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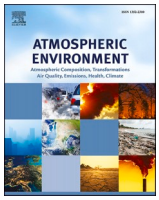

Determining the filtration effectiveness of non-standard respiratory protective devices by an ad-hoc laboratory methodology

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HIGHLIGHTS

- Innovative and low-cost lab methodology to define filtration efficiency of facemasks.
- The non-standard devices resulted in very low filtration efficiency.
- Using less cotton to create community masks increases particle filtration efficiency.
- Community masks have a limited protective effect on the users.

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ABSTRACT

The recent pandemic caused by COVID-19 profoundly changed people's habits. Wearing a face mask has become usual in everyday life to reduce the risk of infection from airborne diseases. At the beginning of the pandemic, the massive request of surgical or filtering face piece (FFP) masks resulted in a global shortage of these devices for the most exposed people, such as healthcare workers. Due to this high demand for respiratory protective devices, many industrial plants have partly converted to the production of face masks using adapted materials and not complying with any specific regulation (non-standard respiratory protective devices or community masks). In this work, an ad-hoc laboratory methodology has been developed to evaluate the filtration efficiency of the materials that compose the community masks using specific instrumentation. The instrumentation consists of three main tools: an aerosol generator, a specifically designed measuring chamber, and an optical particle sizer (OPS) for the measurement of aerosol concentration. The generated aerosol was sent into the measuring chamber, divided into two separate sections by the respiratory mask. The OPS measured the aerosol mass concentration upstream and downstream of the respiratory mask, and from the concentration difference the filtration efficiency was evaluated. The proposed methodology has been validated by evaluating the particle filtration efficiency (PFE) of certified respiratory masks and was then applied for the evaluation of the filtration efficiency of different types of non-standard or community masks to analyze their effectiveness in protecting from the risk of infection of airborne diseases.

1. Introduction

The pandemic caused by COVID-19 revealed significant requests by the world population for respiratory protective devices to reduce the risk of infection.

Various scientific outcomes have demonstrated that viruses are released during exhalation, talking, and coughing in microdroplets and the size distribution of the emitted droplets falls in the range of 0.5–1000 μm (Lednicky et al., 2020; Vuorinen et al., 2020). Large droplets generally settle rather quickly due to gravity while the submicrometric droplets (<100 μm in diameter) remain suspended in the air for a long time (Cortellessa et al., 2021; Scungio et al., 2022). Hygiene of the hands and the use of a face mask were often recommended to reduce the risk of infection from airborne diseases.

During the period of restrictions due to COVID-19, many countries have introduced the obligation to wear masks (also called half-face masks) in many indoor environments, such as public transport or stores, and outdoors if it was not possible to maintain social distancing measures. The face masks differ primarily regarding their intended use and consequently there are a variety of filtration efficiency tests of a

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filter layer, according to the material to be filtered: particulates, bacteria, and viruses. The test can then be divided into particulate filtration efficiency (PFE), bacterial filtration efficiency (BFE), and viral filtration efficiency (VFE).

The filtering half-face masks are designed to guarantee protection against fine specks of dust (generated by the crushing of solids), water-based mists and organic-based mists (liquid aerosols), and fumes (vaporized liquids). The half-face mask is intended to provide an adequate seal on the face of the wearer (Ippolito et al., 2020). The air passes through the mask or through one or more inhalation valves (if any) and goes directly to the nose and mouth area; the exhaled air passes through the filter material and/or exhalation valve (if present), directly to the ambient.

The European standards UNI EN 149:2009 and EN 13274–7:2008 define the specifications of respiratory protective devices (FFP, filtering face piece), in terms of particle filtration efficiency, and the test methodology. The standard UNI EN 149:2009 defines "the minimum requirements for the dust filtering half masks, used as respiratory protective devices" predicting three protection classes for these devices: FFP1, FFP2, and FFP3 (Fig. 1).

The three classes of FFP protection differ from each other because of the filtration effectiveness (penetration limit of the filter) and for total loss in TIL (total inward leakage, percentage of incoming air in the breathing area also including environmental pollutants or potentially pathogenic) (Rengasamy and Eimer, 2011; Rengasamy et al., 2018). The protection offered by FFP2 or FFP3 devices includes the protection offered by the lower-class device (FFP1); the presence of valves on these devices does not affect filtering capacity, but guarantees better comfort when the device is worn for a long time (Lee et al., 2016). Other standards concern the classification of the material filter, the U.S. and Chinese standards, such as NIOSH 42 CFR 84 and GB2626-2006 define the filtration efficiency limits for the personal respiratory protective device that guarantees protection for nanoparticles (Andrews et al., 2021; Duncan et al., 2021).

The filtration materials and devices designed to protect against biological aerosols, such as face masks, surgical gowns, and air filters are subject to bacterial filtration efficiency (BFE). Medical masks are regulated, in Europe, according to EN 14683:2019 + AC:2019, and categorized into Type I (BFE $\geq$95%), Type II, and Type IIR (BFE $\geq$98%) (Tessarolo et al., 2021; Whyte et al., 2022). These devices restrict the spread of large respiratory droplets and splashes, protecting the mouth and nose of the wearer and helping reduce the virus spread. Viral filtration efficiency (VFE) is a parameter used by mask manufacturers and the VFE test is utilized in the same procedure and setup as recommended by EN 14683 for BFE, by using a virus aerosol, instead of a bacterial one (Armentano et al., 2021; Whiley et al., 2020).

The medical (or surgical) masks are obtained by overlapping three layers of non-woven fabric with different capabilities (Armentano et al., 2021; Chua et al., 2020; Drabek and Zatloukal, 2019).

- Outer layer: confers mechanical resistance and hydrophobic properties.
- Middle layer: filter function.
- Internal layer: protective function for the face, avoiding direct contact with the middle layer.

One or more overlapping layers of non-woven fabric are used to realize both medical masks and community masks. Non-woven fabric is a generic term for fabric-like material made from fibers bonded together by chemical, mechanical, heat, or solvent treatment (Avinash Patil et al., 2021). The typical features of non-woven fabric are water repellence, resistance to high and low temperatures, softness, and non-abrasive to the touch.

A further classification regards the non-medical face masks, or community masks, as complementary hygiene measures. These devices include various forms of self-made face masks, made of cloth or other textiles disposable or reusable materials. These devices are not standardized and are not intended for use in healthcare settings but can decrease the release of respiratory droplets from the mouth.

In the first months of the pandemic, due to the high demand for respiratory protective devices, many industrial plants have partly converted to the production of these face masks using adapted materials and not complying with any specific regulation. In this work, an ad-hoc laboratory methodology has been developed to evaluate the filtration efficiency of the materials that compose the community masks using specific instrumentation. The instrumentation is composed by an aerosol generator (TSI Model 3076), a specifically designed measuring chamber, and an optical particle sizer (OPS - TSI Model 3330) for the measurement of airborne particle concentration (Scungio and Parlani, 2021). By means of this instrumentation an aerosol of sodium chloride is generated from saltwater solution; the aerosol was then sent into the measuring chamber, divided into two separate sections by the respiratory mask. The OPS measured the aerosol concentration upstream and downstream of the respiratory mask and from the concentration difference the filtration efficiency was evaluated. The proposed methodology has been validated by evaluating the particle filtration efficiency (PFE) of certified respiratory masks. These tests on certified respiratory masks confirmed the respect of the value of maximum aerosol penetration defined by the current regulations, and so the reliability of the methodology. The validated methodology was then applied for the evaluation of the particle filtration efficiency of different types of non-standard or community masks to analyze their effectiveness in protecting against the risk of infection from airborne diseases.

2. Materials and methods

The filtration efficiency of respiratory masks is defined based on the quantity of airborne particles (aerosol) that the mask can trap in its own fibers. The efficiency could be evaluated by means of specific tests, which are required for the certified masks, and whose detailed procedures are provided in the various standards. In general, the filtration

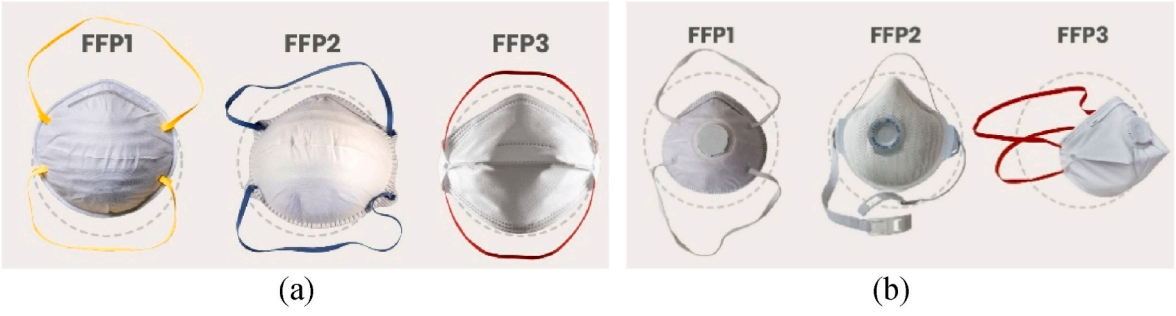

Fig. 1. Classification of certified face masks as provided by the European standard UNI EN 149:2009: (a) without valve; (b) with valve.

efficiency test is realized in a specific chamber, divided in two sections by the mask itself, crossed by an aerosol flow rate with specific characteristics. From the measurement of particulate mass concentration in the section before and after the mask, it is possible to calculate the percentage of particles trapped (particle filtration efficiency - PFE) or the percentage of particles that pass through the mask (penetration - P).

2.1. Experimental apparatus

The instrumentation used in this study for the evaluation of PFE, schematized in Fig. 2, is composed of a compressed air supply system, an aerosol generator system Model 3076, TSI, Minnesota, USA, HEPA filters, an aerosol drying system, connecting pipes, a measuring chamber and an Optical Particle Sizer (OPS) Model 3330, TSI, Minnesota, USA. The main components of the experimental setup are briefly described below.

- Aerosol generator (Model 3076, TSI, Minnesota, USA): able to atomize aqueous solutions or suspensions, generating submicrometer aerosols. The solvent for solid particles generation is distilled water. The particle size distribution of the generated aerosol depends on the concentration of the solute.
- Optical Particle Sizer (OPS Model 3330, TSI, Minnesota, USA): is a particle spectrometer that measures aerosol concentrations in terms of mass (μg/m^3), number (#/cm^3) and surface area (μm^2/m^3) as well as size distributions of particles with optical diameters from 0.3 μm to 10 μm.
- The measuring chamber, specifically designed and realized for the purpose of this study, consists of two mirror-like zones, separated by the filter material (mask). The two zones of the chamber are provided with a connecting element through which the aerosol concentration measurements are realized by means of the OPS 3330.

2.2. Aerosol generation

The aerosol generation process starts from a compressed airflow which is split and filtered through a membrane dryer to reduce the water and oil content generated by the compression process. Once filtered, the air flows pass through pressure regulators, connected to pressure gauges, allowing to regulate the pressure at 3.5 bar. After the first dehumidification, the two air flows are further filtered through two HEPA filters: the first airflow is sent to the aerosol generator while the second one is sent to the upstream measuring chamber as dilution air. In the aerosol generator, the water-based solution of NaCl is nebulized by means of a nozzle generating particles of different dimensions. The liquid fraction of the solution evaporates because of the interaction with the dry air flowing in the atomizer, generating sodium chloride aerosol. The larger particles are removed by impact on the walls of the atomizer, while the excess liquid is drained in the withdrawal reservoir. The dispersed aerosol passes through a drying system and then is flown in the measuring chamber as dry sodium chloride aerosol with a flow rate of 3 l/min. The total flow rate of NaCl aerosol and filtered dilution air is 50 l/min (3 l/min of dry sodium chloride aerosol and 47 l/min of dilution air) detected through a flowmeter.

2.3. Aerosol concentration measurement

The analysis of the filtration efficiency of the face masks tested in the measuring chamber was made by connecting the OPS 3330 at the two sections of the measuring chamber: upstream of the respiratory protective device (zone M1 in Fig. 3), and downstream of the respiratory protective device (zone M2 in Fig. 3).

The OPS TSI 3330 spectrometer operates according to the principle of optical scattering of individual particles. Particles are illuminated using a laser beam which illuminates the downstream area of the aerosol flow inlet nozzle. The pulses produced by the passage of particles through the laser are divided into 16 different channels, the intensity of the pulse is proportional to the size of the particles (dimensional range between 0.3 μm and 10 μm).

The total length of a single sample is 100 s: the first half of the sample (50 s) is made in the upstream zone of the measuring chamber, while the second half is made in the downstream zone. The switch between the two zones is made with the three-way valve installed before the inlet of the OPS; the sampling frequency is 1 s, so the total number of concentration data for the single sample is 100.

This process was repeated ten times for each respiratory protective device. The analysis was repeated on three samples for the same type of face mask. The value of aerosol penetration P through the filter material was measured by comparing the upstream and downstream mass concentration of particles in the measuring chamber, by using the following equation:

$$P[\%] = \frac{T}{C} \times 100 \quad (1)$$

where C is the average on the 50 data of upstream concentration, and T is the average on the 50 data downstream concentration.

The particle filtration efficiency, PFE, was defined using the following equation:

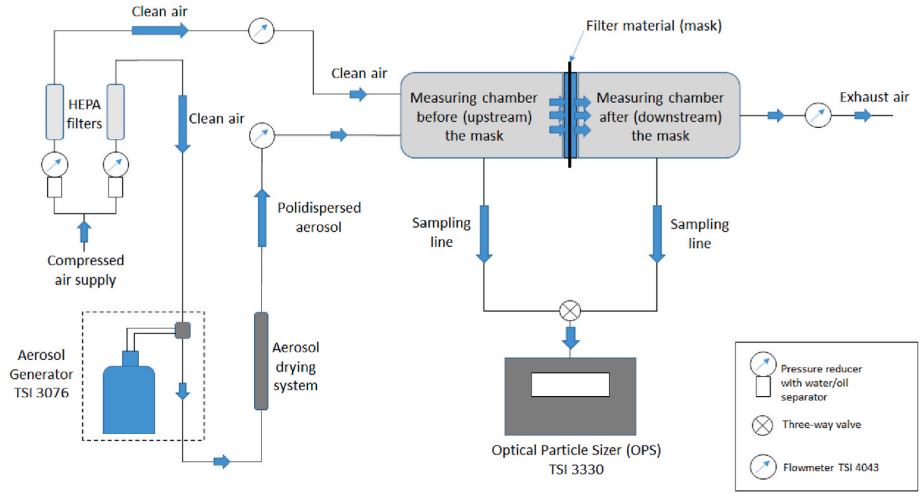

Fig. 2. Layout of the proposed setup for the particle filtration efficiency (PFE) or penetration (P) tests.

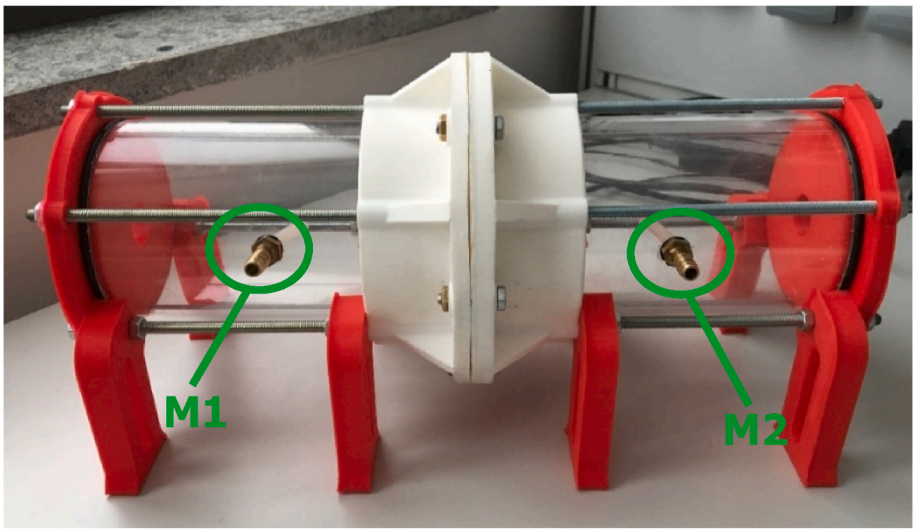

Fig. 3. 3D printed measuring chamber specifically designed and realized with the two-connecting elements for aerosol sampling.

$$PFE[\%] = (1 - P) \times 100 = \left(1 - \frac{T}{C}\right) \times 100 \quad (2)$$

2.4. Comparison of the proposed methodology with the European standard

The European standard UNI EN 149:2009 specifies the minimum requirements for the dust filtering half masks used as respiratory protective devices to guarantee the characteristics of efficiency, breathability, and stability of the structure. It also contains laboratory and practical use tests instructions for the assessment of conformity with requirements.

All the dust filtering half masks (with or without valves) must respect the requirements shown in Table 1 for the penetration test as reported in the EN 13274–7:2008 standard (Agolini et al., 2008).

According to the standard EN 13274–7:2008, the tests shall be carried out using sodium chloride aerosol, generated by one percent solution of NaCl reacting in distilled water. It is required a total aerosol flow rate of 95 l/min and an airflow pressure of 3.4–3.6 bar. The average aerosol concentration of NaCl in the measurement chamber must be 12 ± 4 mg/m^3. The dimensional distribution of the particle must be between 0.02 and 2 μm of the equivalent aerodynamic diameter with a mean diameter of 0.6 μm (on particle mass basis).

Due to the characteristics of the instrumentation used in the present work, the test parameters here described differ from the EN 13274–7:2008 in terms of volume flow rate of NaCl and mean aerosol concentration. A comparison between the test parameters provided by the EN 13274–7:2008 and the parameters used in the proposed methodology is reported in the following Table 2.

Due to these differences in test parameters, a validation of the methodology was necessary. In particular, a series of P and PFE tests on certified respiratory protective devices, for which the values of maximum aerosol penetration are known (Table 1), have been carried out.

Table 1
Value of maximum aerosol penetration allowed, according to UNI EN 149:2009.

Classification	Maximum aerosol penetration allowed [%]
FFP1	20
FFP2	6
FFP3	1

Table 2
Comparison between EN 13274–7:2008 standard test parameter values and test parameter values of the proposed methodology (laboratory value).

	Standard Value	Laboratory Value
Solutes in solvents [%]	1	1
Mass flow rate of NaCl [l/min]	95	50
Flow rate pressure [bar]	3.4–3.6	3.5
Mean aerosol concentration [mg/m^3]	12 ± 4	50–60 × 10^{-3}

2.5. Classification of the main filtering materials

Depending on their intended use, the facemasks differ each other and for this reason are subjected to different filtration efficiency tests of a filter layer: particulates, bacteria, and viruses. The filtering capacity, and hence the level of protection offered, depends on the materials of which they are composed. Facemasks are usually obtained with the use of synthetic thermoplastic polymers such as polypropylene (PP), polyurethane, polystyrene, polycarbonate, polyethylene (PET), or polyester, materials characterized by a random pattern of the fibers layered or crossed and mechanically joined together through different production processes (thermal bonded, chemical bonded, or mechanical reinforced) (Armentano et al., 2021; Pu et al., 2018). These materials characterize the main respiratory protective devices such as FFP masks and surgical masks (Blosi et al., 2021). Facemasks are made of a particular material called nonwoven, or TNT for short. Two different types of TNT are used for the manufacture of masks: TNT Spunbond and TNT Meltblown. The spunbond, is used to produce the outer layers because it is anti-drip. Within these layers is contained a variable quantity of TNT meltblown, which represents the main filtering material. In surgical masks there is only one layer of TNT meltblown, while in FFP1, FFP2 and FFP3 the layers are respectively 2, 3 or more (Armentano et al., 2021; Blosi et al., 2021; Pu et al., 2018).

For the realization of facemasks, the natural materials, as cotton fibers and their derivatives, are often used. They have different advantages related mainly to stretchability and wicking properties (Armentano et al., 2021; Babaarslan et al., 2018). Nevertheless it is well established that fibrous cellulosic materials, like cotton, are able to release large quantities of micron-scale particles into the air due to the molecules that are oriented parallel to one another and not arranged in a random pattern as in synthetic polymers (Chen et al., 2021; Feng, 2017; Ho et al., 2020; Licina et al., 2017). Recently, the idea of the use of the bio polymers to manufacture the facemasks as attempt to reduce the environmental impact from used masks during COVID-19 pandemic is

gaining ground (Hartanto and Mayasari, 2021; Junter and Lebrun, 2017; Pandit et al., 2021).

3. Results and discussion

3.1. Characteristics of the generated aerosol

Before starting the PFE tests, five preliminary analyses were conducted in order to investigate the aerosol characteristics in terms of number and mass concentration and size distribution. These analyses were performed by sampling with the OPS in the upstream section of the measuring chamber considering a total length of each sampling of 25 s.

The aerosol characteristics measured inside the measuring chamber, in terms of mass and number of particles per unit volume of sampled air, were evaluated in the dimensional range 0.3–10 μm, in 16 contiguous channels. The figures reported in hereafter show the main aerosol characteristics (Fig. 4, Fig. 5).

The results are reported in the dimensional range 0.3–1.117 μm, and not for the entire measured range 0.3–10 μm, since for larger diameters the concentrations in terms of mass and number were not significant. As can be seen from the previous figures, the main contribution in terms of both number and mass concentration is due to particles with diameters between 0.3 and 0.579 μm.

The data are shown as average values of particles number and mass concentration with the relative standard deviation of all the measurements. Therefore, the analysis of the data relating to the physical characteristics of the aerosol generated with the proposed methodology showed a predominance of small particles (average value of the five samples of 1.9×10^5 part./cm^3 in the size range 0.3 μm–0.374 μm) and a negligible number of large particles (average value of the five samples of 2.5×10^2 part./cm^3 in the size range 0.897 μm–1.117 μm). From the analysis of the data reported in Figs. 4 and 5, as well as in Table 3 and Table 4, it can be concluded that the main particles size was found in the range 0.3–0.579 μm, being negligible the contribution for the upper dimensional classes, as already reported. The results showed in this section, in terms of particle size distributions, are coherent with the operative characteristics of the aerosol generation system (Model 3076, TSI, Minnesota, USA), since this instrument is mainly used for submicrometer aerosol generation (with mode around 100 nm), therefore only the tail of the distribution of the generated aerosol can be observed with the OPS.

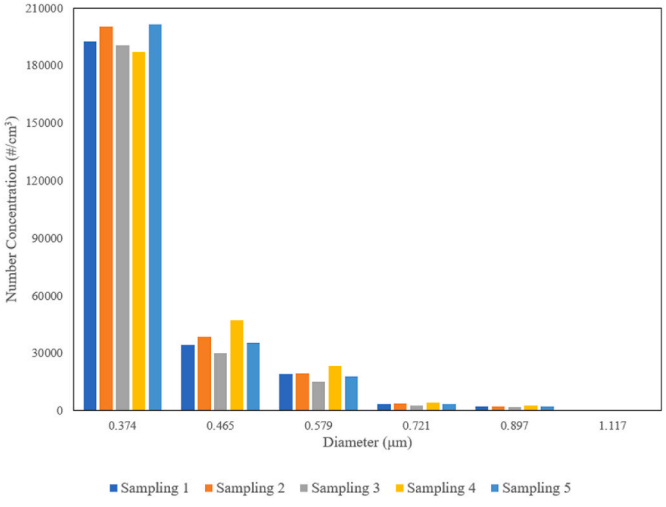

Fig. 4. Dimensional distribution of the aerosol measured in the upstream section of the measuring chamber in terms of particles number per cm^3 of sampled air, in the size range 0.3 μm–1.117 μm diameter.

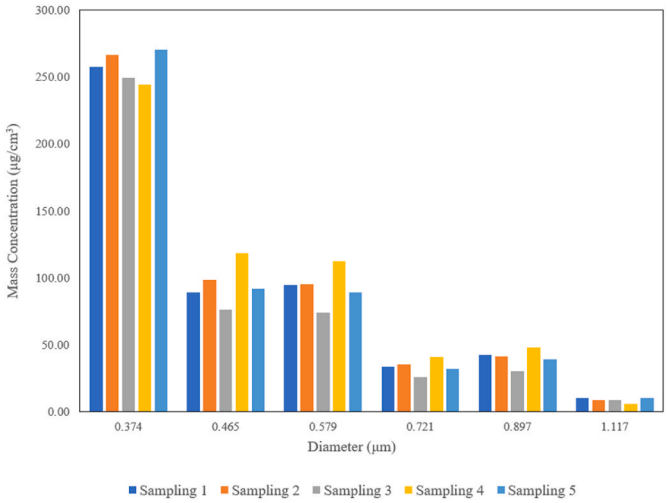

Fig. 5. Dimensional distribution of the aerosol measured in the upstream section of the measuring chamber in terms of particles mass concentration per cm^3 of sampled air, in the size range 0.3 μm–1.117 μm in diameter.

Table 3
Average concentration of the preliminary analysis of the aerosol measured inside the measuring chamber in terms of particle number concentrations per cm^3 of air.

Diameter [μm]	Average number concentration [#/cm^3]	σ
0.374	1.9×10^5	6.3×10^3
0.465	3.7×10^4	6.3×10^3
0.579	1.9×10^4	2.9×10^3
0.721	3.5×10^3	5.8×10^2
0.897	2.2×10^3	3.5×10^2
1.117	2.5×10^2	4.6×10^1

Table 4
Average concentration of the preliminary analysis of the aerosol measured inside the measuring chamber in terms of particle mass concentrations per cm^3 of air.

Diameter [μm]	Average mass concentration [μg/cm^3]	σ
0.374	257.64	9.88
0.465	94.91	13.84
0.579	93.31	12.27
0.721	33.67	4.78
0.897	40.35	5.72
1.117	9.00	1.53

3.2. Validation of the instrumentation and analysis of certified device

The validation of the instrumentation was conducted through PFE tests of certificated respiratory protective devices, for which the penetration P value was known. The results obtained are shown in the following table as the mean value of penetration (P), particle filtration efficiency (PFE), and standard deviation (σ).

Three different types of certified respiratory protective devices have been tested; the device EN 149:2001 FFP2 NR D and the device EN 149:2001 + A1:2009 FFP2 NR D must respect the requirements defined in the European standard UNI EN 149:2009 considering a maximum value of aerosol penetration of 6%, and then a maximum value of aerosol filtration efficiency of 94% (Table 1). For the other certified respiratory protective device analysed, named KN95 GB2626-2006, the filtration efficiency limits that guarantee protection are defined in the standard GB2626-2006 that establishes a maximum value of aerosol penetration of 5% and a maximum value of aerosol filtration efficiency of 95% (Andrews et al., 2021; Duncan et al., 2021).

From the analysis of the data reported in Table 5 relating to the P and PFE tests on certified respiratory protective devices, it can be concluded that the results in terms of penetration P for the three different types of mask are fully compliant with the limit values defined by the regulations for the aerosol penetration tests thus allowing to validate the proposed laboratory methodology. It is then possible to apply the validated methodology for the evaluation of the filtration efficiency of different types of non-standard or community masks, in order to analyze their effectiveness in protecting against the risk of infection from airborne diseases.

3.3. Filtration effectiveness tests on non-standard devices

3.3.1. Medical masks

For medial masks, the filtration materials are subjected to bacterial filtration efficiency (BFE) tests since these devices are designed to protect from biological aerosols. The validated methodology, however, made it possible to perform analysis also on the medial masks to define their particle filtration efficiency. The results of the P and PFE tests realized on surgical mask Type II (certified as ISO 10993 and EN 14683) are shown in Table 6.

Three different PFE tests on the same type of respiratory protective devices (surgical mask Type II) were realized. Aerosol concentration measurements were repeated ten times for each device. The results for the three PFE tests are respectively equal to 79.67%, 77.40% and 83.34% with values of standard deviation respectively equal to 0.30, 0.89, 0.39. From the analysis of the data reported in Table 6, the results in terms of PFE for the three different tests highlight lower particle filtration efficiency compared to the test realized on the certificated respiratory protective devices (FFP or KN, Table 5), where the particle filtration efficiency detected through the PFE tests was between 99.68% and 99.78%. These differences can be attributed to the fact that the FFP2 face mask has a structure of five layers of nonwoven material (Blosi et al., 2021), while the surgical masks are obtained by overlapping only three layers of non-woven fabric with different capabilities.

It is not pointless recalling that because of the use in a healthcare environment, the surgical masks are not subject to particles filtration efficiency (PFE) tests; for certification, they are subjected to bacterial filtration efficiency (BFE) tests in order to measure the resistance of the materials above-described to bacteria penetration and establish the appropriate efficiency category: Type I (BFE $\geq$95%), Type II, and Type IIR (BFE $\geq$98%) (Tessarolo et al., 2021; Whyte et al., 2022).

3.3.2. Community masks

The proposed validated methodology has been applied for the evaluation of the filtration efficiency of different types of non-standard or community masks in order to analyze their effectiveness in protecting against the risk of infection from airborne diseases. The different models of community masks tested are reported in Fig. 6.

The respiratory protective devices tested were realized by some Italian companies operating in the workwear industry and partially reconverted to produce masks at the beginning of the sanitary emergency related to the Covid-19 outbreak. A summary of the main features of the respiratory protective devices analysed is reported in the following Table 7.

In the following tables the results of the measurements on the community devices are reported. The results are summarised as average values of penetration P (Table 8) and PFE (Table 9); three samples for each kind of device were analysed. The different compositions of the community masks analysed, in terms of combination of various materials, result in different values of penetration and particle filtration efficiency.

From the analysis of the data reported in Tables 8 and 9 (average values of P and PFE), it can be observed a general reduction of the value of penetration P, and a consequent increase of the PFE, with the increasing of the number of layers and varying the weight of the TNT.

More in details, by carrying out a comparison between the results of average values of PFE between the device 1 (two layers: cotton - cotton) and the device 4 (three layers: polyester - TNT [30] - cotton), the particle filtration efficiency varies by more than 148% (15.88% for Device 1 and 39.45% for Device 4), conversely the penetration P varies from 84.12% for Device 1–60.55% for Device 4. An additional analysis can be made by evaluating the P value for Device 3 (three layers: TNT [60] – TNT [40] – cotton) and 4 (polyester – TNT [30] – cotton) and for surgical mask (that has an additional internal layer of TNT). The P values for devices 3 and 4 are equal to 67.78% and 60.55%, respectively, while for the surgical masks the P value was found between 16.66% and 22.60% (Table 6). Comparing the data, it can be observed a positive contribution to the overall filtration efficiency linked to the increasing use of TNT in the layering of the masks. The analysis of P and PFE values on the community masks has highlighted a significant increase of filtration efficiency with the use of TNT due to the random pattern of the fibers unlike an arrangement of weft and orthogonal warp, used for example for the manufacture of cotton. Increasing the number of layers and the quantity (weight) of TNT and reducing the use of cotton (limited for example for the internal layer just to provide protection for the face) results in a significant improvement of particle filtration efficiency. As a final thought, considering that the maximum value of penetration provided by the UNI EN 149:2009 is equal to 20% (for the lower-class FFP1 masks, Table 1), it can be concluded that the community masks can only have a limited protective effect for the users due to their scarce filtration capacity.

Finally, in Fig. 7 are reported as an example some time series of the measured mass concentration of aerosol inside the measuring chamber. It is clearly visible the difference in the concentration values measured before and after the masks, and the differences in filtration efficiency of the different devices analysed. In particular, it can be seen that with almost the same value of mass concentration of aerosol particles in the upstream section of the measuring chamber, there is a significant difference of the concentration levels measured after the masks, with the greatest difference for the FFP2 device.

Several studies about particle filtration efficiency of face mask materials are available in scientific literature (LaRue et al., 2021; Rengasamy et al., 2017; Sipkens et al., 2022). All these studies, however, have been carried out using highly specialized instrumentation which requires large upfront investments. The experimental apparatus proposed in the present work include specialized (spectrometer OPS 3330 and aerosol generator 3076, from TSI) and non-specialized (measuring chamber) equipment that, even showing some technological limits, has been validated for performing preliminary filtration efficiency tests. Referring in particular to the measuring chamber, it is worth mentioning that it can be easily realized just using a standard 3D printer, avoiding the high costs of dedicated specialized instrumentation. Therefore, among the advantages of the proposed experimental apparatus, the

Table 5
Results of the P and PFE tests on certified respiratory protective devices (mean values).

Device	$\overline{P}$ [%]	$\overline{PFE}$ [%]	σ
EN 149:2001 FFP2 NR D	0.32	99.68	0.06
EN 149:2001 + A1:2009 FFP2 NR D	0.22	99.78	0.04
KN95 GB2626-2006	0.23	99.77	0.05

Table 6
Results of the PFE tests on the respiratory protective device (surgical masks, subject to BFE tests according to the standard ISO 10993 and EN 14683).

Device	$\overline{P}$ [%]	$\overline{PFE}$ [%]	σ
Surgical mask Type II – Test 1	20.33	79.67	0.30
Surgical mask Type II – Test 2	22.60	77.40	0.89
Surgical mask Type II – Test 3	16.66	83.34	0.39

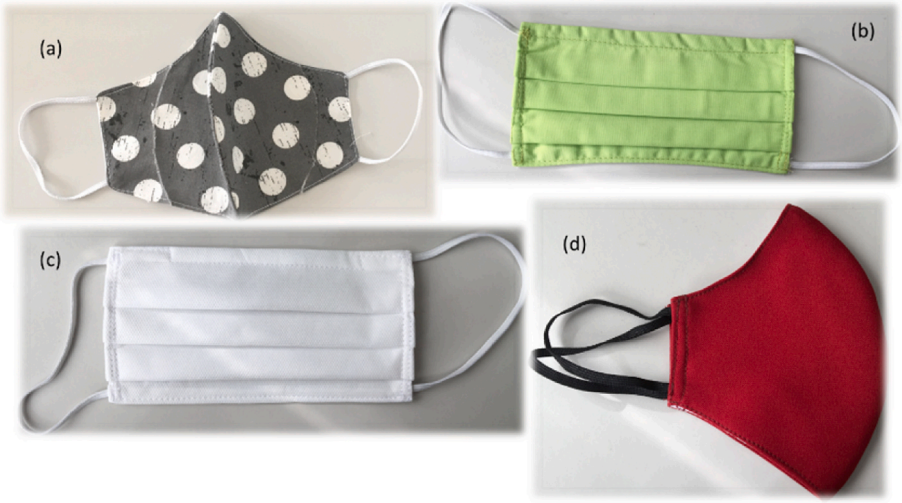

Fig. 6. Community masks examined in the present work: a) Device 1; b) Device 2; c) Device 3; d) Device 4.

Table 7
Characterization in terms of the number of layers and filter material of the community masks analysed in the present work (the value reported in square brackets is the weight of the material).

Device	Nr. layers	Outer layer material [g/m^2]	Middle layer material [g/m^2]	Internal layer material [g/m^2]
1	2	Cotton	/	Cotton
2	3	Cotton	TNT [30]	Cotton
3	3	TNT [60]	TNT [40]	Cotton
4	3	polyester 100%	TNT [30]	Cotton

Table 8
Results of the penetration 'P' tests on the community masks.

Device	Test 1 [%]	Test 2 [%]	Test 3 [%]	Average [%]	σ
1	84.33	84.37	83.67	84.12	0.32
2	78.21	79.28	79.43	78.97	0.54
3	67.19	67.86	68.30	67.78	0.46
4	60.60	60.87	60.19	60.55	0.28

Table 9
Results of the particle filtration efficiency "PFE" tests on the community masks.

Device	Test 1 [%]	Test 2 [%]	Test 3 [%]	Average [%]	σ
1	15.67	15.63	16.33	15.88	0.32
2	21.79	20.72	20.57	21.03	0.54
3	32.81	32.14	31.70	32.22	0.46
4	39.40	39.13	39.81	39.45	0.28

economic aspect plays a key role, as the significant costs related to the use of specialized equipment are often an obstacle to overcome, especially for small companies.

Furthermore, the particle analyzer used in this work (OPS 3330) can eventually measure particles from 0.3 to 10 μm in size allowing filtration measurements on various particle sizes beyond those defined by standards.

These aspects make the experimental setup presented in this paper a versatile, reliable, and relatively cheap solution for conducting preliminary filtration analysis of face masks.

4. Conclusion

In this work an ad-hoc laboratory methodology for the evaluation of the filtration efficiency of non-standard respiratory protection devices has been developed and tested. The experimental setup is composed of three main components: i) sodium chloride aerosol generator; ii) specifically designed measuring chamber and iii) optical particle sizer for the measurement of aerosol concentrations. In particular, the measuring chamber is composed of two sections separated by the filtration material under examination. The aerosol generated is flown inside the measuring chambers and passes through the filtering material: a measurement of aerosol mass concentration in the upstream and downstream sections of the measuring chamber allows to evaluate the particle filtration efficiency (PFE) or penetration (P) from the mass concentration difference.

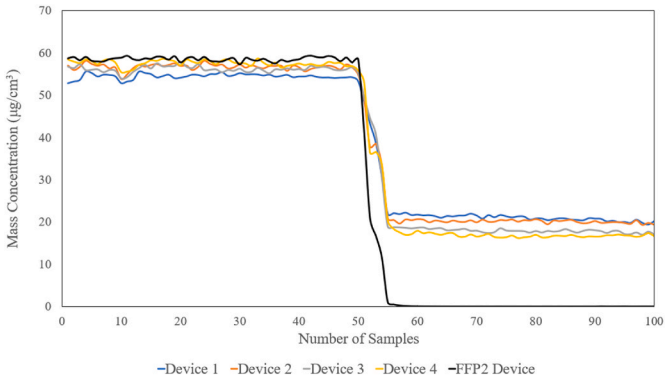

Fig. 7. Typical time series of mass concentration measured upstream (first 50 s of sampling) and downstream (last 50 s of sampling) of the different face masks tested inside the measuring chamber.

The proposed experimental setup was firstly validated by measuring the PFE values of certified FFP2 masks and then was applied in the evaluation of particle filtration efficiency of surgical masks and "community" masks (or non-standard respiratory protection devices).

The results of penetration P tests on certified devices (FFP2) were fully compliant with the limits provided by the reference regulations, which allow a maximum value of aerosol penetration equal to 6%, being between 0.22% and 0.32%.

The filtration tests on the surgical masks (Type II) showed PFE values between 77.40% and 83.34% with values of standard deviation between 0.30 and 0.89. Even if for surgical masks the filtration materials are subjected to Bacterial Filtration Efficiency (BFE), the filtration efficiency in terms of PFE was found lower with respect to the certificated respiratory protective devices (FFP or KN), for which the particle filtration

efficiency detected through the PFE tests was found between 99.68% and 99.78%.

As regards the community masks, the filtration efficiency was found lower with respect to both surgical and FFP2 masks, with values of penetration P between 60.55% and 84.12% (and PFE values between 15.88% and 39.45%). As a general remark, it can be observed a general reduction of the value of penetration P, and a consequent increase of the PFE, with the increasing of the number of layers and varying the weight of the TNT in the filtering material due to the random pattern of the fibers unlike an arrangement of weft and orthogonal warp. Finally, considering that the maximum value of penetration P provided by the UNI EN 149:2009 is equal to 20% (for the lower-class FFP1 masks), it can be concluded that the community masks can only have a limited protective effect for the users due to their scarce filtration capacity.

CRediT authorship contribution statement

Mauro Scungio: Conceptualization, Resources, Methodology, Writing – original draft, Supervision. **Giulia Parlani:** Validation, Data curation, Formal analysis, Investigation, 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.

Data availability

No data was used for the research described in the article.

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