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Henrietta Essie Whyte, Aurélie Joubert, Lara Leclerc, Gwendoline Sarry, Paul Verhoeven, et al.. Reusability of face masks: Influence of washing and comparison of performance between medical face masks and community face masks. *Environmental Technology and Innovation*, 2022, 28, pp.102710. 10.1016/j.eti.2022.102710 . hal-03844335v2

HAL Id: hal-03844335

<https://hal.science/hal-03844335v2>

Submitted on 18 Jul 2024

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Reusability of face masks: Influence of washing and comparison of performance between medical face masks and community face masks

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ARTICLE INFO

Article history:

Received 6 May 2022

Received in revised form 25 May 2022

Accepted 25 May 2022

Available online 3 June 2022

Keywords:

Medical face mask

Community face mask

Reuse

Washing

Particle filtration efficiency

Breathability

ABSTRACT

Reusability of masks is a rising environmental concern. Community face masks present a more eco-friendly option as they can be washed and reused several times. The potential reuse of single use medical face masks is also of interest. In this work, the impact of 20 wash cycles (at 60 °C with detergent and air-drying) on the particle filtration efficiency (particle size range 0.1–6.5 μm) and breathability of masks was studied. With regards to the performance of new masks, the medical mask had breathability of 31 Pa.cm⁻² whilst it ranged from 9 to 59 Pa.cm⁻² for the community face masks. Additionally, for 3 μm particles, the filtration efficiency was 99% for the medical mask and ranged from 28%–89% for the community face masks. Mixed fabric masks were able to maintain their performance up to 20 washing cycles. The washed 100% cotton masks were less breathable but with higher filtration efficiency because of shrinkage of the fabric. The washed medical face mask was able to maintain its breathability and filtration efficiency for sizes ≥ 3 μm, however the filtration efficiency was significantly reduced for the submicron particles. This was because the presence of detergent caused the loss of electrostatic charges and led to a decrease of the particle collection by the electrostatic forces. All things considered, both the medical face mask and community face masks can be reused several times, with performances in terms of breathability and filtration efficiency (for particle sizes ≥ 3 μm) that remain globally little changed after washing.

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1. Introduction

The virus responsible for the novel coronavirus (COVID-19), severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), has caused a global pandemic, infecting more than 440 million people worldwide and causing over five million deaths since its initial outbreak in December 2019 (World Health Organization (WHO), 2022). Among all the plausible

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transmission routes, increasing evidence suggested that airborne transmission is likely the dominant route of transmission especially in the indoor environment with low levels of ventilation (Allen and Ibrahim, 2021; Greenhalgh et al., 2021; Tang et al., 2021). In addition to other measures such as social distancing, face masks have been demonstrated to reduce respiratory emissions when worn properly (Li et al., 2022; Wang et al., 2020; Worby and Chang, 2020). Therefore, in a bid to reduce the spread of the virus, policy makers from different governments and organizations recommended the use of face masks (European Center for Disease Control, 2020; Howard et al., 2021). Initially, this led to an increase in the use and demand of single-use medical face masks by both the medical community and the general public. The increased use of medical face masks caused a shortage worldwide, stimulating the mass production of masks in turn. Community face masks or cloth masks have been introduced as one of the means to attempt to address this global shortage of medical face masks (Bourrous et al., 2021; Clapp et al., 2021; Konda et al., 2020).

It is estimated that during the pandemic, 3.4 billion medical face masks were used globally and disposed of daily (Benson et al., 2021) with Asia alone consuming about 2.2 billion daily (Sangkham, 2020). The increased use of these medical face masks containing polypropylene and other synthetic polymers presents an environmental hazard and adds to the already existing issue of micro plastic pollution in marine and land environments (Asim et al., 2021; Du et al., 2022; Ray et al., 2022). These masks may be swallowed by marine animals and potentially kill them. The majority of these masks end up on streets or landfills. The main plastic in single-use medical face masks is polypropylene which can take more than 25 years to breakdown in a landfill (Kilmartin-Lynch et al., 2021; Nghiem et al., 2021; Tabatabaei et al., 2021; Tuñón-Molina et al., 2021). In a comprehensive review of the implications of COVID-19 on sustainability practices, Ranjbari et al. (2021) similarly highlighted the importance of sustainable measures to address the negative environmental implications of single use face masks.

The reusability and end-of-life of face masks is therefore an important subject of interest during increased mask usage during pandemics. The main advantage of community face masks is that they are reusable and provide a more environmental friendly option. Although the medical face masks are originally designed to be single use, studying their reusability is interesting for environmental reasons.

Mask reuse involves typically a decontamination step between two uses. Alcaraz et al. (2021) in a study of the potential reuse of medical face masks, found washing, washing then autoclaving and washing then sterilizing (with radiations or ethylene oxide) as promising methods of cleaning the medical face masks whilst maintain their safety and functionality for reuse. Community face masks on the other hand are typically reused by washing.

The performance of these community face masks is based on two parameters. The breathability (*i.e.* the differential pressure noted DP, measuring the respiratory resistance provided by the mask) and the particle filtration efficiency (PFE). Unlike the medical face masks that are regulated and certified (*e.g.* in Europe with the EN 14683:2019 standard procedure (EN 14683+AC - European Standards, 2019)), the community face masks are not standardized nor strictly regulated. In France, however, in order to assure a certain level of protection, the French Standardization Association (AFNOR), published a guideline (AFNOR SPEC S76-001 (AFNOR, 2020)) which proposes the minimum performance requirements of the community face mask. Currently masks with a PFE for 3 μm particle size of $\geq 90\%$ and a DP ≤ 60 Pa cm^{-2} are advised.

The emergence of these community face masks led to an increase in the desire to evaluate their performance (Kwong et al., 2021). The community face masks come in various designs and are made with a large variety of fabrics and whilst not as effective as medical face masks, they are known to reduce particles emitted by the wearer (Wilson et al., 2020). Morais et al. (2021) tested the filtration levels of a medical face mask and several cloth masks for 60–300 nm sodium chloride (NaCl) aerosols and reported average filtration efficiency for this range of 89% for the medical face masks compared to 12%–78% for the cloth masks. Numerous studies performed on cloth masks have shown that various characteristics of the fabrics (material type, fabric type (woven or knitted), fiber characteristics) may influence their filtration and breathability (Drewnick et al., 2021; Konda et al., 2020; Kwong et al., 2021; Rogak et al., 2021). It is currently unclear though which of these characteristics are the most influential on filtration efficiency and breathability. Zhao et al. (2020) tested several materials (cotton, silk, flannel, chiffon) with NaCl particles and observed that fabrics with tight weave, particularly cotton, presented the best efficiencies.

There is however very little information concerning how these different community face masks compare to each other and also to medical face masks in terms of their performance after being washed. This study seeks to evaluate the influence of washing on the performance of community face masks and compare their performance (in terms of PFE and DP) to that of a medical face mask under the same conditions. In this work, the medical face mask is subjected to AFNOR SPEC S76-001 requirements (PFE for 3 μm particle size of $\geq 90\%$ and a DP ≤ 60 Pa cm^{-2}) in order to compare to the community face masks.

Though the SARS-CoV-2 diameter has been reported within 60–150 nm (Kim et al., 2020; Park et al., 2019; Ren et al., 2020; Zhu et al., 2020), respiratory viruses are emitted from the respiratory tracts attached to droplets in the respiratory secretions during respiratory activities. Particles generated by respiratory activities range from 10 nm to 500 μm (Gralton et al., 2011). However, their size after emission varies strongly, depending on environmental conditions. Consequently, the particle size distributions are heterogeneous but their diameter can be assumed as mainly smaller than 5 μm (Asadi et al., 2019; Johnson et al., 2011; Morawska et al., 2009).

Therefore evaluating the filtration efficiency of masks covering sizes from sub-micron to a few microns is essential. In this regard, this study seeks not only to evaluate the influence of washing on the PFE of mask at 3 μm to ascertain their compliance with AFNOR SPEC S76-001 requirements but also at smaller particle sizes (< 1 μm) to be able to know the impact of washing on the collection efficiency of these particles.

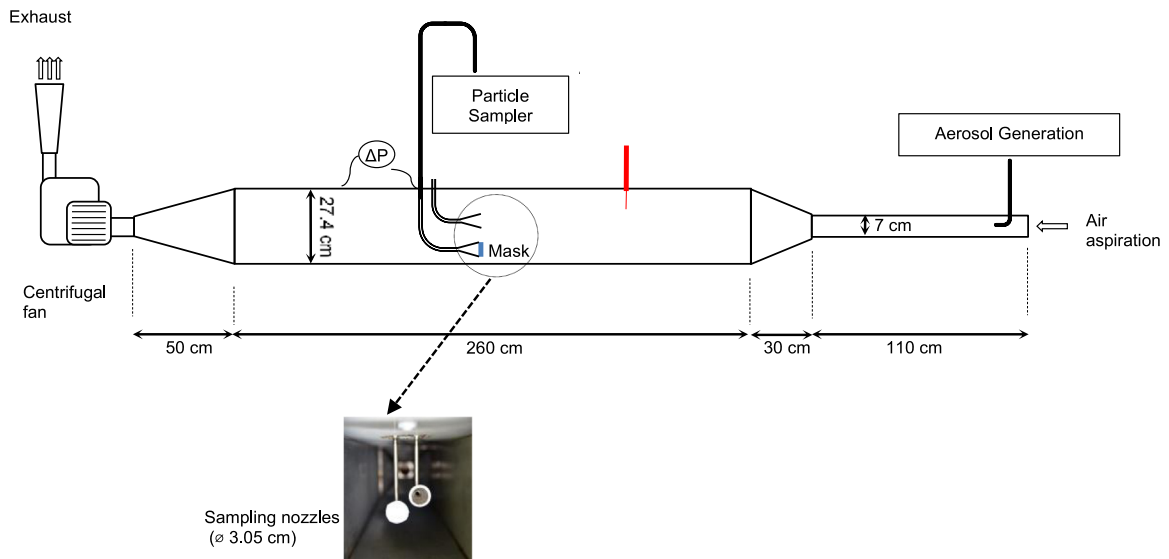


Fig. 1. Schematic representation of particle filtration efficiency experimental set-up.

2. Materials and methods

2.1. Masks tested

Nine community face masks from different French manufacturers were purchased and used in this study. The masks were classified into two groups based on the composition of the fabric. The first group consisted of masks that were made from 100% cotton material and the second group consisted of masks that were made from a mixture of fabrics (cotton, polyester and/or elastane). The medical face mask that was used in this study is a type IIR medical mask certified according to the [EN 14683+AC - European Standards \(2019\)](#). The mask references are provided in [Table A.1](#) in [Appendix](#).

2.2. Particle filtration efficiency (PFE)

The PFE of the masks were evaluated using a non-standardized protocol. The experimental configuration used to determine the PFE of the masks is presented in [Fig. 1](#). The set-up is equipped with a centrifugal fan to draw air through a modular test section. The air is first sucked in through a circular duct and then the flow is driven into a long duct in which the velocity is kept constant at 9.6 cm s^{-1} . For the filtration test, two sampling probes attached to identical sample holders with 30.5 mm internal diameters were used. The face mask material was fixed on the sample holder of one of the probes and a particle counter was connected to each of the two sampling probes in turn, for sampling upstream (empty probe) and downstream (probe with mask sample) of the mask filtering material respectively. Two test aerosols were considered in this study: DEHS (di-ethyl-hexyl-sebacate) and sodium chloride (NaCl). The DEHS aerosol was produced using two generators simultaneously: a MAG 3000 (Palas, Germany) which generates condensation from DEHS vapor at $300 \text{ }^\circ\text{C}$, and an AGK 2000 (Palas, Germany) which atomizes the liquid DEHS. The NaCl aerosol was generated by atomizing a solution of 10 g L^{-1} with the AGK 2000. The NaCl aerosol stream passes through a diffusion dryer to remove water before injected into the test duct.

The DEHS particle concentrations and size distributions were measured with an Aerodynamic Particle Sizer (APS) system. Particles are first drawn into the aerosol diluter (TSI model 3302A, United States of America) of the APS at a flow rate of 5 L min^{-1} . Diluted particles are introduced into the APS spectrometer (TSI model 3321, United States of America) at same flow rate of 5 L min^{-1} to measure the particle concentrations and aerodynamic particle size distribution. This allowed for the possible detection of particle size range from $0.5\text{--}20 \text{ }\mu\text{m}$. The test aerosol generated had a number median diameter of $0.8 \text{ }\mu\text{m}$ (geometric standard deviation of 2.1). With the mask material area set at 7.3 cm^2 , the flow rate provided by the particle counter of 5 L min^{-1} ensures a filtration velocity of 11.4 cm s^{-1} .

The NaCl particle concentrations were measured using a scanning mobility particle sizer (SMPS, Grimm, Germany). The SMPS consisting of a long differential mobility analyzer (DMA) and a condenser particle counter (CPC) was employed to measure particle size distribution base on real-time selective (mobility-equivalent diameter) number concentration at a sampling flow of 0.3 L min^{-1} . The SMPS allows the possible detection of particle size range from $10\text{--}1000 \text{ nm}$. The test aerosol had a number median diameter of 65 nm (geometric standard deviation of 1.0). As the SMPS was used at the same

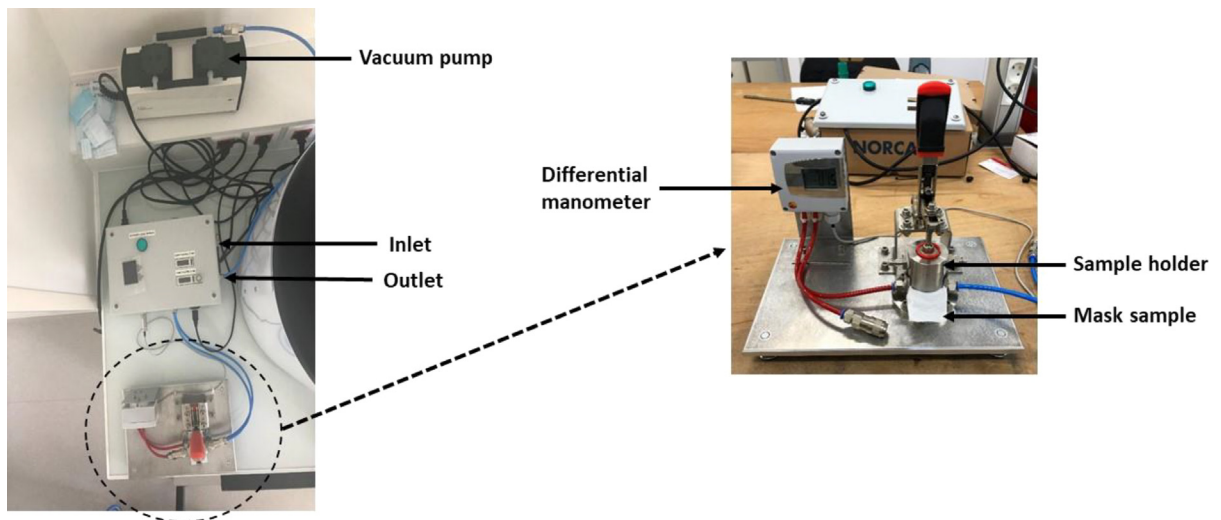


Fig. 2. Experimental set-up for the evaluation of the differential pressure (indicating breathability).

time as the APS, the flow rate through the mask is assured by the APS which allows us to maintain a filtration velocity of 11.4 cm s^{-1} as described previously for the DEHS particles.

The particle filtration efficiency corresponding to a particle diameter d_p was calculated using Eq. (1):

$$PFE(d_p) = \frac{C_{empty}(d_p) - C_{mask}(d_p)}{C_{empty}(d_p)} \quad (1)$$

where $C_{empty}(d_p)$ is the number concentration of particles with diameter d_p for the empty sample holder and $C_{mask}(d_p)$ is the number concentration of particles with diameter d_p for holder on which mask samples are fixed. Efficiency measurements are conducted on three samples of a mask.

2.3. Breathability

The test for the breathing resistance was performed according to the EN 14683+AC (2019) standard procedure, which evaluates the performance of medical face masks. The breathing resistance was calculated by measuring the differential pressure drop across the mask material. The mask was attached between two sample holders with a circular cross-section of 4.9 cm^2 (25 mm diameter), and the air passed through the mask at a fixed airflow rate of 8 L min^{-1} . The differential pressure (DP) was expressed in Pa cm^{-2} . The value is the average of five measurements of the mask sample (see Fig. 2).

2.4. Microscopic mask characterization

The microscopy analyses were made using a Leica DM LB Microscope (Leica Microsystems, Germany) with a C Plan lens model. The images were taken with a Bresser MikroCam SP 5.0 (Bresser GmbH, Germany) at 4X magnification. Scanning electron microscopy (SEM) was performed on surfaces of the masks using a JEOL JSM-6500F (Jeol Ltd, Japan). Samples were mounted on brass support with double sided carbon tape and coated with 14 nm of gold (Quorum Q 150R ES, Quorum Technologies, United Kingdom). Images were taken with beam accelerating voltage of 5 keV.

2.5. Washing procedure

Washing was performed with a domestic washer (Candy Smart CSWS 4852DWE). The masks were washed 20 times at $60 \text{ }^\circ\text{C}$ and with laundry detergent (X-Tra Total 3+1 Trio-Caps, Henkel Ltd). After a rinse and spin (400 rpm) cycle, the masks were dried in open air.

3. Results and discussion

3.1. Performance of new masks

In this section the PFE and DP (indicating breathability) of the unwashed (new) medical and community face masks is described.

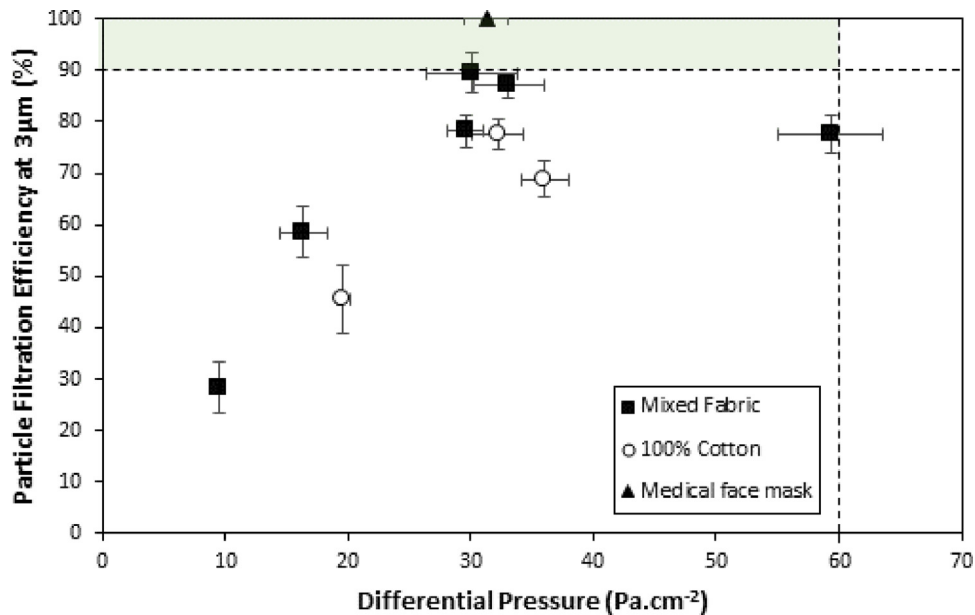


Fig. 3. Particle filtration efficiency (%) for 3 μm DEHS particle diameter vs. differential pressure (Pa cm^{-2}) for the medical face mask (black triangle), mixed fabric masks (black squares) and 100% cotton masks (clear circles). Average values ($N = 3$) \pm standard-deviation for particle filtration efficiency and Average values ($N = 5$) \pm standard-deviation for differential pressure.

3.1.1. Particle filtration efficiency for 3 μm particle size and differential pressure

We tested the PFE and DP (indicating breathability) of the nine commercially available community face masks and 1 medical face mask when new. Only the material constituting the masks was evaluated and leakage is not considered in this study. The PFE for 3 μm particle diameter and the differential pressure of each mask category is represented in Fig. 3. The results are obtained with the APS counter using the DEHS particles.

The horizontal and vertical dashed lines represent the AFNOR SPEC S76-001 performance requirement ($\geq 90\%$ collection efficiency for 3 μm particle diameter and $\leq 60 \text{ Pa cm}^{-2}$ DP respectively). The shaded green area allows the identification of the mask that is compliant with both filtration efficiency and breathability requirements. Considering the community face masks, there was a general tendency of PFE increasing with an increase in DP but no direct correlation can be observed between these two parameters. With the exception of a mixed fabric mask which was in the limit of compliance, all the masks are in compliance with the breathability requirement of the AFNOR SPEC S76-001 requirement ($\leq 60 \text{ Pa cm}^{-2}$). Except two mixed fabric masks that were quite close, all the community face masks were not in compliance with the AFNOR SPEC S76-001 requirement ($\geq 90\%$ collection efficiency for 3 μm particle diameter). The medical face mask on the other hand had the highest PFE of 99% and was the only mask that presented acceptable performance for both requirements.

It is important to note that all the community face masks were however certified by the appropriate French agencies as conforming to the AFNOR SPEC S76-001 PFE requirement ($\geq 90\%$ collection efficiency for 3 μm particle diameter). In this case the PFE values obtained in this study are lower than what is claimed by the certification agency. The AFNOR SPEC S76-001 does not impose a test method thus parameters such as the type of aerosol to use for testing is not indicated. Characteristics of the type of aerosol used including surface properties, such as the rugosity which favors the adhesion of particles to each other, the irregular particle shape and the charge properties may influence the filtration efficiency. A charged aerosol will be collected more efficiently by the mask fibers than a neutral aerosol such as DEHS used in this study (Han et al., 2010). DEHS by its surface properties tends to have lower efficiency values than mineral aerosols such as SiO_2 or organic aerosols such as HOLI (Joubert et al., 2021). This could be a possible explanation to why the values reported in this study are lower than values claimed by the certification agency.

The capture of particles by the face mask media is as a result of several capture mechanisms; Brownian diffusion for small particles agitated by Brownian motion, direct interception for bigger particles driven close to the fibers, and impaction for the biggest particles with high inertia and leaving airflow lines (Brown and Richard, 1993; Hinds, 1999; Tcharkhtchi et al., 2021). Brownian diffusion is the most effective mechanism for capturing particles with sizes $< 0.1 \mu\text{m}$ whilst impaction/interception is dominant for particles sizes $> 0.5 \mu\text{m}$. When the mask material is charged, electrostatic forces contribute to particle capture especially for particles in the size range of 0.1–0.5 μm (i.e. the Most Penetrating Particle Size (MPPS) zone where no mechanism is dominant) (Wang and Sen, 2001). Various structural characteristics of the fabrics may influence their PFE. It is however currently unclear which characteristics are the most influential for filtration efficiency or breathability (Kwong et al., 2021). Fabric characteristics that are likely to be important include the

Table 1
Particle filtration efficiency for 3 particle sizes and fabric characteristics of masks.

Mask category	Mask	PFE _{3 μm} (%)	Fiber diameter (μm)	Pore size ^b (μm)
Medical face mask	Medical face mask Spunbound	99.93 ± 0.05	25 ± 1	100 ^a
	Medical face mask Meltblown		6 ± 3	20 ^a
Mixed fabric	MF-A-3L	28.3 ± 5.1	12 ± 1	981 ± 17
	MF-B-2L	58.5 ± 4.9	14 ± 3	548 ± 18
	MF-C-3L	77.7 ± 3.6	12 ± 3	218 ± 44
	MF-D-2L	78.2 ± 3.1	14 ± 4	154 ± 13
	MF-E-2L	89.6 ± 3.9	12 ± 2	113 ± 29
100% cotton	MF-F-3L	87.1 ± 2.4	18 ± 3	147 ± 27
	CF-A-2L	45.6 ± 6.6	12 ± 1	621 ± 17
	CF-B-3L	68.9 ± 3.6	14 ± 4	334 ± 41
	CF-C-3L	77.6 ± 2.9	18 ± 4	253 ± 47

^aValues obtained from Ju et al. (2021) and Zhao et al. (2020).

^bPore size for community face masks corresponds to gaps between yarns. The spunbound and meltblown are layers of the same medical mask. MF: Mixed Fabric, CF: Cotton Fabric, 2L: 2-Layer, 3L: 3-Layer.

composition of the material (natural, synthetic, mixed fibers), fiber size, pore size and number and thickness of fabric layers (Ju et al., 2021; Kwong et al., 2021; Liu, 2009; Rogak et al., 2021).

In this study, the community face masks include two categories of material compositions: 100% Cotton and mixed fabric (cotton, polyester and elastane). A Mann-Whitney U non-parametric statistical test (Spiegel and Stephens, 2011) applied to data at confidence interval of 95% showed that there was no significant variation of PFE for 3 μm particle diameter between the two categories of community face masks.

Fibrous filter materials are usually comprised of fibers arranged in several ways. For non-woven materials, fibers are randomly oriented whilst woven and knitted materials contain yarns (bundles of fibers) that are interlaced to each other (Adanur and Jayswal, 2020).

Fig. 4 presents the scanning electron microscope (SEM) and optical microscope images of the masks. Some material characteristics (fiber diameter and pore size) based on an Image J analysis of the images are presented in Table 1. Although the pore shape and size in community face masks were not uniform, we tried to extract quantitative information on the size of the pores by measuring the longest dimension of each pore.

The differences in performances can be partly explained by structural differences evident from the micrographs (Fig. 4). Generally, smaller fiber diameters yield better filtration efficiency. Indeed the meltblown filter has the smallest fiber diameter (~6 μm) and had the highest PFE. However, the community face masks have similar fiber diameter (12–18 μm) thus performance differences of the community face masks may not be strictly correlated with fiber diameter. Other structural characteristics appear to be relevant. In woven and knitted fabrics, the pores are formed at yarn interstices while they are formed by small spaces between individual fibers in non-woven filters (Adanur and Jayswal, 2020). For the fabrics studied in this work, fibers are bound tightly into yarns. In this case, one of the relevant scales interacting with the aerosol stream is the yarn diameter thus, the pore sizes of community face masks are considered as the spaces/gaps between yarns.

From the microscopic images in Fig. 4, it can be observed that MF-A-3L has the highest pores sizes (spaces between yarn) of ~900 μm, CF-C-3L has moderate pore size of ~200 μm whilst MF-E-2L had the lowest pore sizes of ~100 μm. This probably contributes to why MF-E-2L had the highest PFE_{3 μm} whilst MF-A-3L had the lowest PFE_{3 μm}.

Medical face masks are typically made up of 3 layers of non-woven polypropylene fibers (Spunbound, Meltblown, and Spunbound). The middle meltblown layer is charged electrostatically by corona effect to increase particle collection efficiency. These non-woven materials create a tortuous path with air to improve the probability of a particle to be captured by the fibers. In general, the meltblown layer used in medical face masks has a pore size of ~20 μm and the spunbound ~100 μm (Ju et al., 2021; Zhao et al., 2020). The relatively smaller pore size of the medical face masks possibly leads to a better capture by impaction and interception compared to the community face masks and could explain why the medical face mask had a better PFE_{3 μm}.

The number of layers of the mask, in this study, was not the most influential parameter. MF-A-3L which is a 3 layers mask had the lowest PFE_{3 μm} whilst MF-E-2L, a 2 layers mask, had the highest PFE_{3 μm}. Based on our results, it seems that layering fabrics with very high pore size does not necessarily improve filtration efficiency.

3.1.2. Spectral filtration efficiency

The spectral efficiency curves of the medical face mask and community face masks are presented in Fig. 5. The graph combines the electrical mobility particle sizes (0.01–0.2 μm) measured with the SMPS for NaCl aerosols and the aerodynamic particle sizes (0.5–6.5 μm) measured with the APS for the DEHS particles. The filtration curves exhibited the classical U-shape which is as a result of the interaction of the main filtration mechanisms (diffusion, impaction,

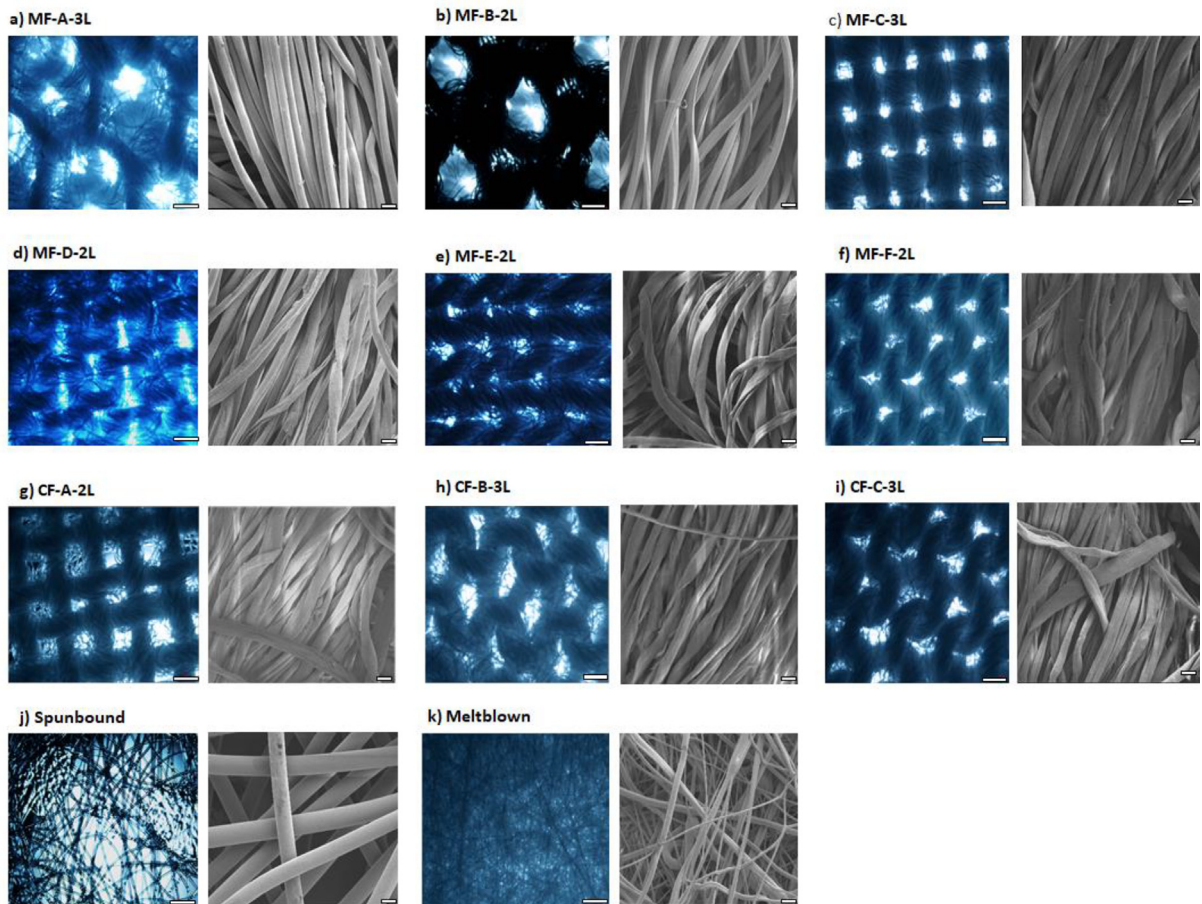


Fig. 4. Optical microscopy and SEM images of the microscopic structure of the various masks. Each image is presented in pairs. The left image is the optical micrograph (4X magnification and white scale bar corresponds to 300 μm). The right image is the SEM micrograph (400X magnification and white scale bar corresponds to 30 μm).

interception and electrostatic charges (if the material is charged)) (Yeh and Lui, 1974). The MPPS of the mask is presented by the minima of the curve, whose width has a direct impact on the ability of the mask to protect the user.

The medical face mask exhibited PFE greater than 90% for the range of particles studied. A wide range of filtration efficiencies (3%–100%) were observed across particle sizes for the community face masks. The strict technical specifications and certification for medical face masks resulted in low variability on filtration performance. However the community face masks PFE presented higher variability between samples of the same mask due likely to the heterogeneity of fabric properties. The MPPS for both the medical face mask and community face masks could be assumed to be for particles between 0.2–0.5 μm . This is similar to what Rengasamy et al. (2009) found for medical face masks and Drewnick et al. (2021) found for cloth masks. Whilst the PFE observed for the MPPS range was >90% for the medical face mask, it was lower (3%–30%) for the community face masks.

3.2. Influence of washing on mask performance

In this section the PFE and DP (indicating breathability) of the washed medical and community face masks is described.

3.2.1. Particle filtration efficiency for 3 μm particle size and differential pressure

The effect of washing on the particle filtration efficiency for 3 μm particle size and the differential pressure are shown in Fig. 6.

Washing the mixed fabric masks led to either a slight variation of the PFE_{3 μm} and DP, however for each mask, the Mann–Whitney U test (with confidence interval of 95%) showed that for both differential pressure and the particle efficiency for 3 μm the results obtained on the new and washed masks were not significantly different. Optical microscopic and SEM images of new and washed masks for a mixed fabric mask (MF-A-3L) are shown in Fig. 6a. There was

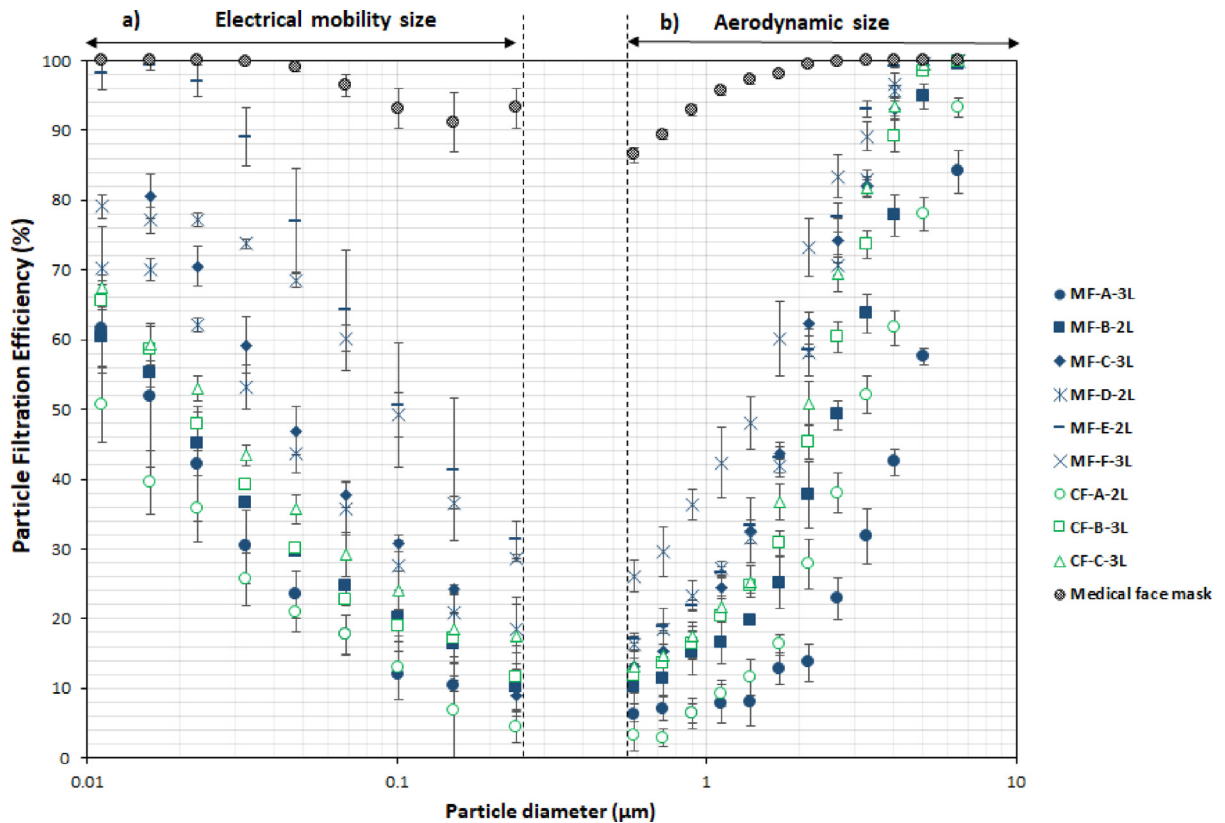


Fig. 5. Spectral particle filtration efficiency measured for medical face mask and community face masks. Left part of the graph (a) represents the SMPS measurements (electrical mobility size) and right part (b) represents the APS measurements (aerodynamic size). Average values (N = 3) ± standard-deviation. MF: Mixed Fabric, CF: Cotton Fabric, 2L: 2-Layer, 3L: 3-Layer.

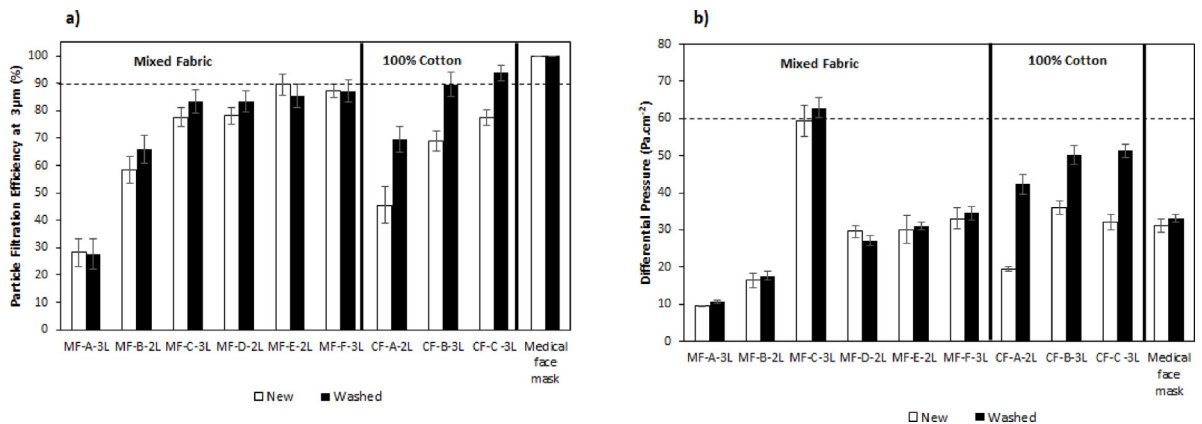


Fig. 6. Comparison of (a) particle filtration efficiency (%) for 3 μm particle sizes and (b) differential pressure (Pa cm⁻²) for the mixed fabric, 100% cotton and medical face masks. Average values (N = 3) ± standard-deviation for particle filtration efficiency and Average values (N = 5) ± standard-deviation for differential pressure. MF: Mixed Fabric, CF: Cotton Fabric, 2L: 2-Layer, 3L: 3-Layer.

no significant change in pore sizes (gaps between yarns) for both masks. The fibers showed very slight deconstruction, however, this did not seem to impact significantly the performance of the mask.

For the 100% cotton masks, there was an increase in the differential pressure with a corresponding increase in the filtration efficiency of 3 μm particle size. Natural fibers like cotton are less heat resistant and more hydrophilic compared to synthetic fibers are therefore known to shrink when washed (Hassan and Carr, 2019; Khan et al., 2020).

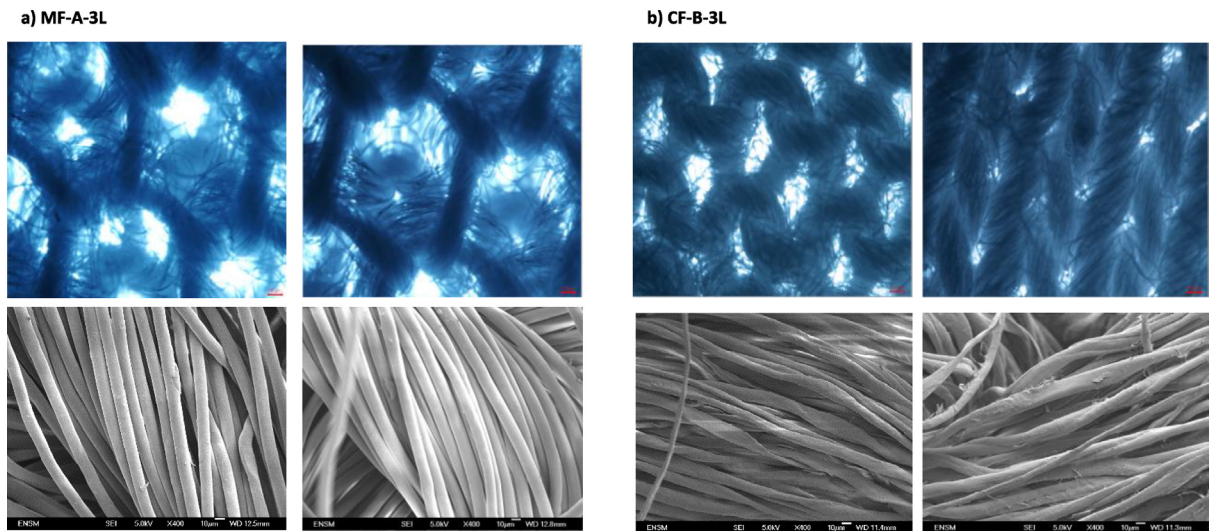


Fig. 7. Optical microscopy and SEM images of the microscopic structure. (a) a mixed fabric mask, (b) 100% cotton mask. For each mask four images are presented. The top images show optical micrograph (4X magnification and red scale bar at bottom right corresponds to 100 μm) for new mask (left) and washed mask (right). The bottom images show the SEM micrographs (400X magnification and white scale bar corresponds to 10 μm) for new mask (left) and washed mask (right).. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Cotton can easily absorb moisture, so when a cotton fabric gets wet, the fibers are somewhat relaxed. When the cotton fibers are met with the heat and friction that happens in the washer, the fibers lose their tension, and the cotton will shrink (Collins, 2009). Basra et al. (2020) studied the effects of washing on socks and concluded that synthetic fibers or combination of natural and synthetic fibers comprised negligible shrinkage as compared to natural fibers. The shrinkage leads consequently to a reduction of the pore sizes (gaps in between yarns) which increase the probability of aerosols coming in contact with fibers. Microscopic images of one of the 100% cotton masks (CF-B-2L) shows the reduction in yarn spaces (Fig. 6b). In this case the 100% cotton masks become more resistant to air flow (less breathable) but more efficient in removing particles of 3 μm . The microscopic images also showed that there was however some deconstruction of the fibers after 20 wash cycles (Fig. 6b).

For the medical face mask, there was no significant influence of 20 washes on the breathability or its capacity to remove particles of 3 μm size. However, if the collection efficiency remains unchanged for the 3 μm particles, this was not the case for lower particle sizes as will be described in the next section.

3.2.2. Spectral filtration efficiency

The comparison of PFE and DP for some new and washed masks is shown in Fig. 7. It can be observed that as the new medical face mask exhibited collection efficiency greater than 90% for the range of particles studied, washing the mask however, led to a reduction of the filtration efficiency for the lower particle sizes (Fig. 7a). For particle sizes $\geq 1 \mu\text{m}$, the dominant filtration mechanisms are impaction and/or interception but at submicron particle size, other dominant mechanisms including electrostatic mechanisms (in the case of a medical face mask), are involved. As the presence of the intermediate meltblown layer of charged polypropylene fibers contributes to the filtration efficiency by electrostatic charges, washing the medical face mask leads to a decrease in the efficiency of the submicron particles because the surfactants present in the detergent bind to the surface and remove charges on electret fibers of the filtering material (Alcaraz et al., 2021; Chua et al., 2020; Hossain et al., 2020; Lin et al., 2017; Viscusi et al., 2009). This phenomena of discharge was confirmed by Charvet et al. (2022) who showed that the spectral filtration efficiency of a mask discharged by immersion in isopropanol was similar to that of a washed mask. The MPPS range (0.2–0.5 μm) was not affected by the washing but the minimum filtration efficiency had decreased to 30% after washing.

On the other hand, the community face masks showed the same behavior for the lower particle sizes as for 3 μm particle sizes. There was no significant change in filtration efficiencies for the mixed fabric masks (Fig. 5b) whilst washed 100% cotton masks (Fig. 5c) showed an increase in filtration efficiencies as a result of the reduction in pore spaces caused by the shrinkage of the material (see Fig. 8).

4. Conclusions

In this work, the reusability of community face masks and single-use medical face masks is considered by evaluating the impact of a single washing condition on the Particle Filtration Efficiency (PFE) and Differential Pressure (DP) of community

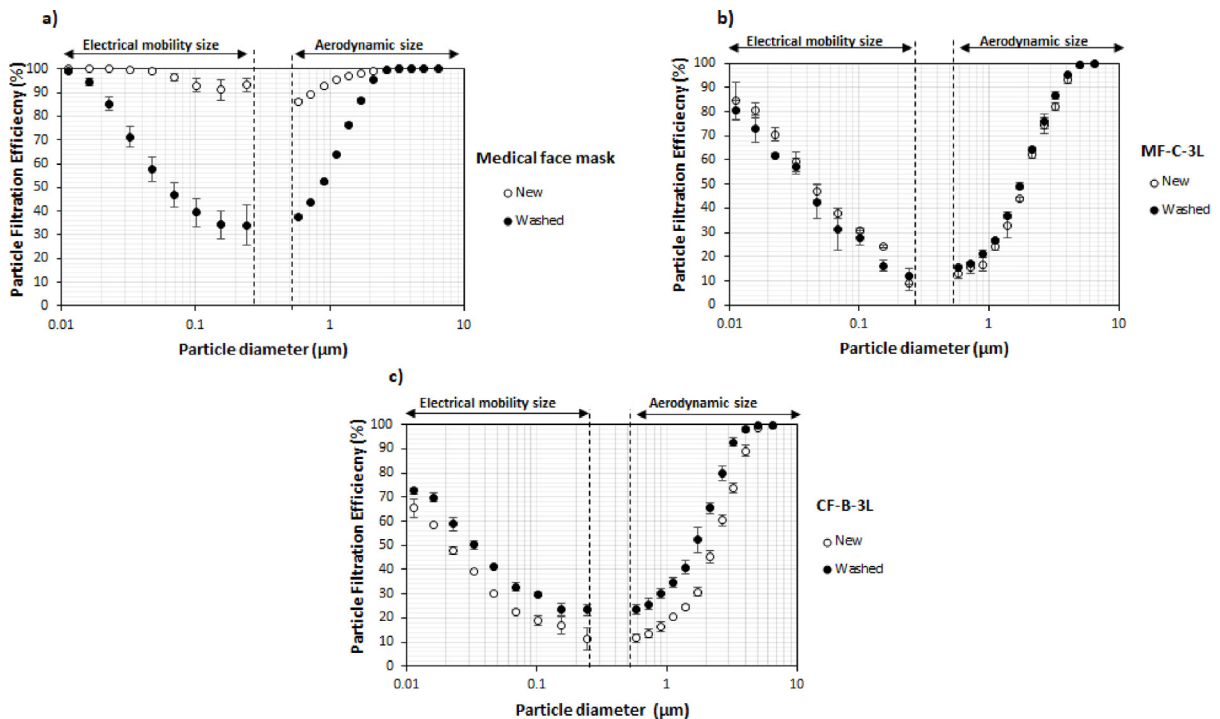


Fig. 8. Comparison of Spectral particle filtration efficiency measured for new and washed masks (a) medical face mask, (b) mixed fabric mask (MF-C-3L) and (c) 100% cotton mask (CF-B-3L). Left part of the graph represents the SMPS measurements (electrical mobility size) and right part represents the APS measurements (aerodynamic size). Average values ($N = 3$) \pm standard-deviation.

face masks was studied and compared to that of a medical face mask under similar conditions. The community face masks used were categorized into mixed fabric (cotton, polyester and elastane) and 100% cotton masks.

For the new community face masks, although certified by the appropriate agencies to conform to the AFNOR SPEC S76-001 PFE requirement ($\geq 90\%$ for $3 \mu\text{m}$ particle size) our results showed that only two of the masks were in the limit of conformity. As the AFNOR SPEC S76-001 does not impose a test protocol, our lower values compared to that of the certification agency may possibly be as a result of differences in the nature and charge of the aerosol used. With regards to the breathability, all but one of the community face masks was in compliance with the AFNOR SPEC S76-001 ($DP \leq 60 \text{ Pa cm}^{-2}$). The medical face mask was however compliant with both requirements.

It was established that for the panel of community masks studied the pore size was the influential parameter concerning the $PFE_{3 \mu\text{m}}$. The spectral filtration efficiencies (for $0.01\text{--}6.5 \mu\text{m}$ particles) showed that the MPPS range ($0.3\text{--}0.5 \mu\text{m}$) was similar for both the new medical face masks and the community face masks however, the filtration efficiency for MPPS was 90% for the medical face mask and $3\text{--}30\%$ for the community face masks.










The results indicated that washing (20 times at 60°C , rinsed, spun and air dried) did not significantly impact the breathability and the PFE (across all size ranges) of the mixed fabric masks. On the other hand, due to shrinkage of the fabric when washed, the 100% cotton mask experienced an increase in the differential pressure which would render them less breathable but corresponded to an increase in the PFE (across all size ranges). Microscopic analysis showed some slight deconstruction of fibers of the community masks but this did not impact significantly the performance.

Washing the medical face masks did not affect the PFE of medical face masks for particle sizes $\geq 3 \mu\text{m}$ however the efficiency was greatly reduced for the submicron particles. The charged meltblown layer improves filtration efficiency especially in the submicron particles by electrostatic forces. The presence however of surfactants in the detergent was responsible for the loss of electrostatic charges which then led to a decrease of the particle collection by the electrostatic forces mechanism. The MPPS range remained the same after washing but the minimum filtration efficiency decreased to 30% which was similar to that of some community face masks. The breathability of the medical face mask was not impacted by washing.

This study has shown that community face masks although less performing in terms of PFE compared to the medical face mask, do present a non-null PFE even when washed. Washing medical face masks can be a suitable solution to reduce the negative environmental implication of their use. Both community face masks and medical face masks can be reused in a non-medical setting several times as a protective barrier against particles sizes $\geq 3 \mu\text{m}$ particle sizes as long as the masks are wearable.

Table A.1

Medical and community face masks references used in this study. 2L refers to 2 layers masks whilst 3L refers to 3 Layers masks.

Mask Category	Trademark	Reference in article	Photo
Mixed Fabric	Medimasque (MT-CN)	MF-A-3L	
	Proneem (VIRAL STOP®)	MF-B-2L	
	Le Mahieu (Le solidaire)	MF-C-3L	
	Gyneas (masque en tissu réutilisable)	MF-D-2L	
	Thuasne (Start Security)	MF-E-2L	
	Hero Lab (J17P75)	MF-F-3L	
100 % Cotton Fabric	Rozen (Masque 6 ROZEN)	CF-A-2L	
	Dim (masque barrière)	CF-B-3L	
	Champion (masque de protection)	CF-C-3L	
Medical face mask	Bioserenity (SKU: 1016-07007-EU)	Medical face mask	

One key limitation of this work is the fact that we did not consider possible leakage through the gaps around the masks as a result of mask design and improper wearing of masks. Community face masks and medical face masks unlike respirators are not designed to fit tightly, normal everyday use will result in unfiltered air being exhaled and inhaled through the gaps. These gaps could potentially affect the filtration efficiency and could lead to an increase in the risk of infection. In the future, effort should be placed on evaluating how these gaps may potentially affect the performance of new and washed masks.

CRedit authorship contribution statement

Henrietta Essie Whyte: Conceptualization, Conducting experiments, Writing – original draft. **Aurélien Joubert:** Conceptualization, Supervision, Writing – review & editing. **Lara Leclerc:** Conceptualization, Writing – review & editing. **Gwendoline Sarry:** Conceptualization. **Paul Verhoeven:** Conceptualization. **Laurence Le Coq:** Conceptualization, Supervision, Writing – review & editing. **Jérémy Pourchez:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Authors would like to thank the technical team of the Department of Energetic Systems and Environment (DSEE) of IMT Atlantique and the Department of Biological Materials and Inhaled Particles (BioPi) of Mines Saint Etienne for all technical help. We thank Nicolas Curt for the fabrication of the set-up for differential pressure measurements. We also thank Mathilde Escot for aiding with the washing of the masks.

Appendix

See [Table A.1](#)

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