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Study of Surface Morphology and Effectiveness of Common Nasopharyngeal Masks: A Case of Kathmandu, Nepal

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Abstract: Facemasks are widely used worldwide to prevent inhaling airborne particles and viruses, especially after the outbreak of COVID-19. To assess the effectiveness of various facemasks against PM_{10} and $PM_{2.5}$, experiments with a mannequin head were conducted at 10 and 55 LPM airflow rates. A total of 38 masks, including 26 CMs, 7 SMs, and 5 N95 masks, were tested against PM_{10} and $PM_{2.5}$ at 55 LPM airflow rate, while 18 masks, including 10 CMs, 6 SMs, and 2 N95 masks, were tested at 10 LPM airflow rate. The surface morphology of these facemasks was examined using a simple digital microscope of 0.3 M image sensor. SMs and N95 masks had smaller pore sizes and higher porosity, resulting in higher filtering efficiency. In contrast, CMs had larger pore sizes and lower porosity, leading to poor filtering efficiency. The average pore sizes of SMs and CMs were 70 µm and 160 µm, respectively, while their porosities were 99 pores/mm^2 and 20 pores/mm^2, respectively. N95FFRs had an average pore size of 49 µm with a porosity of 88 pores/mm^2. The average filtering efficiency of facemasks followed the order N95 FFRs > SMs > CMs. The Prototype Cloth Masks (PTCMs) were stitched using cotton fabrics with adjustable ear straps, nose pins, and polypropylene (PP) fabric as the filter. Their filtering efficiency was found to be nearly equivalent to N95 masks and their performance did not deteriorate even after five washing and drying cycles. This facemask can help reduce particulate exposure, particularly in developing countries with high air pollution, such as the Kathmandu Valley.

Keywords: PM_{10}, $PM_{2.5}$, Efficiency, Facemasks, Particulate Matter

Introduction

Air pollution is becoming a serious concern in many low and middle-income countries due to the rapid and unplanned growth of urban areas, the increasing number of vehicles, and the growing industrial activities. The prime cause of air pollution is Particulate Matter (PM), a complex mixture of chemically and physically heterogeneous substances that exist as discrete suspended particles such as liquid droplets or solid fragments (Hankey *et al*., 2017; Duffney *et al*., 2023). PM particles with an aerodynamic size of 10 µm or less (PM_{10}) and 2.5 µm or less ($PM_{2.5}$) are associated with a negative impact on health, climate, and visibility that can have adverse impacts on the environment (Davidson *et al*., 2005).

The Kathmandu Valley, the capital city of Nepal, is facing severe air pollution and is one of the most polluted cities in the world (Mahapatra *et al*., 2019). Pollution levels have skyrocketed in recent years, with levels several times higher than the recommended limit by the World Health Organization (WHO). In 2021, the Kathmandu Valley was ranked 232nd out of the 7323 cities in the world for air pollution by IQAir, with a yearly average $PM_{2.5}$ level more than ten times higher than the WHO safer limit (IQAir, 2021). The deteriorating air quality in the valley has put hundreds of thousands of people at risk of health problems (Karki *et al*., 2016) and air pollution is the leading risk factor for death and disability in Nepal, according to the WHO (WHO, 2023). Several factors have contributed to the poor air quality in the Kathmandu Valley, including growing vehicle numbers, dust from unpaved roads, different construction activities, emissions from brick kilns, and open burning of biomass and solid wastes (Kim *et al*., 2015). The bowlshaped topography of the valley and temperature inversion by slow vertical convection (Panday *et al*., 2009; Parajuly, 2016) further aggravates the situation. The air pollution in the valley is causing a severe impact on the health and welfare of people (Karki *et al*., 2016; Mage *et al*., 1996), with anticipation of 24,000 premature annual deaths in the country by 2030 (Shindell *et al*., 2012).

The enforcement of long-term and short-term policies (personal-level interventions such as using respiratory protective devices) are the two possible risk-mitigating measures for harmful particulate exposure (Januszkiewicz and Kowalski, 2019; Neupane *et al*., 2019). The government of Nepal has implemented some long-term policies, such as the National Ambient Air Quality Standards 2012, Nepal Vehicle Mass Emission Standards 2012 (NVMES), Environment-Friendly Vehicle and Transport Policy 2014 (Pant and Gurung, 2019) and Municipal Action Plan for Air Quality in the Kathmandu Valley 2022 (USAID, 2022), to name a few, to improve the air quality of Nepal. However, these policies have not yet manifested any impact on the quality of air in the valley and it may take a couple of years before the pollution level subsides to a safer limit. Therefore, short-term personal-level interventions, such as using respiratory protective devices like facemasks, are one of the practical solutions to reduce exposure to harmful particulate matter before the pollution level subsides due to the enforcement of the long-term policy. Wearing facemasks is an immediate and short-term practical solution to protect from exposure to particulate matter and other contaminants (MacIntyre and Chughtai, 2015; Tcharkhtchi *et al*., 2021).

There are different facemasks, such as Cloth Masks (CMs), Surgical Masks (SMs), and Filtering Facepiece Respirators (FFRs). Cheaper cloth masks are usually made of synthetic or natural cloth fabric and come in double-layer (two-ply) with stretchable elastic straps that are knotted behind the head or worn over the ears for better adherence to the face (Neupane *et al*., 2019; Shakya *et al*., 2017). Surgical masks are made of non-woven polypropylene and come in three layers, with the outer layer being non-woven and the middle layer being melt-blown polypropylene fabric (Drabek and Zatloukal, 2019). Other polymer products like polyurethane, polystyrene, polycarbonate, polyethylene, and polyester are also used to produce surgical masks on a commercial scale (Konda *et al*., 2020). N95 Filtering Facepiece Respirators (FFRs) are made of layers of synthetic fabrics and have multiple layers, including spun-bond non-woven polypropylene fabrics in outer layers followed by a pre-filtration layer and melt-blown electret non-woven material in the inner layer (Liu *et al*., 2017; OSHA, 2015). FFRs are labeled as N95, N99, and N100 in the USA that meets the U.S. National Institute for Occupational Safety and Health (NIOSH) standards (Yim *et al*., 2020), whereas FFRs are labeled as KN90, KN95 and KN100 in China that meets Chinese standards (Ippolito *et al*., 2020). Facemasks with a filtering efficiency of over 95% are considered effective (Neupane *et al*., 2019). However, their efficiency is affected by factors such as particle size, aerosol charge, types of mask material, pollutant concentration, and airflow rate (Gardner *et al*., 2013; He *et al*., 2014; Mueller *et al*., 2018). The edge-seal leakage between the edge of the respirator and the face is crucial in determining the efficiency of facemasks and depends on factors like the size and shape of a human face, facial hair, respiratory design, and way of wearing (Cherrie *et al*., 2018).

In the Kathmandu Valley, many people, especially pedestrians and bike riders, used to wear locally stitched cheaper cloth masks before the outbreak of COVID-19 to protect themselves from exposure to air pollution. Surgical masks were used only in hospitals and a few industrial settings, while N95 FFRs were barely available in Nepal. However, with the COVID-19 pandemic in 2019, the use of facemasks has become widespread in Nepal and now, different types of facemasks are readily available in the Nepalese market. Despite this, many people still prefer locally stitched cloth masks because they are cheaper than surgical and N95 FFRs, reusable after washing, and stitched by local tailors. While N95 FFRs have a better filtering efficiency than cloth and surgical masks (Sankhyan, *et al*., 2021; Yim *et al*., 2020), they are expensive and not accessible to most people. Surgical masks are cheaper than N95 FFRs but are not reusable and more costly than cloth masks. Various studies have shown that cloth masks have poor filtering efficiency, but if their filtering efficiency is improved, these mask can help protect thousands of people from exposure to harmful particulate matter in Nepal.

Following the COVID-19 outbreak, various types of facemasks flooded the Nepalese market. However, there has been limited research conducted in Nepal to examine the effectiveness of these masks. In a study by Shakya *et al*. (2017), three cloth masks and one pleated surgical mask were collected from street vendors in Kathmandu, Nepal, in 2014. The filtering efficiency of these masks was assessed using five different monodispersed aerosol sphere sizes (30, 100 and 500 nm and 1 and 2.5 um) and diluted whole diesel exhaust. The result was then compared to the standard N95 mask performance. Although this study examined the efficiency of some facemasks available in the Nepalese market, only a few samples were used in this study. Neupane *et al*. (2019) studied the morphology of twenty different kinds of cloth masks and seven brands of surgical masks available in Nepal to measure their filtering efficiency. They also studied the impact of washing and drying on the filtering efficiency of cloth masks. This study concluded that the filtering efficiency of cloth masks is inferior to surgical masks and washing and drying further deteriorate the efficiency of these masks. Although this study included a considerable number of cloth masks, examined their surface morphology, and studied the effects of washing and drying on their filtering efficiency, they did not work on improving the efficiency of these masks.

This study aims to examine the filtering efficiency of different kinds of CMs, SMs, and N95 FFRs available in the Nepalese market, study their surface morphology, and improve the filtering efficiency of locally stitched cloth masks which is not affected by multiple washing and drying cycles.

Materials and Methods

This experimental study was conducted in 2020 from February to March and August to November at North Valley School open ground in Kathmandu. The study aimed to determine the filtering efficiency of different facemasks in a real-world scenario where humans inhale respirable fractions of atmospheric aerosols. To achieve this, an experimental setup was built consisting of a mannequin head, two hand-held air quality monitors, a piece of plastic pipe (1 cm diameter), a plastic bag with pores, a power supply and an air pump (ISO-certified ACO-308 model having a pressure of >0.025 MPa) as shown in Fig. 1. The supply side of the air pump is connected to the facemask attached to the mannequin's nostrils through a connector and two pieces of plastic pipe, while the delivery side of the pump is connected to the plastic bag through a plastic pipe. One air quality monitor measures the PM concentration in the ambient air, while the other in the plastic bag measures the PM concentration in filtered air through the facemask attached to the mannequin. The air pump draws in ambient air containing PM of different sizes through a facemask attached to the mannequin's nostrils and discharges it to the plastic bag. The hand-held air quality monitors used were from BLATN Science and Technology Beijing Co., Ltd. (Model: BR-Smart-125), a real-time monitoring device for both indoor and outdoor environments. It has a resolution of 1.0 μg/m^3, an accuracy of ±10%, and a measuring range of 0-999 μg/m^3. This device automatically averages the measured data every minute and records it on the memory card. It employs light scattering measurement technology to measure the concentration of particulate matter.

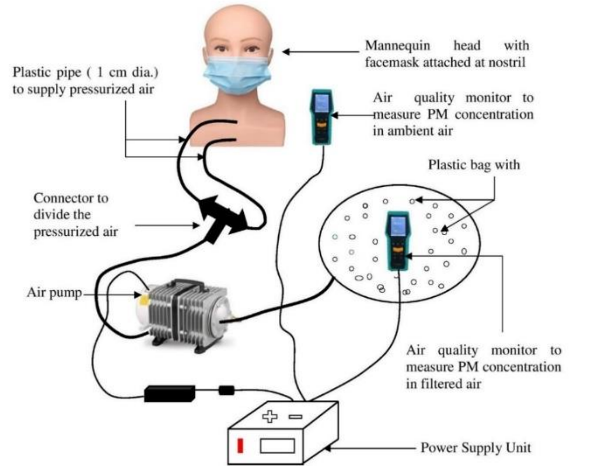


Fig. 1: Schematic diagram of the experimental setup to test the filtering efficiency of facemasks

This experiment was conducted at two air flow rates, first at a 55 LPM airflow rate to mimic walking and running conditions (Cherrie *et al*., 2018) and second at a 10 LPM air flow rate to mimic normal human breathing conditions (Nishi, 2004). The purpose of testing at two different airflow rates was to assess how much the filtering efficiency of the facemask changes with a change in airflow rate. Each facemask was tested for an hour.

Sample Size

A total of 38 masks, including 26 cloth masks, seven surgical masks, and five N95 masks, were collected randomly from various locations in the Kathmandu Valley. Their filtering efficiency was tested at a 55 LPM air flow rate. Additionally, eighteen masks consisting of ten cloth masks, six surgical masks, and two N95 masks were obtained from street vendors and tested at a 10 LPM airflow rate. All the cloth masks we collected had two layers, while the surgical masks and N95 masks had three layers.

Surface Morphology

The surface morphology of facemasks was studied using a simple digital microscope with a 0.3 m Complementary Metal-Oxide-Semiconductor (CMOS) image sensor (interpolated to 2.0 MPIX). The microscope has a default image resolution of 2560×1920 and a magnification of ~1000× with a focus range of ~15 to 40 mm. This microscope was pre-calibrated with a 5 mm micro calibration ruler. The facemasks were placed on it where pore size and porosity (number of pores per unit area) of the sampled fabrics were visually counted multiple times using its default HiView image analysis software in a Field of View (FOV) of 4.5 mm^2 for better accuracy.

(a)

(b)

Fig. 2: Images of the sample PTCM; (a) Front surface; (b) Back surface

Efficiency Estimation

The filtering efficiency of facemasks is known as effectiveness and it was calculated using Eq. (1) (Cherrie *et al*., 2018; He *et al*., 2014):

$$Effectiveness = (No\ Mask - With\ Mask)/No\ Mask \times 100\% \quad (1)$$

In Eq. (1), '*No mask*' is the PM concentration measured without wearing a facemask, and '*with mask*' is the PM concentration measured wearing a facemask on a human mannequin head.

Stitching of Prototype Cloth Masks (PTCMs)

Thirty number of Prototype Cloth Masks (PTCMs) were stitched in collaboration with a local garment factory in Kathmandu, Nepal. These Prototype Cloth Masks (PTCMs) were stitched using cotton fabrics with adjustable ear straps, nose pins for better adherence to the face, and pockets for inserting filters. We used Polypropylene (PP) fabric as the filter in this study. To ensure user comfort**,** the breathability of stitched PTCMs was tested on 20 random users. Fig. 2 shows the images of PTCM used in this study.

Results

Surface Morphology

The surfaces of all facemasks had irregular pores with varying shapes and sizes. Their quantitative information was gathered by measuring the longest and shortest dimensions of the fabric pores and porosity. Porosity refers to the the number of pores per unit area which is also known as pore number density.

The data presented in Table 1 displays the average pore sizes and porosity of surgical masks. The average pore size was found to be 70 μm, with a range of 60-80 μm. Additionally, the average porosity was found to be 99 pores/mm^2, with a range of 81-115 pores/mm^2. It is evident from Table 1 that as pore size decreases, porosity increases. Fig. 3 demonstrates that the surgical masks possess a complex network of microfibers interconnected and exhibits similar surface characteristics. The surgical masks used in this study had three layers of Polypropylene fabrics (PP).

Table 2 presents the average pore sizes, the porosity, and the fabrics used in the cloth masks. The average pore size of the cloth masks was 160 μm, with a range of 80-290 μm. The porosity level varied from 8-32 pores/mm^2, with an average of 20 pores/mm^2. The table shows that porosity increases as pore size decreases. As shown in Fig. 4. the cloth masks had a simple woven bonded fabric integration with a wide range of pore sizes and different surface characteristics from each other. The cloth masks used in this study had two layers.

Table 1: Average pore size and porosity of Surgical Masks (SMs)

SN	SMs	Average pore size (μm)	Porosity (No. of pores/mm^2)
1	SM1	60	113
2	SM2	70	97
3	SM3	70	105
4	SM4	60	115
5	SM5	80	81
6	SM6	80	86
7	SM7	70	95
Average		70	99

Table 2: Average pore size, porosity, and fabrics used in the Cloth Masks (CMs)

SN	Cloth Masks (CMs)	Pore size (μm)	Porosity (No. of pores/mm^2)	Fabric used in CMs
1	CM1	290	8	Polyester
2	CM2	270	12	Polyester
3	CM3	140	20	Polyester
4	CM4	140	20	Polyester
5	CM5	220	14	Viscose
6	CM6	110	24	Polyester
7	CM7	160	18	Lycra
8	CM8	150	19	Synthetic
9	CM9	170	21	Lycra
10	CM10	200	16	Lycra
11	CM11	190	20	Synthetic
12	CM12	130	23	Synthetic
13	CM13	110	27	Synthetic
14	CM14	180	15	Lycra
15	CM15	140	21	Cotton
16	CM16	170	22	Polyester
17	CM17	150	16	Synthetic
18	CM18	80	32	Cotton
19	CM19	170	21	Synthetic
20	CM20	130	24	Cotton
21	CM21	90	31	Synthetic
22	CM22	120	20	Cotton
23	CM23	140	21	Cotton
24	CM24	130	26	Cotton
25	CM25	210	16	Cotton
26	CM26	180	18	Synthetic
Average		160	20	

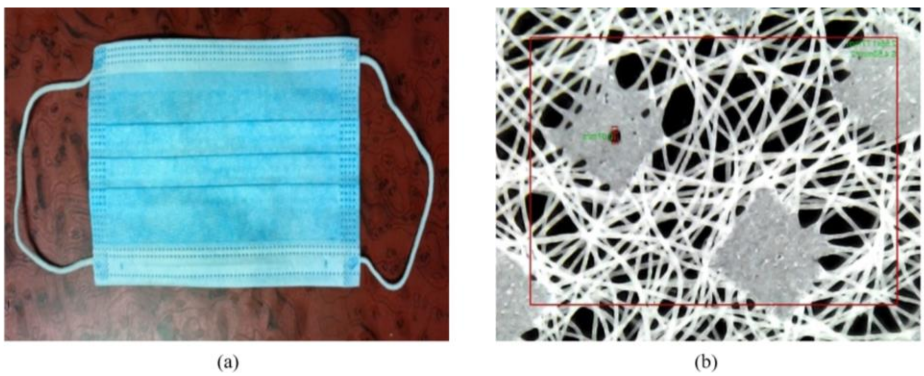


Fig. 3: (a) Representative image of the surgical masks and; (b) Microscopic image of its inner layer

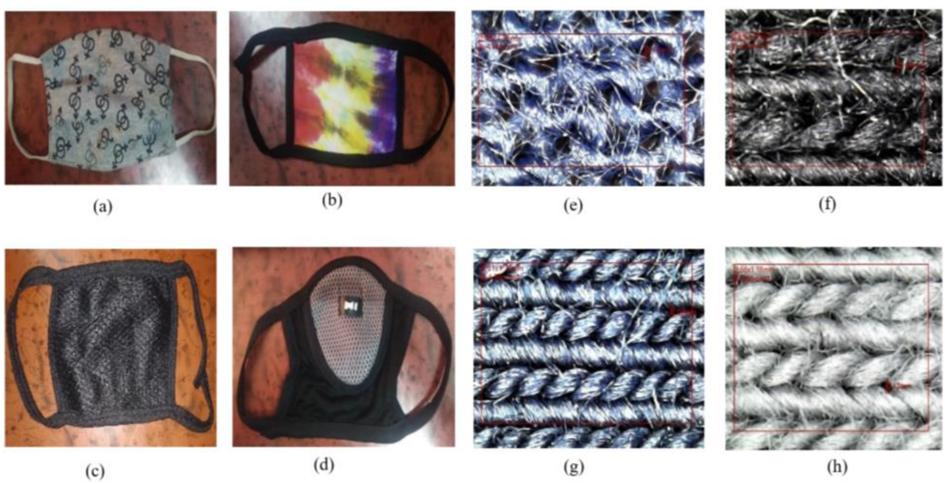


Fig. 4: Representative surface images of CMs; (a) CM2; (b) CM14; (c) CM20; (d) CM26 and microscopic images of their inner layers; (e) CM2; (f) CM14; (g) CM20 and; (h) CM26

Table 3: Average pore size and porosity in the N95 FFRs

SN	N95 FFRs	Pore size (μm)	Porosity (No. of pores/mm^2)
1	N95 (i)	54	74
2	N95 (ii)	50	80
3	N95 (iii)	41	100
4	N95 (N.P)	66	60
5	$PM_{2.5}$ (N.P)	42	96
6	NIOSH Respirator	40	115
Average		49	88

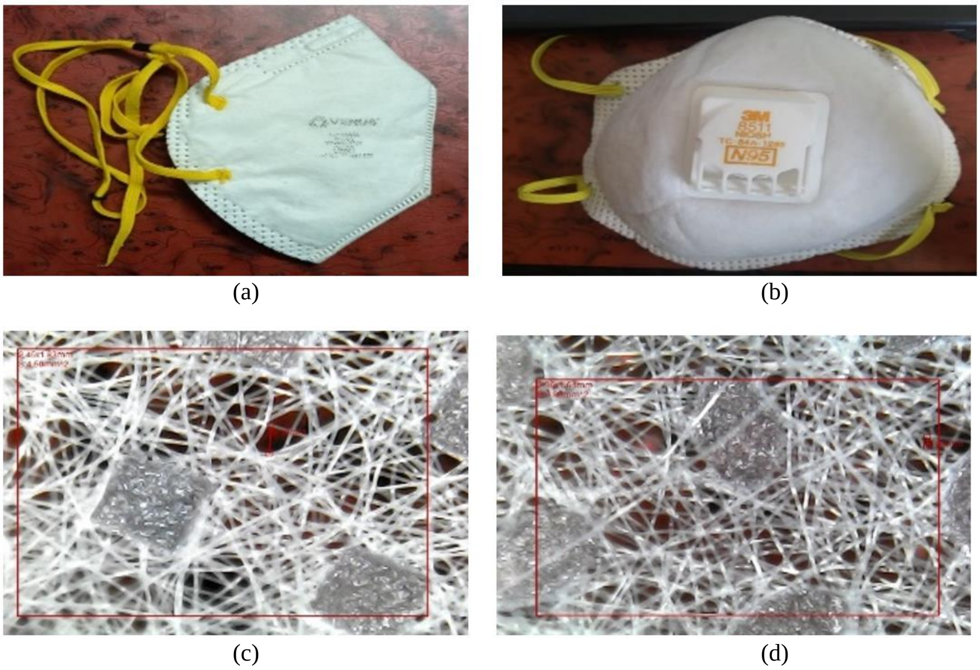
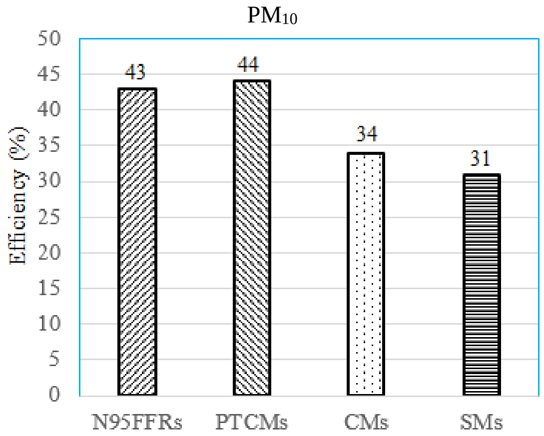


Fig. 5: Representative surface images of N95 FFRs; (a) N95 (i); (b) N95 (ii) with exhaust valve and microscopic images of their inner layer; (c) N95 (i); (d) NIOSH respirator

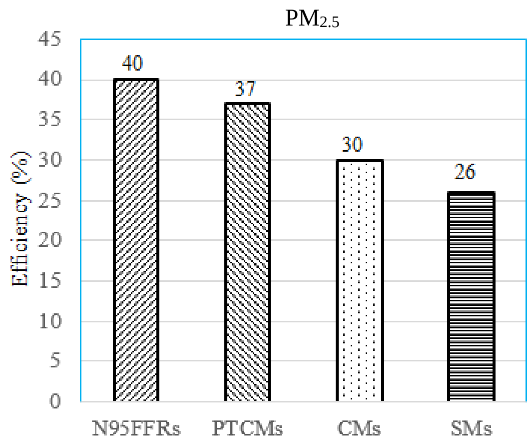
Table 3 provides information on the pore sizes and porosity of N95 FFRs. The average pore size of the sampled N95 FFRs was 49 μm and ranged from 40-66 μm. The average porosity was 88 pores/mm^2, with a range of 60-115 pores/mm^2. The N95 NP (NP-Nepal Product) had the lowest porosity (60 pores/mm^2), while the NIOSH respirator had the highest porosity (115 pores/mm^2). The N95 FFRs had a complex web-like network of microfibers interconnected and exhibited similar surface characteristics. They come in two variants, one with an Exhaust Valve (EV) and another without. Fig. 5 shows the surface structure of N95 FFRs. The N95 FFRs used in this study had four layers of Polypropylene fabrics (PP).

Facemasks Filtering Efficiency

Several experiments were conducted at 10 LPM and 55 LPM airflow rates to assess the filtering efficiency of facemasks against PM_{10} and $PM_{2.5}$. During the 55 LPM airflow rate test against ambient PM_{10}, the filtering efficiency of the SMs varied from 19-40%, with a mean of 31% and an average variance of 14.8%. The efficiency of the CMs ranged from 24-40%, with a mean of 34% and an average variance of 14.4%. We observed that N95 FFRs exhibited better filtering efficiency (mean 43%) against ambient PM_{10} than surgical and cloth masks, with an average variance of 13.8%. The PTCMs performed slightly better than N95FFRs and their efficiency ranged from 35-56%, with a mean of 44% and an average variance of 14%. It was observed that all the facemasks had a lower filtering efficiency against ambient $PM_{2.5}$ compared to PM_{10} at 55 LPM airflow rate. The efficiency of surgical masks varied between 18-33%, with a mean of 26% and an average variance of 10% against $PM_{2.5}$. The cloth masks had a filtering efficiency of 10-35%, with a mean of 30% and an average variance of 16.1% compared to surgical masks. Likewise, the N95 FFRs and PTCMs had efficiencies ranging from 30-57% (mean 40% and average variance of 8.9%) and 28-51% (mean 37% and average variance of 11.72%), respectively. Fig. 6 shows the average filtering efficiencies of cloth masks, surgical masks, N95FFRs, and PTCMs against PM_{10} and $PM_{2.5}$ at 55 LPM airflow rate.



(a)



(b)

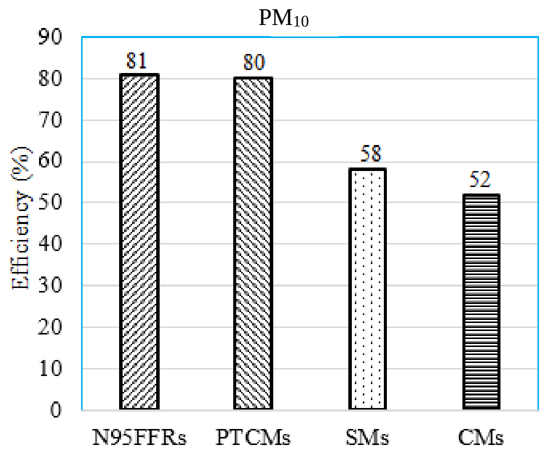
Fig. 6: Average filtering efficiency of facemasks (a) against PM_{10}; (b) against $PM_{2.5}$ at 55 LPM airflow rate

Based on the experiments conducted to assess the filtering efficiency of facemasks against PM_{10} and $PM_{2.5}$, it was observed that all the facemasks performed better at a 10 LPM airflow rate compared to the 55 LPM airflow rate experiment. In the 10 LPM airflow rate experiment, the filtering efficiency of surgical masks against ambient PM_{10} ranged from 50-69%, with a mean of 58% and an average variance of 12.7%. On the other hand, the cloth masks had a wide variation in efficiency from 34-63%, with a mean of 52% and an average variance of 20.15%. However, N95 FFRs had good efficiency, ranging from 74-88%, with a mean of 81% and an average variance of 5.25%. The efficiency of PTCMs was slightly lower than that of N95 FFRs, with a mean of 80% and an average variance of 5.44%. Its efficiency varied from 74-89%.

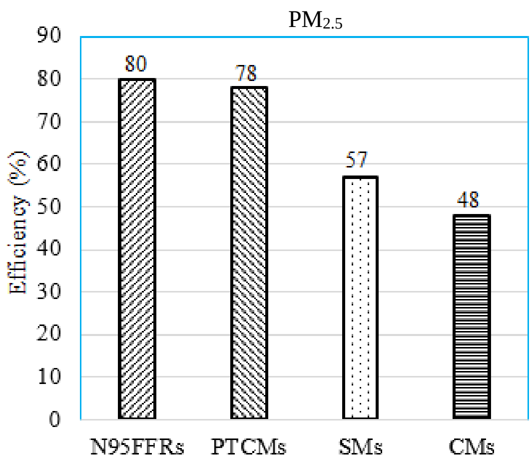
However, it was observed that facemasks had a slightly lower filtering efficiency against $PM_{2.5}$ compared to PM_{10} at 10 LPM airflow rate. The filtering efficiency of surgical masks against ambient $PM_{2.5}$ ranged from 48-64%, with a mean of 57% and an average variance of 9.96%. The cloth masks had a filtering efficiency of 32-62%, with a mean filtering efficiency of 48% and an average variance of 16.1%. N95 FFRs had a filtering efficiency ranging from 73-86%, with a mean of 80% and an average variance of 4%, while PTCMs had a slightly lower filtering efficiency than N95FFRs, with a mean of 78% and variance of 4% and its efficiency varied from 71-87%. Fig. 7 illustrates the average filtering efficiency of cloth masks, surgical masks, N95 FFRs and PTCMs against PM_{10} and $PM_{2.5}$ measured at 10 LPM airflow rate.

Efficiency as a Function of Length of Use

Each facemask was tested for an hour to assess the filtering efficiency. As the instrument used in this study automatically averages the measured data every minute, the facemask efficiency was calculated for each recorded data and plotted in the graph to examine whether the length of use affects facemask efficiency. The plotted graphs are presented in Fig. 8 for different types of facemasks. This figure shows no specific trend in the efficiency of the facemask within an hour.



(a)



(b)

Fig. 7: Average filtering efficiency of facemasks (a) against PM_{10}; (b) against $PM_{2.5}$ at 10 LPM airflow rate

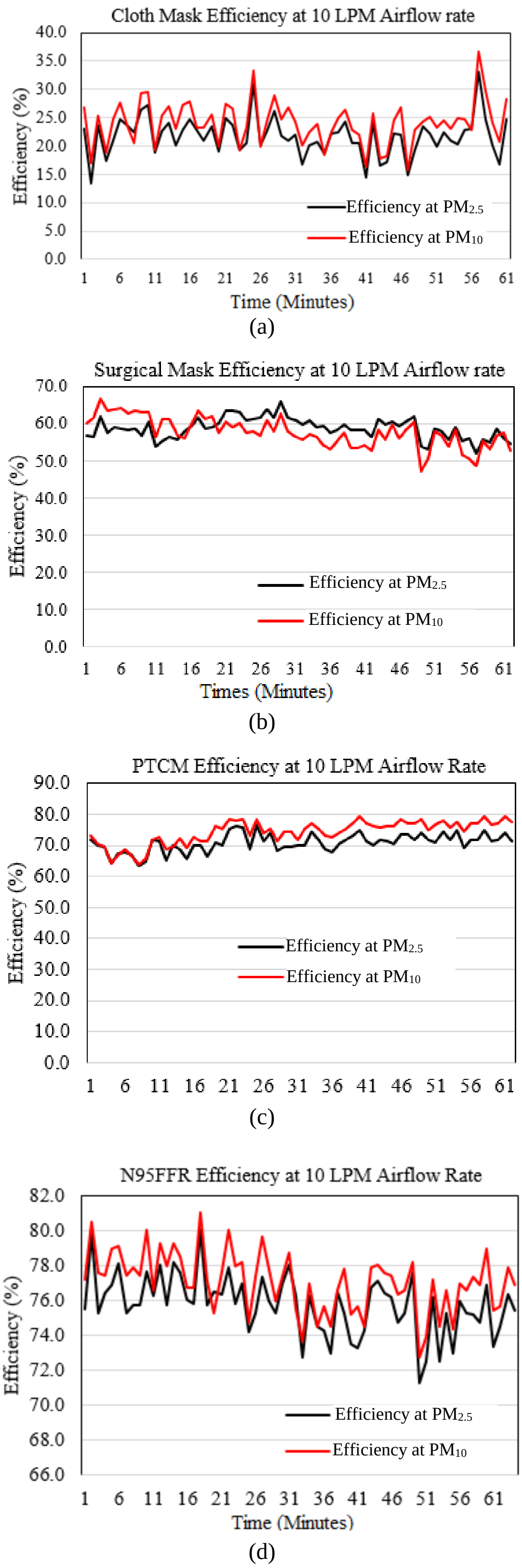


Fig. 8: Filtering efficiency of (a) Cloth Mask; (b) Surgical Mask; (c) PTCM ; (d) N95FFR with length of use

Drying and Washing Cycle Test

To determine the impact of washing and drying on the effectiveness of PTCMs, washing and drying experiments were carried out on five PTCMs at a 55 LPM air flow rate and on five PTCMs at a 10 LPM air flow rate. After each test, the PTCMs were cleaned using washing soap and then sun-dried for a full day (10 A.M 4:00 P.M) before testing their filtering efficiency against PM_{10} and $PM_{2.5}$ at 10 LPM and 55 LPM airflow rates. This process was repeated five times and the resulting data were labeled W1, W2, W3, W4, and W5. The average efficiency of the PTCM against PM_{10} at 55 LPM airflow rate was 44, 50, 50, 51 and 46%, respectively, while its average efficiency against $PM_{2.5}$ was 35, 46, 46, 45 and 38%, respectively in five consecutive washing and drying cycle. Fig. 9 shows the efficiency of PTCMs after the washing and drying cycle test at 55 LPM airflow rate against PM_{10} and $PM_{2.5}$. These figures show that the washing and drying tests have no appreciable impact on the efficiency of PTCMs.

The same process was followed to evaluate the filtering efficiency of PTCM at a 10 LPM airflow rate. Over five washing and drying cycles (W1, W2, W3, W4, W5), PTCM showed an average efficiency of 86, 89, 88, 89 and 87%, respectively against PM_{10} and 84, 87, 86, 87 and 86%, respectively against $PM_{2.5}$. Fig. 10 shows that the efficiency does not follow a specific pattern at 10 LPM airflow tests.

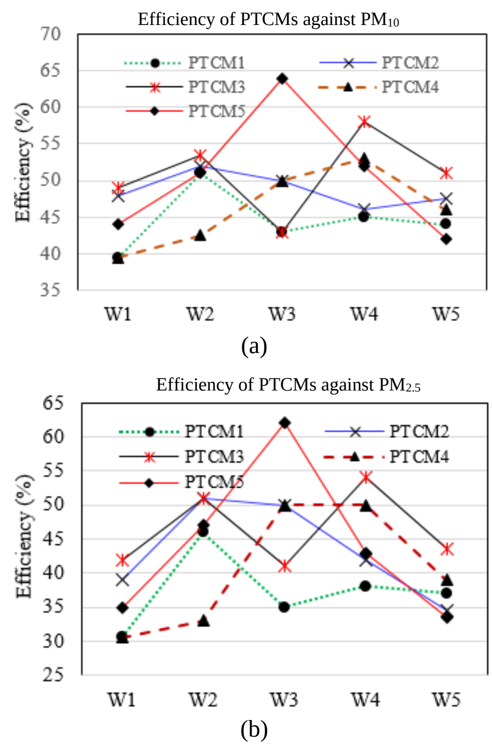


Fig. 9: Average filtering efficiency PTCMs (a) against PM_{10}; (b) against $PM_{2.5}$ after washing and drying cycles at 55 LPM airflow rate

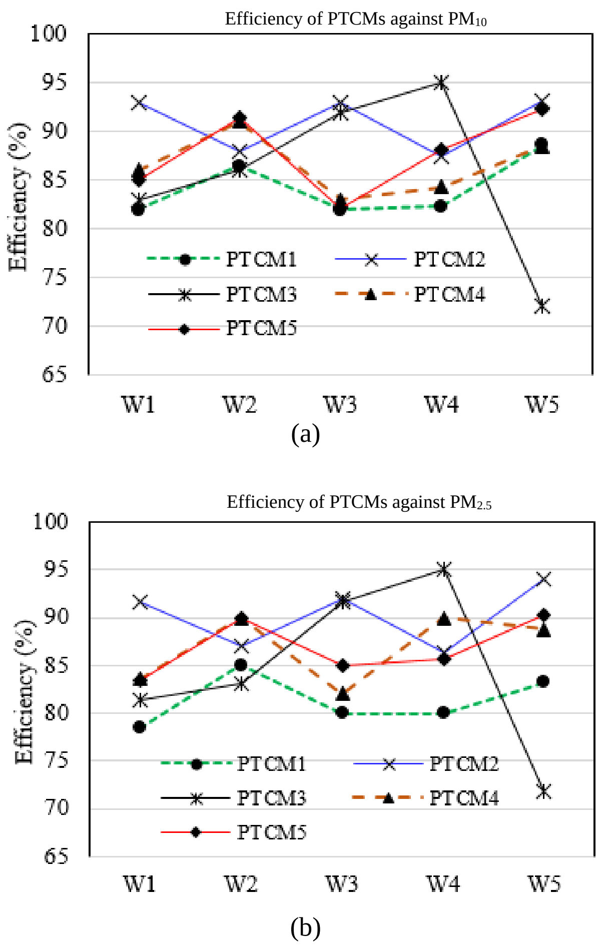


Fig. 10: Average filtering efficiency of PTCMs after drying and washing cycles (a) against PM_{10}; (b) against $PM_{2.5}$ at 10 LPM airflow rate

Statistical Analysis

Karl Pearson's Correlation (r) analysis of filtering efficiency at 10 LPM and 55 LPM showed a significant negative correlation ($r = -0.72$, $p = 3.73\ e^{-10}$) between airflow rate and efficiency (PM_{10}) and between airflow rates and efficiency ($PM_{2.5}$) ($r = -0.73$, $p = 2.25\ e^{-10}$), respectively (Table 4).

One-way Analysis of Variance (ANOVA) test showed that the efficiency of all facemasks against PM_{10} and $PM_{2.5}$ at 10 LPM and 55 LPM airflow rates were significantly different from each other ($p<0.05$).

Breathability Test

A test was conducted to assess the ease of breathing while wearing the stitched PTCMs. Twenty stitched PTCMs were randomly distributed to 20 users, consisting of ten males and ten females. All users responded that the masks were easy to breathe in.

Table 4: Correlation matrix showing a relationship between variables

	Efficiency (PM_{10})	Efficiency ($PM_{2.5}$)	Airflow rate
Efficiency (PM_{10})	1		
Efficiency ($PM_{2.5}$)	0.98^{*}	1	
Airflow rate	-0.72^{*}	-0.73^{*}	1

Discussion

This research was conducted to study the filtering efficiency of different types of facemasks available in Nepal, including their surface morphology, and improve the filtering efficiency of locally made cloth masks, allowing them to retain their filtering efficiency during multiple washing and drying cycles. An experiment setup was designed using a mannequin's head and other accessories and facemasks were tested at two airflow rates (10 and 55 LPM) to mimic the real-world scenario where humans breathe during running and resting conditions.

The performance of all the facemasks was found to be higher when tested at a 10 LPM airflow rate than at 50 LPM. Additionally, all the masks showed better performance against ambient PM_{10} compared to $PM_{2.5}$ at both airflow rates. In the present study, it was observed that the filtering efficiency of CMs was lower compared to N95 FFRs at both 10 LPM and 55 LPM airflow rates and they have a wide variation in their efficiencies. This is due to the larger pore sizes (80-290 μm) in CM fabric than the size of particulates themselves, allowing them to pass without any restriction, but CMs perform well for larger particles >300 nm (Konda *et al*., 2020). The filtering efficiency of CMs against $PM_{2.5}$ at 10 LPM airflow rate varied from 32-62%, with an average of 48% in this study. Shakya *et al*. (2017) reported the filtering efficiency of CMs between 5-57%, while Cherrie *et al*. (2018) obtained efficiency from 7-66%. Likewise, Bagheri *et al*. (2021) found efficiency between 34-66% in their study. It shows that our result is in close agreement with previous studies. The wide variation between the lower and the upper value of efficiency can be attributed to different factors, such as fabric types, facial adherence, fabric material, and airflow (Gardner *et al*., 2013; He *et al*., 2014; Cherrie *et al*. 2018; Mueller *et al*., 2018) and sizes, shapes and properties of aerosols (Tcharkhtchi *et al*., 2021).

Likewise, it was observed that surgical masks were slightly better than cloth masks in their exposure reduction potential because it has all but similar surface characteristics to N95 FFRs. The average filtering efficiency of the surgical masks in this study was 57% against $PM_{2.5}$ at a 10 LPM airflow rate, which closely agrees with 66% in the study of Shokri *et al*. (2015) and 71.5% in the study of Steinbrook (2021).

The N95 FFRs have a complex network of multiple layers of nanofibers preventing nanoparticles from penetrating through fabrics and have an average pore size of 46 μm. The N95 FFRs outperformed all the facemasks that were tested in this study and were found to have an average filtering efficiency of 40% against $PM_{2.5}$ at a 55 LPM airflow rate. This result is in close agreement with the efficiency of 46% in the study of Faridi *et al*. (2020). Although N95FFRs and surgical masks offer better protection against particulate exposure of various sizes, they are expensive and not accessible to the general public. Moreover, they are disposable masks and are not reusable after washing and drying. Additionally, they are polymer products (Drabek and Zatloukal, 2019) and sources of plastic particle pollution (Aragaw, 2020; Fadare and Okoffo, 2020; Selvaranjan *et al*., 2021)

On the contrary, the PTCMs used in this study made of cotton fabrics with additional accessories like adjustable earloops, pockets for placing filters with woven non-synthetic layers, and nose pins for better facial adherence showed a filtering performance of almost equivalent to standard N95 FFRs. Moreover, the efficiency of these masks did not drop significantly over several drying and washing cycle tests, while the efficiency of ordinary CMs dropped by 20% linearly in each drying and washing cycle (Neupane *et al*., 2019). Therefore, these masks can be used as an alternative to N95 FFRs. Moreover, they are affordable compared to N95 FFRs, breathable, ergonomic, and environmentally friendly. This facemask can be helpful in reducing the risk of particulate exposure and save thousands of lives in urban areas, particularly in cities like the Kathmandu Valley in developing countries with high air pollution.

Although the sample sizes employed in this study are higher than those used in the previous studies, the sample sizes are still smaller. For better results, the standard sample sizes that represent the population should be used in the study. Also, ambient particulate matter of varying aerosol sizes was used instead of laboratory-generated specific aerosol sizes. Therefore, the filtering efficiency of facemasks at particular aerosol sizes was not assessed. Each facemask was tested only for an hour. To observe the impact of the length of use on the filtering efficiency of the masks, they should be tested for more than an hour. The hand-held air quality monitors utilized in this study were general-purpose measuring instruments. Additionally, the washing and drying cycle tests were conducted on only five PTCMs. These tests could be performed on multiple PTCMs to ensure better results. Furthermore, the PTCM was dried on a sunny day from 10 A.M to 4:00 P.M. after each washing cycle. However, neither the solar irradiance was measured during the drying process nor the moisture content of the mask measured after each washing and drying cycle. Also, the surface morphology of the PTCM after each washing and drying cycle test was not examined. In future research, these factors need to be considered for a good understanding of the effect of the washing and drying cycle on PTCM. Likewise, different factors that affect the efficiency of facemasks, such as the electrostatic charge of non-woven melt-blown Polypropylene (PP) fabric, the way of wearing facemasks, facial hair, size and shape of the human face, were not considered in this study.

Conclusion

It has become a common practice to wear a facemask to protect from exposure to airborne particulates. However, past studies have questioned the effectiveness of such masks. This study assessed the filtering efficiency of commercial facemasks available in Nepal and investigated the improvement of the efficiency of cheaper cloth masks, which can withstand multiple washing and drying cycles without a reduction in filtering efficiency. All the facemasks performed better at 10 LPM airflow rate over 55 LPM airflow rate and against ambient PM_{10} over $PM_{2.5}$ at both airflow rates. N95 FFRs exhibited the best filtering efficiency, while cloth masks showed the lowest performance. However, the cloth masks made of cotton fabric with polypropylene filter, adjustable earloops, and nose pins for better facial adherence significantly improved the performance, almost equivalent to N95 FFRs. Moreover, these improved cloth masks retained the quality over multiple washing and drying cycles and are more affordable than N95FFRs as they are reusable after washing. Therefore, these masks can be used as an alternative to N95 FFRs and may help reduce exposure to air pollution for people living in cities in underdeveloped countries where air pollution level is high.

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Author's Contributions

Prasidha Raj Neupane: Conducted the experiment, prepared the initial manuscript and performed the data analysis.

Iswor Bajracharya: Conceptualized the research problem, devised the methodology, fabricated the experimental setup, supervised the research work, reviewed, revised and edited the manuscript.

Sunil Babu Khatry: Co-supervised the research worked, experimentation and preparation of the drafted manuscript.

Ethics

The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues are involved.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest in the research reported in this study.

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