, including so-called yellow sand (dust storm protection) masks, quarantine masks, medical masks, and handkerchiefs. All adult yellow sand masks tested in this study met KF80 regulatory standards as filtering facepiece respirators; all quarantine masks either met KF94 or NIOSH N95 regulatory standards as filtering facepiece respirators. The authors used the TSI 8130 Automatic Filter Tester and conducted tests according to NIOSH procedures and, separately, the procedures from the Korean Food and

Drug Administration. Since 314 cm^2 of fabric was tested rather than ~150 cm^2 tested in the NIOSH protocol, but the flow rate was the same, the face velocity in this study was 4.5 cm/s instead of 9.4 cm/s as in the NIOSH protocol. Additionally materials in this study were not preconditioned as specified in NIOSH standard TEB-APR-STP-0003/0007/00059. The Korean Food and Drug (KDFA) method was similar to the NIOSH method except that the NaCl concentration was 1%, the filtration flow rate was 95 L/min, and the pressure differential flow rate was 30 L/min. The authors also examined whether penetration changes as load of particles on the mask increases. Results of filtration efficiency were similar when the materials were tested with the two protocols ($p = 0.12$), so only the results obtained with the modified NIOSH protocol are reported here.

The primary finding of this study was that handkerchiefs had a very low average filtration efficiency, 13%, even when four layers were used. The results from the other masks are not described here because they were not cloth masks.

The primary limitation of this study was that the characteristics of some of the masks tested were not presented in enough detail to allow for comparisons with other studies or for the experiments to be replicated.

Zangmeister *et al.* 2020

Zangmeister et al. (Zangmeister et al. 2020), in a peer-reviewed report, evaluated 41 fabric materials and combinations of fabrics for filtration efficiency and pressure differential using EN 1822 and ISO 29463 methods (polydispersed charge neutralized NaCl 50-825 nm). All but three of the fabrics were tested as two layers. The fabrics were also micro-imaged. The cross-sectional area of fabrics tested was 4.0 cm^2 and the face velocity was 6.3 cm/s, for a flow rate of 1.5 L/min. For each fabric, five pieces were tested. Filtration efficiency curves for each fabric were generated for 50 to 825 nm size particles, and the particle size with the lowest filtration efficiency, FE_{min}, was reported.

The primary finding from this study was that the filtration efficiency of the cotton fabrics tested was less than 35%, and the filtration efficiency of the polyester knit fabrics tested was less than 25%. The fabrics with the best filtration efficiency were woven cotton with a moderate to high thread count and woven synthetics with moderate thread count. Cotton material FE_{min} ranged from 7.1 to 33.6% (down proof ticking had the highest FE_{min}), with differential pressure ranging from 28 to 334 Pa (down proof ticking had highest Pa). Polyester knits and weaves FE_{min} ranged from 1.3 to 21.4% with differential pressure ranging from 13 to 217 Pa. One to 5 layers of lightweight flannel (cotton fiber poplin weave) were tested and filtration efficiency and pressure differential increased monotonically with the number of layers. The manuscript supplement has a detailed description of weave types.

The primary limitation of this study was that the FE_{min} was reported only for one particle size that ranged from 146 to 437 nm, depending on the fabric tested. Therefore, the results are difficult to compare to most studies that reported filtration efficiency for all particles <300 nm.

O'Kelly *et al.* 2020

In this non-peer-reviewed pre-print, O'Kelly et al. (O'Kelly et al., 2020) performed an evaluation of twenty widely-available fabrics and other materials (hereafter collectively referred to as "fabrics"). For each fabric, a total of ten samples were taken from at least two sections of the fabric. Fabrics were washed and dried prior to assessment; exact details regarding the effect of this washing step were not reported but shrinkage was noted. Breathability was assessed using a qualitative test; two members of the research team held fabric 'tightly' over their mouth and inhaled sharply through their mouth. Fabrics were scored from 0–3, where 0 represented no difficulty breathing and 3 represented great difficulty in breathing. Filtration efficiency was investigated using two TSI P-Trak 8525 ultrafine particle counters. Fabric was held across a 2.5 cm diameter tube through which air flowed at 1650 cm/s. Only particles <100 nm were counted. Additionally, the impact of dampness was evaluated by applying 7 mL of filtered water to the 5 cm square section of material.

The primary findings from this study was that all tested fabric combinations with high filtration efficiency, a single layers of denim and a windbreaker, were harder to breathe through than an N95 filter material. The combinations with highest filtration efficiency included cotton quilting fabric with quilt batting and fusible interfacing; cotton quilting fabric with cotton flannel, and fusible brand lightweight interfacing; and cotton flannel with minky. Moistening was associated with only minor changes in filtration efficiency for quilting cotton, cotton flannel, and craft felt, while denim showed a large decrease in filtration efficiency when moist. Washing caused the wool felt to shrink but did not change the material's filtration efficiency.

The primary limitation of this study was that the type of particle used to test the materials for filtration efficiency and dispersion of particle size were not specified. They state that they measured all particles <0.1 μm in diameter, but the P-trak model 8525 used measures particles 0.2-1 μm in diameter without further size selection. As a result, the filtration efficiency of particles 300 nm in diameter cannot be determined. Another limitation of the study was that breathability was measured subjectively, with investigators rating their breathing difficulty when the fabric was placed over their face; the amount of leakage was not measured. Finally, the characteristics of materials were not presented in enough detail to allow for the experiments to be replicated or for consumers to identify/purchase the most effective fabrics/materials.

Wilson, unpublished

This study sought to determine the differential pressure across layers of fabric relative to that of a Halyard surgical mask. The apparatus involved pressing the fabrics against a 1 cm^2 aperture build of steel washers using an O-ring with 1 kg force. The differential pressure across a Halyard surgical mask was 2 inches H_2O (500 Pa), as assessed by a manometer with resolution 0.01 inches H_2O (personal communication, Robert E Wilson, 2 July 2020).

The primary finding from this study was that every additional layer of material increases pressure differential (Figure S2), which supports intuition. For some materials (e.g., cotton and polyester) this increase is approximately linear (i.e. doubling the layers doubled the pressure differential). However, for other materials the effect of layer is not so precise and there may be large differences in the effect of layer for the same material (e.g., chiffon, interfacing, microfiber).

The primary limitation of this study is that it was not clear to what extent the flow rate changed when materials were tested after the flow rate was set by the surgical mask. If the flow rate changed to a large degree then it may be difficult to compare the pressure differentials between materials.

Aydin *et al.* 2020

This non-peer-reviewed pre-print (Aydin et al., 2020) reported blocking efficiency and pressure differential on 10 different fabrics. They characterized fabrics by weight, hydrophilicity, and texture. Filtration efficiency was measured with 100 nm fluorescent beads in water that were ejected with an inhaler toward the mask at approximately 1500 cm/s (corresponding to an air flow of 7065 L/min). Beads that penetrated the mask were counted. High-speed videography was used to determine particle velocity and to image how particles were caught or passed through single or double layers of fabric. Pressure differential was estimated by mounting the fabric across a tube of area 0.785 cm^2 with air moving through at 5 measured face velocities ranging from less than 10 cm/s to more than 300 cm/s while pressure was measured. This non-standard protocol was meant to mimic and record what happens when a person infected with SARS-CoV-2 sneezes into a mask.

The primary limitation of this study was that materials were not presented in enough detail to allow for the experiments to be replicated or for consumers to identify/purchase the most effective fabrics/materials. The face velocities used when determining filtration efficiencies are 50-300 times higher than the face velocities used in other studies and should not be comparable since filtration efficiency is expected to drop substantially with a dramatic increase in face velocity. Hence the results from this study are not presented in the discussion section.

Lustig *et al.* 2020

In a peer-reviewed study (Lustig et al., 2020), 37 unique combinations of fabrics were evaluated for a permeability index against nanoparticles 10–10000 nm in size. The volumetric airflow through the material (0.785 cm^2) was 14 L/min at steady-state so the face velocity was 297 cm/s. Filtration was assessed by spraying an aqueous solution of fluorescent nanoparticles onto the material and the nanoparticles that passed through the material were captured on a glass slide. Results for each material were expressed as “fractional transmission" and compared to a reference 5-layer N95 filtering facepiece respirator (3M 1860S).

The primary limitation of this study was that the face velocities used when determining filtration efficiencies are 10-60 times higher than the face velocities used in other studies and should not be comparable since filtration efficiency is expected to drop substantially with a dramatic increase in face velocity. Additionally, the study did not test the pressure differential across the material combinations, so it is unclear whether material combinations with high filtration efficiency are useful for mask fabrication. Hence the results from this study are not presented in the discussion section.

Davies *et al.* 2013

In a peer-reviewed and widely-cited paper, Davies et al. (Davies et al., 2013) tested the filtration efficiency of common household materials and a surgical mask against penetration by bacterial and viral aerosols. Materials tested include a scarf, a tea towel, a pillowcase, a cotton mix, linen, silk, and vacuum cleaner bag. No further details are given on these samples. In addition to testing filtration efficiency, volunteer-made masks were also tested on human volunteers for fit.

The primary finding of this study was that a tea towel (with unspecified fabric characteristics) showed the highest performance in filtration efficiency following the surgical mask and vacuum cleaner bag. When two layers of a given fabric were tested, both the filtration efficiency and pressure differential increased.

The primary limitation of this study is that the area of the tested circular coupons was not given, so the face velocity could not be calculated. Consequently, it was unclear how the results compare with results from other studies. Additionally, the pressure measurement technique was not specified and no units were given on pressure measurements, so it was unclear if the materials would pass pressure differential standards or not. As microorganisms were used to test materials, these measurements cannot be directly compared to measurements that rely on particles (typically NaCl particles). Finally, the characteristics of materials were not presented in enough detail to allow for the experiments to be replicated or for consumers to identify/purchase the most effective fabrics/materials.

Konda *et al.* 2020

In a peer-reviewed study, Konda et al. (Konda et al., 2020a) studied filtration efficiency and pressure differential across materials including N95 filtering facepiece respirator and surgical mask materials, cotton (labeled with threads per inch), chiffon, and natural silk.

A fundamental limitation of the study was explained in a later correction (Konda et al., 2020b): Because flow rate was measured only without material impeding the flow, the actual flow rate at which tests were performed was lower than stated and varied with each material. This design flaw makes it impossible to compare filtration efficiency or pressure differential across the study's results. It also may explain puzzling experimental results, such as a pressure differential that did not double as expected for two layers of material. Because this limitation invalidates many of the study's original conclusions, results from (Konda et al., 2020a) are not summarized further.

Amour *et al.* 2020

In this non-peer-reviewed pre-print (Amour et al., 2020), tested four cloth, one N95 filtering facepiece respirator, and two medical masks that were commercially available in Dar es Salaam, Tanzania using non-standard methods. *S. aureus* ATCC 25923 and *E. coli* ATCC 25922 were used to prepare an inoculum that was sprayed at the masks at approximately 31.5 ft^3/min. After spraying, the interior of the mask was swabbed at 0 and 4 hr and the samples incubated and counted. The authors did not assess masks for breathability.

The primary finding of this study was that no mask had an interior surface that was positive for both *S. aureus* and *E. coli* at 0 hr and only one mask, made of cloth, was positive for both when sampled at 4 hr. All positive samples contained only 1 colony-forming unit.

The primary limitation of this study was that it was not clear that the swabbed surface area of the interior of the mask was consistent across all masks; masks with more surface area would be more likely to be positive for bacteria. While the cloth masks were described as two layers of kitenge fabric with or without a middle filter layer, the characteristics of materials were not presented in enough detail to allow for the experiments to be replicated. This study only qualitatively assessed filtration efficiency so the results are not discussed further in this report.

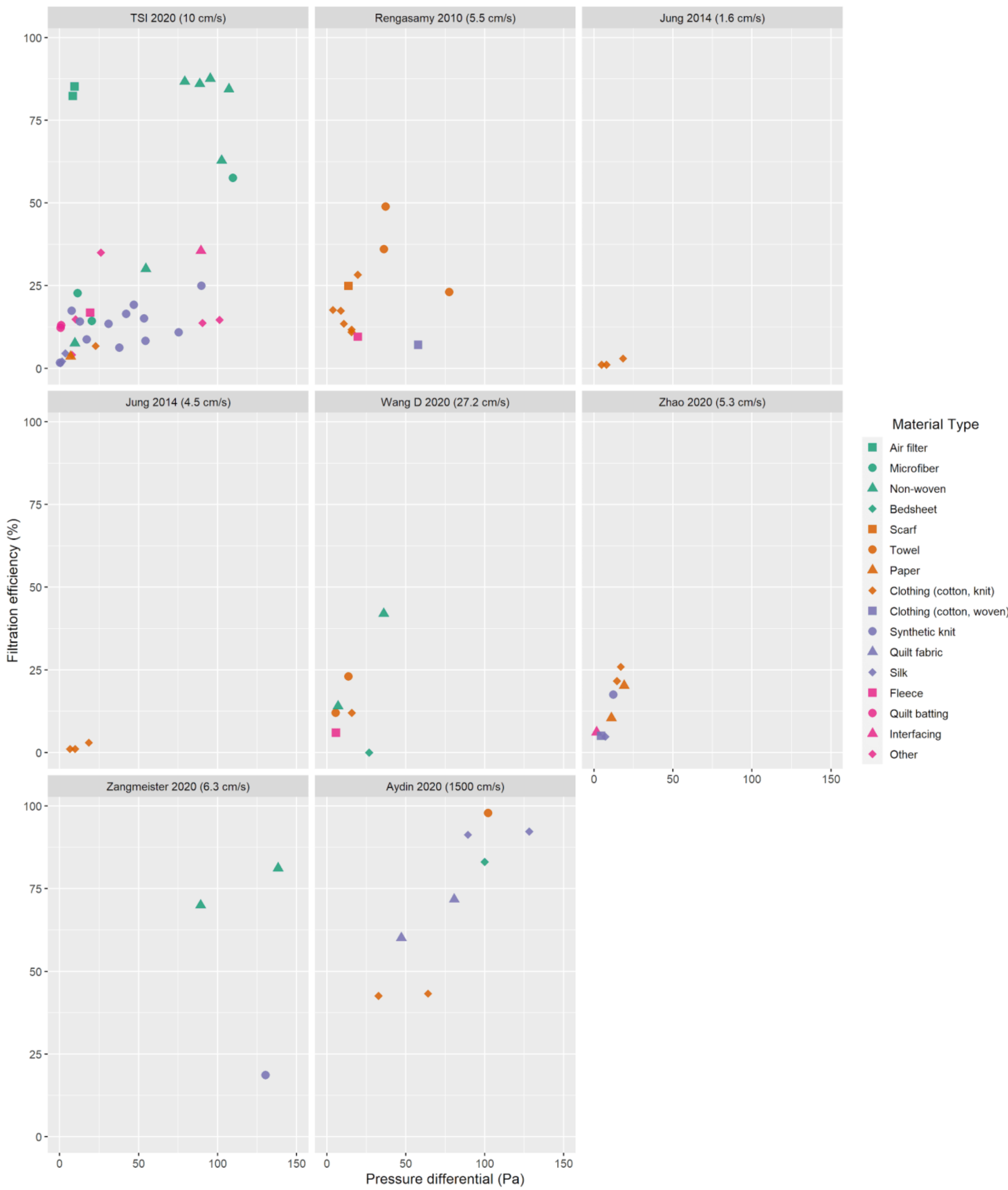

TSI 2020 (10 cm/s)
Rengasamy 2010 (5.5 cm/s)
Jung 2014 (1.6 cm/s)
Jung 2014 (4.5 cm/s)
Wang D 2020 (27.2 cm/s)
Zhao 2020 (5.3 cm/s)
Zangmeister 2020 (6.3 cm/s)
Aydin 2020 (1500 cm/s)
Filtration efficiency (%)
Pressure differential (Pa)
0
25
50
75
100
0
50
100
150
Material Type
Air filter
Microfiber
Non-woven
Bedsheet
Scarf
Towel
Paper
Clothing (cotton, knit)
Clothing (cotton, woven)
Synthetic knit
Quilt fabric
Silk
Fleece
Quilt batting
Interfacing
Other

Figure 1: Filtration efficiency vs. pressure differential for (A) single and (B) multiple layers of various materials for studies with most material pressure differentials of <150 Pa. Single data points from Aydin 2020 and Rengasamy 2010 studies omitted from (B) for clarity.

Discussion

Study quality

Studies varied in quality; many of the studies are not yet peer-reviewed. All but one study (Wilson data) tested filtration efficiency, most also tested pressure differential. Most used minor variations on a standard method for testing filtration efficiency and pressure differentials. Most methods for assessing pressure differential varied from standard methods on cross-sectional area of material tested and face velocity making them difficult to compare (Table 3). Some studies did not report the cross-sectional area of the material through which air flowed. For measuring filtration efficiency, some studies used the NIOSH polydisperse NaCl and reported filtration efficiency for particles <300 nm, while other studies used monodisperse particles or reported filtration efficiency at specific sizes, e.g., 100, 300, 1000 nm. Two studies tested bacterial filtration efficiency with bacterial size of 3.0 um. Airflow velocity or flow rate differed between studies. In addition, some studies measured filtration efficiency with mass weighting MMAD of particles while others used just particle count CMD. Unfortunately, most studies did not characterize fabrics in enough detail to reproduce the experiments (Table 2). Only a few studies evaluated the impact of washing and drying.

Table 2. Quality assessment of studies

Reference	**Peer-reviewed**	**Standard methods used?**	**Quantitative pressure differential available (Pa)**	**Quantitative filtration efficiency available**	**Fabrics described in enough detail so study could be replicated**	**Number of replicates**
Aydin et al., 2020	No	Non-standard	Yes	Yes	Yes	?
Davies et al., 2013	Yes	Similar to ASTM BFE, but different bacterial sizes	No (no units)	Yes	No	9
Jung et al., 2014	Yes	NIOSH and KDFA	Yes	Yes	No	3
Konda et al., 2020a	Yes, with substantial corrections	Like ASTM F2299 PFE, but numerous deviations	No	Yes	No	7
Lustig et al. 2020	No	Non-standard	No	Yes	Yes	9-27
O'Kelly et al., 2020	No	Non-standard	No	Yes	Yes	10
Rengasamy et al., 2010	Yes	NIOSH (33 L/min instead of 85 L/min)	Yes	Yes	No	3
TSI, 2020	No	NIOSH (60 L/min instead of 85 L/min)	Yes	Yes	Yes	1
Wang et al., 2020	No	NIOSH (30 L/min instead of 85 L/min) & Chinese BFE standard YY0469-2011	Yes	Yes	No	5
Wang Y 2020	No	Non-standard	Yes	Yes	Yes	2-8
Wilson R 2020	No	Non-standard	No	No	Yes	1
Zangmeister et al. 2020	Yes	EN 1822	Yes	Yes	Yes	5-11

Zhao et al., 2020	Yes	NIOSH (32 L/min instead of 85 L/min)	Yes	Yes	No	3

Table 3: Summary of experimental methods across studies.

Reference	**Area under test (cm^2)**	**Face velocity (cm/s)**	**Test particle**	**Particle size**	**Particle dispersion**
Aydin et al., 2020	0.785	From <10 to >300 for ΔP, 1500 for FE	Fluorescent beads	100 nm	Monodisperse
Davies et al., 2013	Not specified	Not specified	*B. atrophaeus*, Bacteriophage MS2	95–125 nm, 23 nm	Polydisperse & Monodisperse
Jung et al., 2014	214	1.6 and 4.5	NaCl aerosols	75 ± 20 nm CMD	Polydisperse
Konda et al., 2020a	59	Not determined	NaCl aerosols	<300 nm: 10-178 nm, >300 nm: 300-600 nm	Polydisperse
Lustig et al., 2020	0.785	297	Nanoparticles	10-10000 nm (460 nm CAD)	Polydisperse
O’Kelly et al., 2020	5.1	1650	Not specified	<100 nm	Polydisperse
Rengasamy et al., 2010	100	5.5 for ΔP, 5.5 & 16.5 for FE	NaCl aerosols	75 ± 20 nm CMD & Monodisperse: 20, 30, 40, 50 , 60, 80, 100, 200, 300, 400 nm CMD	Polydisperse & Monodisperse
TSI, 2020	100	10	NaCl aerosol	75 ± 20 nm CMD	Polydisperse
Wang et al., 2020	4.9 for ΔP; 100 for FE	27.2 for ΔP, 5 for FE	NaCl aerosols	75 ± 20 nm CMD	Polydisperse
Wang Y., 2020	111, 67, 43	9,15, 23	NaCl aerosols	300 nm MMAD	Monodisperse
Zangmeister et al. 2020	4.0	6.3	NaCl aerosols	50 - 825 nm	Polydisperse
Zhao et al., 2020	100	5.3	NaCl aerosols	75 ± 20 nm CMD	Polydisperse

Effect of face velocity

Increasing face velocity is associated with little to no effect on filtration efficiency, a decrease in filtration efficiency or an increase in filtration efficiency (Figure 2). Microfibers, non-woven, bedsheets, and woven cotton demonstrated little change in filtration efficiency as face velocity increased. Some cotton knit fabrics declined in filtration efficiency while others appear to be unaffected. In one study that compared face velocity of 5.5 cm/s to 16.5 cm/s, the higher face velocity was associated with slightly lower filtration for monodispersed particles but no significant difference in filtration for polydisperse particles (Rengasamy et al., 2010). Despite differences between studies in face velocities there is value in comparing the combined results of all studies to assess general trends.

An increasing face velocity is associated with a monotonic increase in pressure differential but the slope varies depending on the material (Aydin et al., 2020).

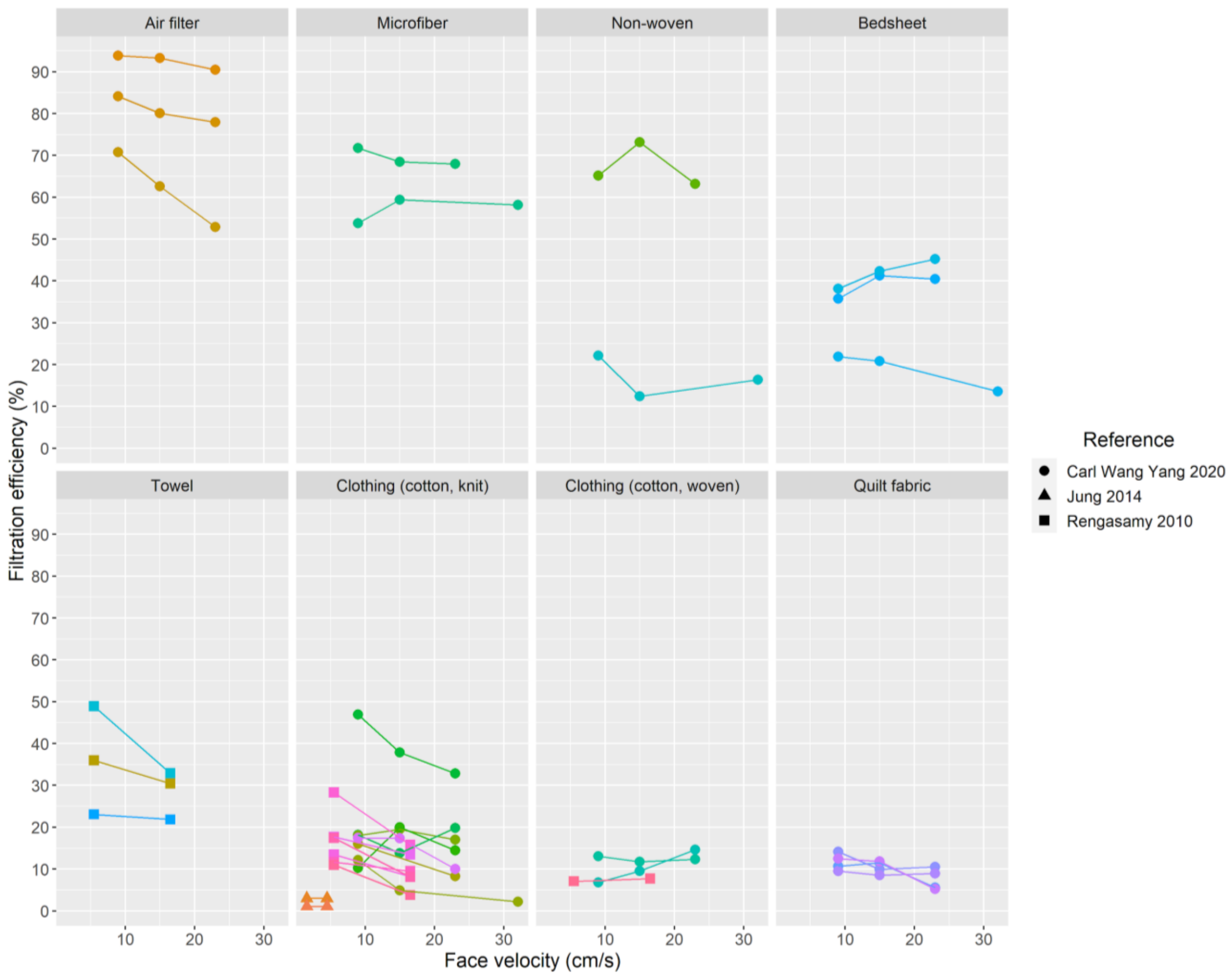


Figure 2. Face velocity vs. filtration efficiency (%) for a single layer of various materials.

Filtration efficiency of various materials

The combined filtration efficiencies across all studies for a single layer of material are presented in Figure 4A. For what are described as the same material types there is a wide range of values for filtration efficiency. These differences may be due to differences in fabric and differences between test methods. However, there are some trends that emerge. Some microfiber and non-woven materials had markedly higher filtration than other materials. Single layer bandanas, interfacing, scarves, non-cotton clothing, cotton clothing, paper materials, towels, and quilt fabric all have median filtration efficiencies of less than 25%.

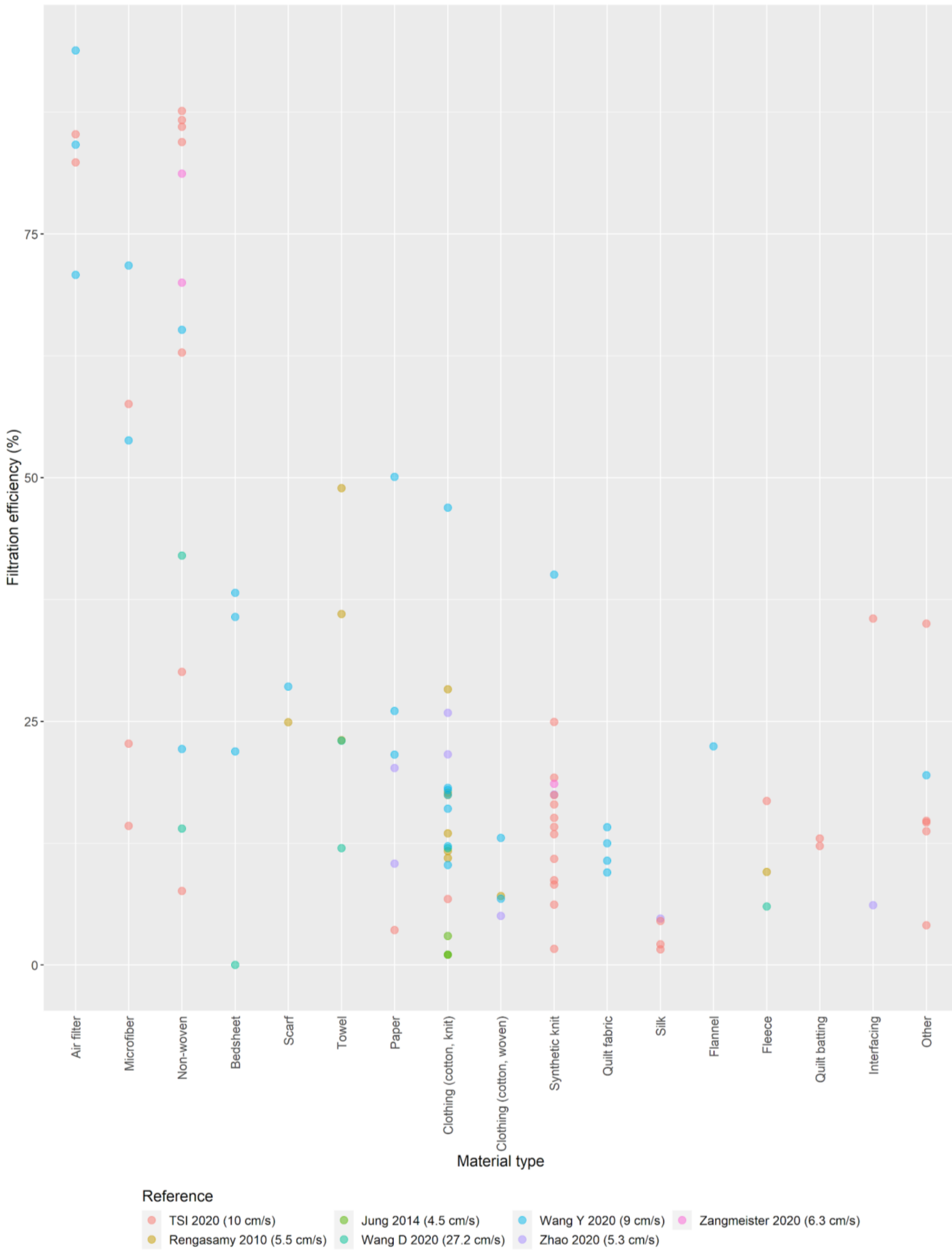
Washing led to a large decline in filtration efficiency for the non-woven material, Filti, but no decline in wool felt (TSI; O'Kelly et al., 2020). Dampening (7 mL water on 5 cm^2 material) on quilting cotton, cotton flannel, and dense, polyester ("craft") felt led to no change in filtration efficiency but caused a large decline in filter efficiency of denim (O'Kelly et al., 2020).

The effect of multiple layers or combined materials on filtration efficiency

There was a monotonic increase in filtration and pressure differential with increasing layers (Figure S2). However, there is a wide spread in slope for the same materials indicating a lack of uniformity across the same material or content differences between materials that are described using the same terms.

The combined filtration efficiencies across all studies for multiple layers of the same material are presented in Figure 4B. Multiple layers of a single material type showed substantial variation across studies (e.g. non-wovens and woven cotton) and within a single study (e.g. woven cotton). The materials that had low filtration efficiency levels as single layers tended to also have low filtrations with 2 or more layers. Multiple layers of synthetic knits, knit and woven cottons, and quilt fabric generally had filtration rates of <25%.

The combined filtration efficiencies across all studies for combinations of materials are also presented in Figure 4B. However, very few of the same material combinations were tested in multiple studies. Given the inter-study variation in filtration efficiencies for single material types, results from combinations of materials that were tested in only one study should be interpreted with caution.


Filtration efficiency (%)
75
50
25
0
Air filter
Microfiber
Non-woven
Bedsheet
Scarf
Towel
Paper
Clothing (cotton, knit)
Clothing (cotton, woven)
Synthetic knit
Quilt fabric
Silk
Flannel
Fleece
Quilt batting
Interfacing
Other
Material type
Reference
TSI 2020 (10 cm/s)
Rengasamy 2010 (5.5 cm/s)
Jung 2014 (4.5 cm/s)
Wang D 2020 (27.2 cm/s)
Wang Y 2020 (9 cm/s)
Zhao 2020 (5.3 cm/s)
Zangmeister 2020 (6.3 cm/s)

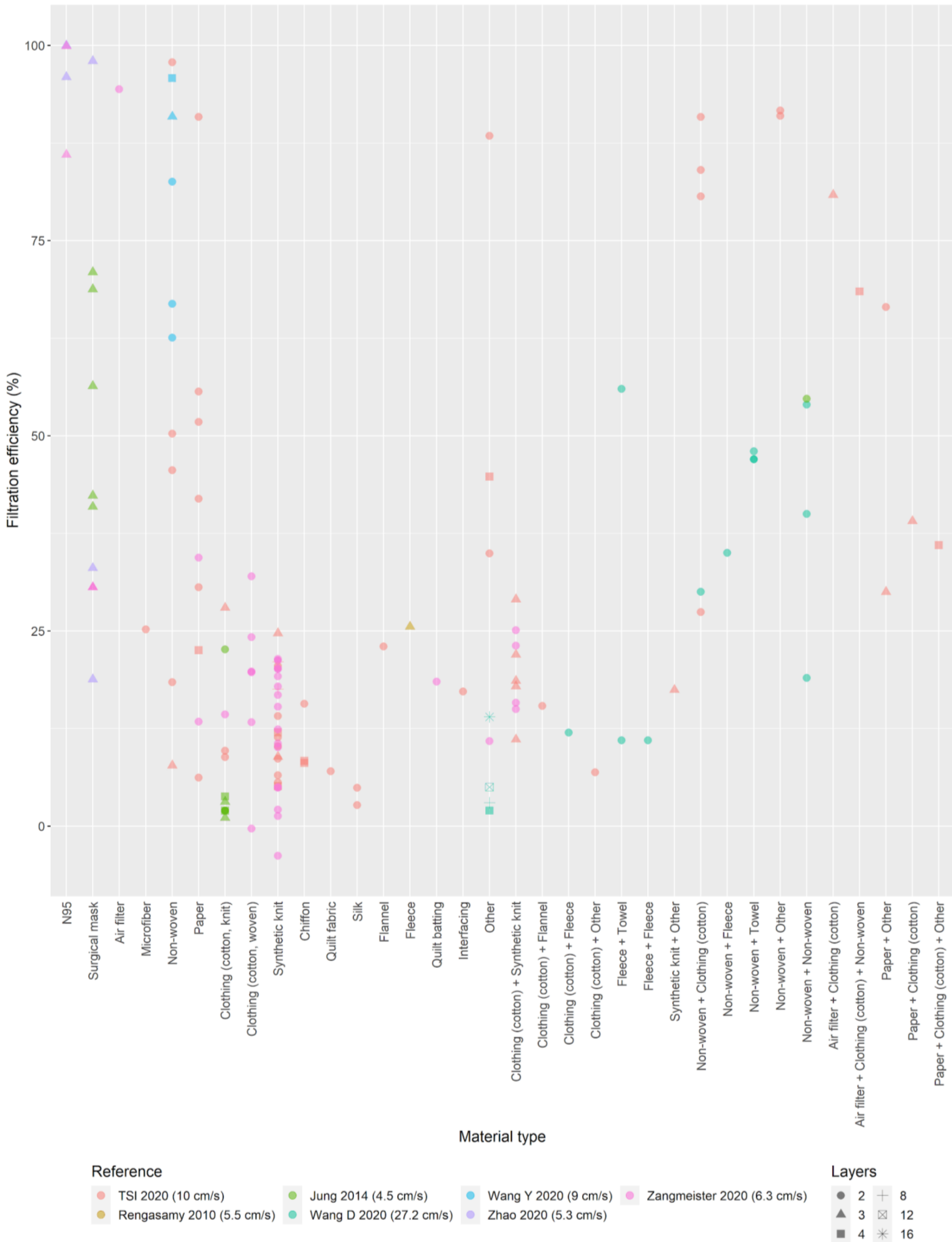


Figure 3. Filtration efficiency for a (A) single and (B) multiple layer of various materials.

7. Hazards

Since masks may be used for long periods each day, it is important that the mask be made of materials that are not impregnated with chemicals or made of materials that will disintegrate into small toxic particles that could be inhaled into the lungs. This may be a problem with repeated washing and drying of some materials. Some vacuum bags if cut are friable and all apart and may generate fibers that could be harmful to the lungs (O'Kelly et al., 2020; Zhao et al., 2020). Some vacuum bags also contain glass microfibers, nanofibers, or fiberglass that could pose a hazard if inhaled. In addition, some vacuum bags are treated with biocides to inhibit bacterial or mold growth (https://www.rivm.nl/en/novel-coronavirus-covid-19/face-masks-and-gloves). The MSDS for a vacuum bag may not list all the additives. Shop-Vac has issued a statement that no one should make a mask from any filters that they sell (http://www.shopvac.com/). Vacuum bags are not intended for use as a mask and should be avoided. In addition, some fabrics are impregnated with fire-retardants and should not be used for making masks.

Some fabrics contain substances that may cause an allergic reaction. For example, while blue shop towels have good filtration efficiency, they also can contain latex, which can cause a skin reaction in some people.

8. Conclusions

General

1. Do-it-yourself mask makers, manufacturers of cloth masks, and scientists should consider the consensus result of a group of well-designed studies (such as those from TSI-MaskFAQ, Zangmeister et al. 2020, Rengasamy et al., 2010, Zhao et al., 2020, Wang et al., 2020, and Wang Y) rather than relying on individual studies or news articles, which may not have followed standard methods or have generalizable conclusions. For example, Konda et al. (2020) concluded in a widely-cited study that a particular brand of stretch chiffon has high sub-micron filter efficiency. However, a blind replication with state-of-the-science apparatus found that the same material performed poorly (TSI-MaskFAQ). When choosing fabrics or planning research it can be crucial to be fully aware of unresolved discrepancies like this.
2. Only a few studies reported the characteristics of fabrics to the level of detail required to compare similar fabrics across studies or allow readers to make masks out of the tested materials.
3. Fabrics were compared across studies but there is some uncertainty in the comparisons because different fabrics and analysis methods were used. For example, face velocity has an effect on the pressure differential and filtration efficiency and the face velocity in the studies reviewed ranged from 5.2 to 27.2 cm/s.

Materials

1. The studies reviewed involved testing fabric that was well-sealed at the edge so that there were no leaks. To be similarly effective, masks made with these fabrics need to be designed to minimize leakage around the sides and by the nose.
2. Some non-woven and microfiber materials (e.g., Filti, Halyard) have >80% filtration efficiency which is higher than woven or knit materials (Figure 4). However, some non-woven and microfiber materials have filtration efficiency <20%. The integrity of non-woven materials may degrade after washing; after washing the filtration efficiency of Filti declined by 50% (TSI-MaskFAQ).
3. Hydrophobic materials can be used to block droplets (Aydin et al. 2020)
4. All tested woven fabrics have lower filtration efficiencies than the best-performing microfiber and non-woven materials. The filtration efficiency of natural fiber and synthetic knit materials is poor. The filtration efficiency of woven materials is highly dependent on the characteristics of the weave (Figure 3). Quilt batting in general has poor filtration efficiency ratings and should be avoided.
5. Using multiple layers of the same material can improve filtration but each layer also increases the pressure differential and reduces breathability (Figure S2).
6. Fabrics (but not non-woven materials) should be washed in hot water and heat dried before making a mask in order to remove additives used to prepare or market the fabric (such as starch) and prevent distorting the shape of the mask if shrinkage occurs after washing. Washing and/or hot-air drying may or may not alter material characteristics, so the filtration efficiency and pressure differential should be assessed after materials have been washed ~10 times. Non-woven materials should NOT be washed with soap and water because washing reduces their filtration efficiency.
7. While it is possible to electrostatically charge materials by rubbing them with latex, the efficiency gained from the induced charge dissipates substantially within 30-120 min (Zhao et al., 2020). Meltblown polypropylene, often used in N95 filtering facepiece respirator and surgical masks, do not maintain their charge after washing with soap and water, and, therefore, lose filtration efficiency (Viscusi et al., 2007).
8. Damp quilting cotton, cotton flannel, and dense, polyester craft felt did not have significantly different filtration efficiency than dry materials (but damp materials may have higher resistance, which was not tested) (O’Kelly et al., 2020).

Cautions

1. Some fabrics contain materials that can cause an allergic skin reaction (e.g., some shop towels contain latex binders).
2. Vacuum bags or HVAC (furnace) filter materials, depending on what they are made of, may release small particles that are toxic to the lungs (O’Kelly et al., 2020). For most

vacuum bags and HVAC filters there is insufficient data available on the materials used; therefore, their safe use as a mask material cannot be established and thus they are not recommended for such use.

3. Some commercial and industrial filters, vacuum bags, and specialty fabrics are treated with fungicides, flame retardants, or other potentially unsafe additives and should not be used for mask materials.

Recommendations for Researchers

Given the wide variability in approaches in the current literature, we strongly advise future work in this space focus on reproducible, replicable research, with clear and precise descriptions of both materials assessed and methods used for assessments. Specifically:

1. Studies should report sufficient details of fabrics tested and how they were acquired. Without these details, other researchers and cloth mask makers cannot obtain and test comparable fabrics. Details that should be included are
    a. Material composition
    b. Brand, product, and batch
    c. Whether the material is knit, woven, or non-woven
    d. If a woven fabric, thread count and weave
    e. Close up photograph with scale
2. Methods and apparatuses used for evaluating material characteristics (filtration efficiency, pressure differential, etc.) should be described clearly and completely, with, if possible, pictures or diagrams to assist replication.
3. Studies should use the same method filtration efficiency to allow direct comparison of results from multiple studies. The NIOSH method for testing N95 masks can be adapted for fabric/material samples; the method uses a TSI 8130 or TSI 8130a machine with a face velocity of 9-10 cm/s.
4. Consider using standardized test materials, e.g., reference media sheets, to evaluate filtration efficiency on the system. These sheets are available in filtration efficiency of 85%, 95% or 99% using a test process with the NaCl particles specified in the NIOSH standard. Use those same conditions and particles for the materials to be evaluated.
5. Critical factors to standardize and report in test methods include
    a. face velocity (or air flow and cross-sectional area of materials tested) mimicking light breathing, heavy working, coughing, and sneezing
    b. characteristics of particles used for filtration efficiency tests (e.g., mono- vs poly dispersed; size; type (NaCl vs polystyrene); charged vs. uncharged)
    c. sufficient details on the fabrics/materials tested that someone else could order the same fabric/material.
7. Washing and hot-air drying may or may not alter material characteristics, so the filtration efficiency and pressure differential should be assessed after materials have

been washed ~10 times. Washing canvas material does not degrade filtration efficiency (TSI). Other materials have not been tested after washing.

Important areas for future research

1. The effect of normal and abnormal wear on filtration efficiency of fabrics (e.g, being crumpled, stored in a pocket with keys, stretched by 10%).
2. The effect of repeated cough-like events on filtration efficiency.
3. The effect of washing and drying (using location-specific washing and drying methods, including wringing out fabric) on filtration efficiency.
4. The process by which moisture from breath accumulates on different types of materials and how this accumulation affects filtration efficiency and pressure differential.

Supplemental Information

Effect of face velocity on differential pressure

There is a consistent pattern of increasing pressure differential with increasing face velocity, despite a consistent volumetric flow rate (Figure S2). However, it should be noted that the Wang Y study pressure differentials are much higher than all other studies.

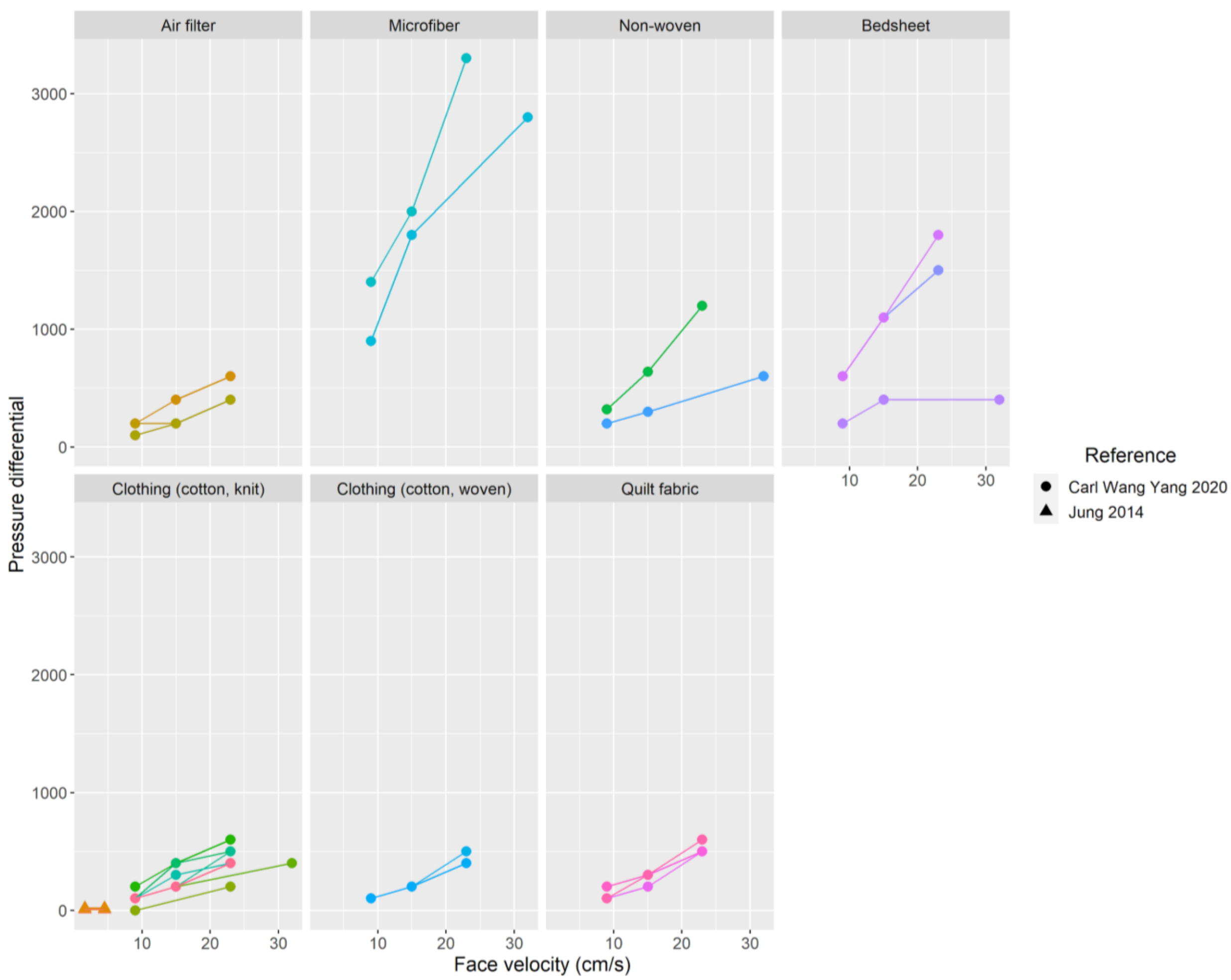


Figure S1. Pressure differential (Pa) vs. face velocity for a single layer of various materials.

Effect of layers on pressure differential

In general, there is a monotonic increase in pressure differential with increasing layers of fabric. However, the slope is different between materials and also different for the same material indicating differences in characteristics of a fabric from one region of the same fabric to the next. Some fabrics, such as bedsheets, microfibers, and quilt fabrics have a high pressure differential with just 1 or 2 layers, but within microfibers and quilt fabric there is a wide range of differences.

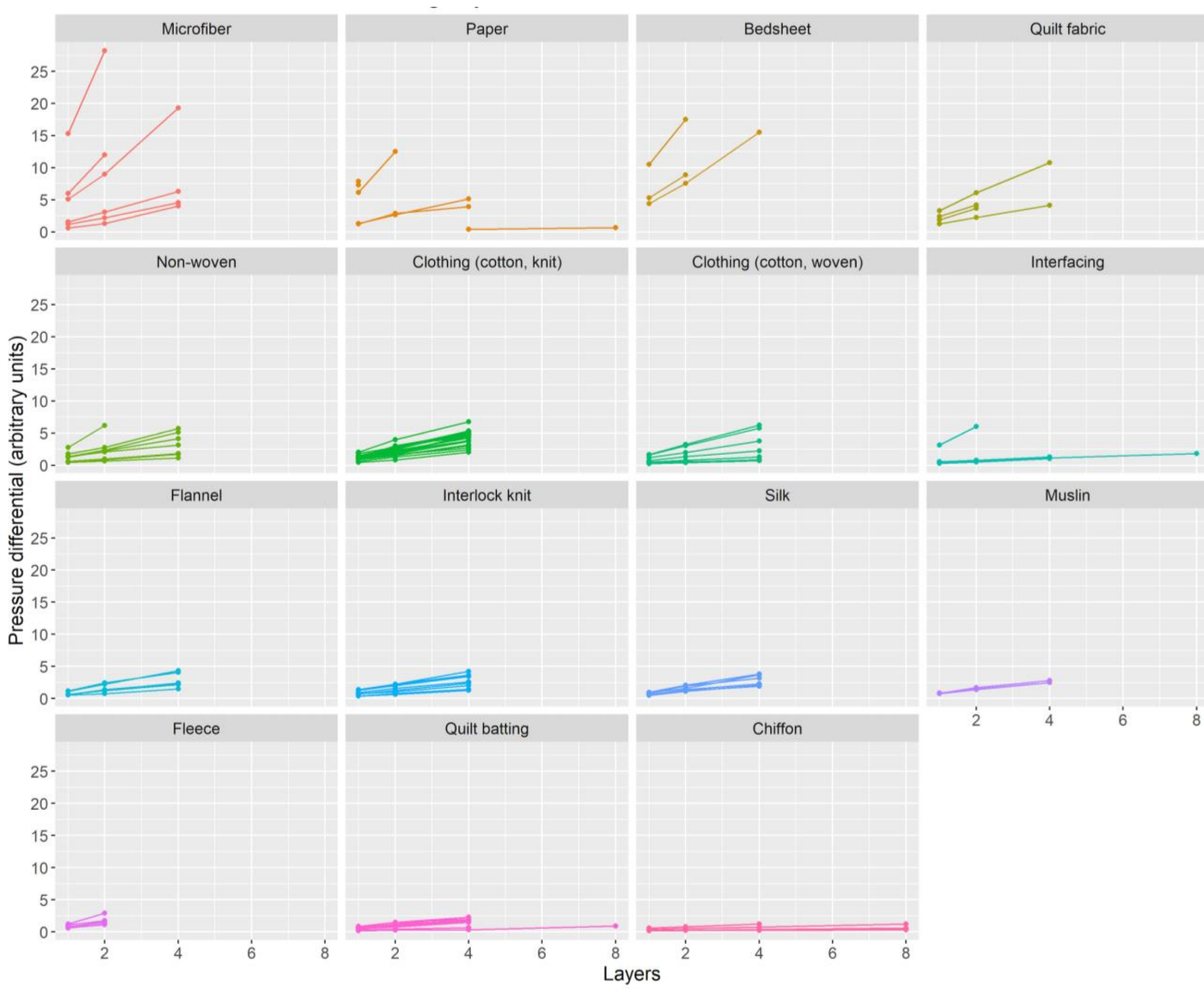


Figure S2. The effect of multiple layers of different fabrics on pressure differential. The horizontal axis is the number of layers of fabric and the vertical axis is the pressure differential.

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