



Development of Test Equipment for Particulate Matter Filter Efficiency in Commercial Face Masks

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ABSTRACT

Air pollution caused by particulate matter is a critical global concern. In Thailand, particulate matter levels frequently exceed the standard threshold, particularly in the northern region, where severe haze episodes are common. These levels were notably higher during the early and late parts of the year, particularly in the dry season. Selecting an appropriate face mask is crucial for respiratory protection. To ensure that the mask used provides adequate filtration efficiency, an accessible, cost-effective, and reliable method for performance assessment is essential. This quasi-experimental study developed testing equipment to evaluate the filtration efficiency of particulate matter under simulated breathing conditions, focusing on the performance of the materials used in face mask production. The primary objective of this study was to design and develop testing equipment for comparing the effectiveness of commercial face masks in filtering PM_{2.5} and PM₁₀. The study also evaluated and compared the filtration efficiencies of three types of commercially available face masks-fabric masks, surgical masks, and KN95 masks-alongside a control scenario without a mask. Data were collected by analyzing the particulate matter across various size ranges. The calibration process employed a reference gravimetric method (NIOSH 0500) to ensure accuracy ($\pm 5\%$ deviation) and sampling pump airflow rates of 1-2 L.min⁻¹. The results revealed that the KN95 mask exhibited the highest filtration efficiency, with an average particle concentration of 0.489 mg.m⁻³ (SD=0.067), followed by surgical masks (0.572 mg.m⁻³, SD=0.127) and fabric masks (0.944 mg.m⁻³, SD=0.167). Wearing a mask significantly reduced the particulate matter concentrations compared to not wearing a mask ($p < 0.001$). Addressing Thailand's severe particulate pollution requires an accessible and cost-effective device for evaluating mask filtration efficiency. Although the equipment used in this study was not industrial-grade, it effectively simulated inhalation conditions. The developed equipment achieved laboratory-grade accuracy, making it suitable for rapid testing in low-resource settings. Its simplified design ensures compliance with the NIOSH Method 0500 standards.

INTRODUCTION

Air pollution has emerged as the leading global environmental health threat, particularly in tropical regions. Asian countries contribute significantly to this problem, accounting for 40-70% of global anthropogenic air pollutant emissions (Abdul Jabbar et al. 2022). This pollution causes over six million deaths and \$8 trillion in economic losses annually, with a disproportionate impact on vulnerable populations in low- and middle-income countries (LMICs). Although global air quality monitoring has improved, significant gaps remain. This is especially true in Africa, where the monitoring density is critically low. Causing 32,300 deaths annually, it disproportionately affects outdoor workers, with PM_{2.5} exposure exceeding the World Health Organization and national standards. The 2022 World Air Quality Report revealed that only 13 of 131 countries met the WHO PM_{2.5} guideline of 5 $\mu\text{g.m}^{-3}$, highlighting the urgent need for global environmental equity measures (IQAir 2023). This significant contribution primarily stems from residential and industrial emissions, coupled with extensive biomass burning during dry seasons (Klimont et al. 2017, Reddington et al. 2019, Xing et al. 2016).

The situation in Thailand has become particularly concerning, especially in urban areas and during certain seasons. In Bangkok, $PM_{2.5}$ levels have been recorded exceeding $43.94 \mu\text{g}\cdot\text{m}^{-3}$ (Archer et al. 2024), in Chiang Mai, particularly during the dry season, with varying concentrations across altitudes owing to the city's topography. This study found average $PM_{2.5}$ and PM_{10} concentrations of $23\pm 13 \mu\text{g}\cdot\text{m}^{-3}$ and $47\pm 18 \mu\text{g}\cdot\text{m}^{-3}$, respectively, in urban areas, and $14\pm 9 \mu\text{g}\cdot\text{m}^{-3}$ and $29\pm 14 \mu\text{g}\cdot\text{m}^{-3}$, respectively, outside urban areas. The ambient dose equivalent rate averaged $95\pm 12 \text{ nSv}\cdot\text{h}^{-1}$, showing no significant altitude-related differences (Kranrod et al. 2024), far above the WHO's recommended 24-hour mean of $15 \mu\text{g}\cdot\text{m}^{-3}$ (Sooktawee et al. 2022). This trend underscores the urgent need for effective personal protective measures.

Recent epidemiological studies have demonstrated the severe health impacts of PM exposure. Long-term exposure to fine $PM_{2.5}$ is associated with an increased mortality risk for respiratory diseases, lung cancer, and cardiovascular diseases. A study of 18.9 million Medicare beneficiaries in the United States (2000-2008) revealed that higher $PM_{2.5}$ exposure (per $10 \mu\text{g}\cdot\text{m}^{-3}$ increase) significantly elevated mortality risks, with risk ratios ranging from 1.10 to 1.33, depending on the exposure duration. Longer moving averages of $PM_{2.5}$ exposure have shown stronger associations (Pun et al. 2017). Short-term exposure to air pollutants, including PM_{10} and $PM_{2.5}$, is positively associated with all-cause mortality, whereas $PM_{2.5}$ and PM_{10} are linked to cardiovascular, respiratory, and cerebrovascular mortality (Orellano et al. 2020). The WHO reports that approximately 99% of the global population breathes air that exceeds the recommended quality limits, with $PM_{2.5}$ identified as particularly dangerous because of its ability to penetrate deep into the respiratory system (World Health Organization 2023).

Face masks are essential in high-PM areas, but their filtration efficiency varies significantly. Current testing methods present several challenges. Traditional approaches require expensive equipment, complex setups, and time-consuming processes, making it difficult to conduct rapid and reliable assessments (Mohanty et al. 2024)

Previous research on PM filtration testing has focused primarily on standardized laboratory conditions, which may not reflect real-world applications. Although researchers have made progress in testing methodologies, significant limitations remain. Although previous studies (Han et al. 2016, Du et al. 2020) have attempted to evaluate masks using ambient air particles, their methods are expensive and require complex setups, limiting their practical applicability, particularly in developing countries.

There remains a critical need for comprehensive yet practical testing equipment to determine face mask filtration

efficiency. This study addresses this gap by developing new test equipment for evaluating commercial face masks against $PM_{2.5}$ and PM_{10} . Our proposed system incorporates recent advances in particle sensing and automated testing while maintaining cost-effectiveness and operational simplicity. This development is particularly timely given the growing global demand for reliable face mask testing methods and increasing awareness of the health impacts of air pollution.

This study aimed to develop a mask filtration testing system that provides accurate, cost-effective, and practical assessments, making it more accessible for evaluating commercial face masks in high-pollution regions such as Thailand. An accurate and accessible testing system will enable more effective screening of high-performance facial masks. Furthermore, the proposed system can serve as a model for future standardization efforts, ultimately contributing to improved public health in high-pollution regions.

MATERIALS AND METHODS

A quasi-experimental study was conducted to evaluate the filtration efficiencies of various commercial face masks against particulate matter. The data collection period spanned July to September 2024. This study developed testing equipment to evaluate the filtration efficiency of particulate matter (PM_{10} and $PM_{2.5}$) in commercial face masks under simulated breathing conditions (Fig. 1). The study was conducted in a standardized laboratory setting using calibrated equipment to ensure accurate measurements. The experimental setup included an air sampling pump, tubing, filter cassettes, and filtration paper, all of which were subjected to calibration procedures. To maintain controlled environmental conditions, the humidity and temperature were regulated by placing the filtration paper in a desiccator before testing.

Testing System Configuration

The experimental setup consisted of a sealed containment chamber (dimensions: $13 \times 20 \text{ cm}$) fabricated from high-grade transparent plastic and sealed with rubber gaskets to ensure air-tightness. A calibrated 12V centrifugal fan facilitated particle circulation (dimensions: $97 \times 95 \times 33 \text{ mm}$) operating at an airflow velocity of $10.19 \text{ m}\cdot\text{min}^{-1}$, validated using a TSI velocity measurement system. The sample mounting system included heat-resistant acrylic tubing (dimensions: $6 \times 13 \text{ cm}$) designed to securely accommodate both the filter and test masks (Fig. 2).

Analytical Equipment

Aerosol sampling was conducted using a GilAir Plus high-flow pump integrated with the TSI calibration system. Gravimetric analysis was performed using an analytical

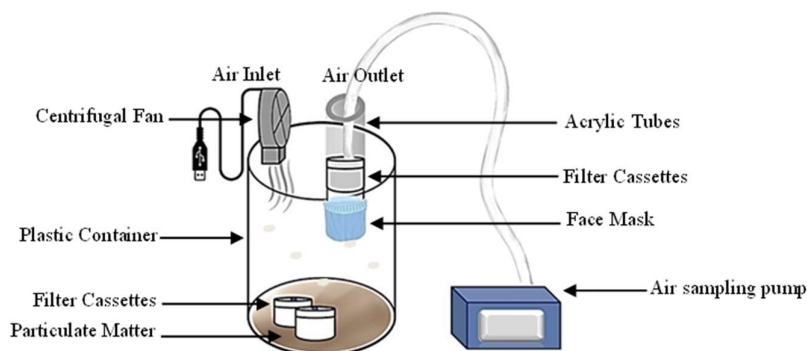


Fig. 1: Schematic diagram of particulate matter filtration efficiency testing equipment.



Fig. 2: Particulate matter filtration efficiency testing equipment.

balance (Mettler Toledo) with a precision of 0.001 g. Sample conditioning was conducted in a vacuum desiccator to maintain the humidity equilibrium. The sampling train incorporated a 37 mm styrene filter cassette assembly, comprising PVC filters (5.0 μm pore size), cellulose support pads, and Parafilm sealing for enhanced integrity. Precision forceps were employed for component manipulation, and flexible tubing ensured proper and secure flow connectivity.

Experimental Design and Setting

The experimental design process consisted of several key steps, including particulate sample collection, calibration methodology, sample preparation and analysis, dust sample preparation, setup and experimental protocol, and post-experimental procedures.

Particulate Sample Collection

Particulate samples, including soil, sand, and atmospheric dust, were collected from the vicinity of the University of Phayao in northern Thailand. The samples were processed using a fine-mesh nylon sieve (10 cm \times 10 cm \times 4.1 cm, overall length 20.5 cm) placed within a transparent containment vessel (190 mL capacity; 13 cm diameter \times 6.5 cm height) (Fig. 3).

Calibration Methodology

The calibration process adhered to the NIOSH Method 0500 protocols (NIOSH, 1994). The high-flow air sampling pump was stabilized for 5 min before calibration. The sampling setup included a three-piece filter cassette containing a 37 mm PVC filter (5.0 μm pore size) supported by a cellulose pad. Secure connections were ensured using flexible tubing with cassette adapters. The calibration configuration connected the filter cassette inlet to a flow calibrator and the outlet to an air sampling pump. The flow rate was adjusted to 1.0 $\text{L}\cdot\text{min}^{-1}$ and verified using a digital calibration display (Fig. 4).

Sample Preparation and Analysis

The filter papers were conditioned in a vacuum desiccator for 2 h to achieve humidity equilibrium. Initial weights (1) were measured using a calibrated analytical balance, with triplicate measurements averaged for precision. Control filter papers were similarly weighed (b_1). Filter cassettes were assembled with cellulose support pads, securely sealed with adhesive tape, and labeled with unique identification codes (Fig. 5).

Dust Sample Preparation

Pre-sieved dust samples (1.000 ± 0.001 g) were weighed using a calibrated analytical balance and allocated to 12 individual



Fig. 3: Particulate sample collection.



Fig. 4: Calibration methodology.

cassettes for testing (Fig. 6). To ensure experimental integrity, two procedural blank sampling cassettes were included in each experimental batch to monitor potential background contamination. These blank sampling cassettes underwent identical handling and analytical procedures as the test samples but contained no particulate matter, thereby validating the absence of laboratory-induced contamination during the experiment.

Experimental Protocol

The humidity within the testing equipment was monitored using an air velocity meter. Test facial masks were securely attached to the acrylic tube interface, and the filter cassettes were installed at the apex of the equipment. A 1.000 g dust sample was introduced into the equipment, and air sampling was conducted at a flow velocity of 10.19 m.s⁻¹ to replicate normal respiratory conditions.

Each test comprised three 20-minute sampling intervals (Fig. 7).

Post-Experimental Procedures

After each test, the equipment was systematically cleaned using a vacuum cleaner (Electrolux ZB3513DB, 1.8V) and thoroughly wiped with tissue. The filter papers were conditioned in a vacuum desiccator for 2 h before being weighed to determine their final weights (m_2). The dust concentration C was calculated using the formula (Fig. 8):

$$C = \frac{(m_2 - m_1) - (mb_2 - mb_1)}{V}, \text{ mg.m}^{-3} \quad \dots(1)$$

Where V is the sampled air volume.

Statistical Analysis

The analysis incorporated both descriptive statistics



Fig. 5: Sample preparation and analysis.



Fig. 6: Dust sample preparation.



Fig. 7: Experimental protocol.

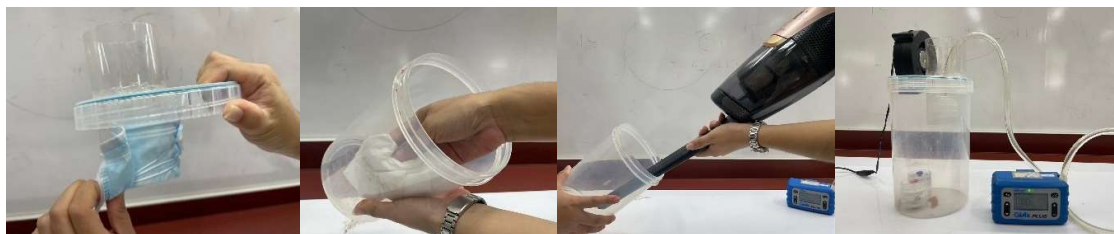


Fig. 8: Post-experimental procedures.

(frequency, mean, standard deviation (SD), and range) and inferential statistics, with one-way ANOVA employed to evaluate differences in filtration efficiency across mask types compared to the control condition. Statistical significance was set at $p < 0.05$.

RESULTS AND DISCUSSION

Gravimetric Analysis of Filter Papers

The filter paper masses were measured gravimetrically pre- and post-sampling across different mask types and control conditions. Initial filter masses were determined to be 12.932 mg.m^{-3} , 13.585 mg.m^{-3} , 13.931 mg.m^{-3} , 15.981 mg.m^{-3} , and 13.076 mg.m^{-3} for fabric masks, surgical masks, KN95 masks, no-mask conditions, and blank cassettes, respectively. Following the sampling period, these values increased marginally to 12.952 mg.m^{-3} , 13.597 mg.m^{-3} , 13.942 mg.m^{-3} , 16.031 mg.m^{-3} , and 13.077 mg.m^{-3} , respectively (Table 1).

Comparative Filtration Performance

The analysis of particulate matter concentrations identified

Table 1: Pre- and post-sampling masses of filter papers across different mask types and control conditions.

Mask types	Gravimetric mass of filter papers [mg.m^{-3}]			
	Pre-sampling x	Post-sampling x	Mass difference x	Filtration efficiency* %
Fabric masks	12.932	12.952	0.020	60.0
Surgical masks	13.585	13.597	0.012	76.0
KN95 masks	13.931	13.942	0.011	78.0
No-mask condition	15.981	16.031	0.050	-
Blank cassette	13.076	13.077	0.001	-

*Filtration efficiency calculated as: $(1 - [\text{mask mass difference} / \text{no-mask mass difference}]) \times 100\%$

Test conditions: Temperature: $22 \pm 2^\circ\text{C}$, Relative humidity: $50 \pm 5\%$, Flow rate: 10.19 m.s^{-1} , Sampling duration: 20 minutes

Table 2: Comparative analysis of particulate matter concentrations and filtration efficiency among commercial face mask types.

Mask types	Particulate matter concentrations [$\text{mg}\cdot\text{m}^{-3}$]		
	\bar{x}	S.D.	Filtration efficiency [%] *
Fabric masks	0.944	0.167	61.3
Surgical masks	0.572	0.127	76.5
KN95 masks	0.489	0.067	78.0
No-mask condition	2.438	0.305	-
Blank cassette	0.944	0.167	-

*Filtration efficiency calculated as: $(1 - [\text{mask mass difference} / \text{no-mask mass difference}]) \times 100\%$

Test conditions: Temperature: $22 \pm 2^\circ\text{C}$, Relative humidity: $50 \pm 5\%$, Flow rate: 10.19 $\text{m}\cdot\text{s}^{-1}$, Sampling duration: 20 minutes

statistically significant differences in the filtration efficiencies of the three commercially available face masks. The KN95 mask achieved the lowest particulate matter concentration ($0.489 \pm 0.489 \text{ mg}\cdot\text{m}^{-3}$), followed by surgical masks ($0.572 \pm 0.127 \text{ mg}\cdot\text{m}^{-3}$) and fabric masks ($0.944 \pm 0.167 \text{ mg}\cdot\text{m}^{-3}$). In contrast, the no-mask condition displayed substantially elevated particulate matter concentrations ($2.438 \pm 0.305 \text{ mg}\cdot\text{m}^{-3}$), indicating the effectiveness of masks in minimizing particulate matter exposure (Table 2).

Comparison of Filtration Efficiency Among Fabric Masks, Surgical Masks, KN95 Masks, and the No Mask Condition

The analysis of particulate matter concentrations during the filtration performance testing across fabric masks, surgical masks, KN95 masks, and no-mask conditions revealed significant differences. All mask types demonstrated superior filtration efficiency compared to the no-mask condition, with

the differences being statistically significant ($p < 0.001$) at the p -value < 0.05 significance level (Fig. 9).

CONCLUSIONS

In this study, we developed a simple piece of equipment to evaluate the filtration efficiency of various dust masks based on NIOSH Method 0500. Data collection was conducted using a recording sheet to analyze the particulate matter samples across all size ranges of the particulate matter. The masks tested included three commercially available types: fabric masks, surgical masks, and KN95 masks, along with a control condition without a mask. Although the testing equipment used in this study did not meet industrial-grade standards, it effectively simulated the inhalation conditions. This design enabled a practical comparison of the filtration efficiencies of different types of dust masks, providing valuable insights into their performance under controlled experimental settings.

The results showed that the fabric masks had an average pre-sampling filter paper mass of $12.932 \text{ mg}\cdot\text{m}^{-3}$ and a post-sampling mass of $12.952 \text{ mg}\cdot\text{m}^{-3}$, resulting in a particulate matter concentration of $0.944 \text{ mg}\cdot\text{m}^{-3}$. Surgical masks exhibited a lower particulate matter concentration of $0.572 \text{ mg}\cdot\text{m}^{-3}$ (pre-sampling: $13.585 \text{ mg}\cdot\text{m}^{-3}$; post-sampling: $13.597 \text{ mg}\cdot\text{m}^{-3}$) than the KN95 mask demonstrated the highest filtration efficiency, with a particulate matter concentration of $0.489 \text{ mg}\cdot\text{m}^{-3}$ (pre-sampling: $13.931 \text{ mg}\cdot\text{m}^{-3}$; post-sampling: $13.942 \text{ mg}\cdot\text{m}^{-3}$). These findings highlight the variability in the filtration performance of different mask types.

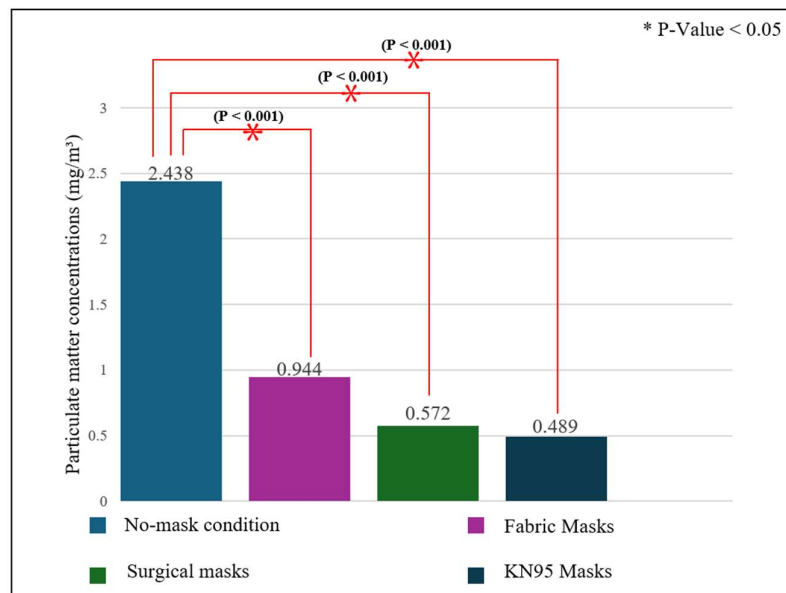


Fig. 9: Comparison of filtration efficiency among fabric, surgical, and KN95 masks and the no mask condition.

KN95 masks meet the filtration standards set by the National Institute for Occupational Safety and Health (NIOSH) and effectively filter airborne particles as small as 0.3 μm in size. This finding aligns with those of previous studies by Whiley et al. (2020) and Dugdale (2020), which confirmed the high filtration efficiency of N95 masks in reducing particulate matter exposure. In contrast, the control condition (no mask) resulted in a significantly higher particulate matter concentration of 2.438 $\text{mg}\cdot\text{m}^{-3}$ (pre-sampling: 15.981 $\text{mg}\cdot\text{m}^{-3}$; post-sampling: 16.031 $\text{mg}\cdot\text{m}^{-3}$). Consistent with Arunnart (2021), our results indicated that KN95 masks exhibited the highest filtration efficiency (97.2%), followed by surgical masks (56.3%–83.2%), fabric masks (40.9%–42.4%), muslin cloth masks (37.8%), and sponge masks (33.5%). Among the supplementary filters, carbon filters achieved the highest efficiency (88.3%–98.8%), followed by face wash tissues (63.3%) and air conditioner filters (43.3%). These results emphasize the superior performance of the KN95 masks and carbon filters for particulate matter filtration.

In conclusion, the KN95 mask demonstrated the highest dust filtration efficiency, followed by the surgical and fabric masks. The developed testing apparatus was constructed using commercially available, low-cost components (less than 500 Thai Baht or approximately 15 USD) while strictly adhering to the NIOSH Method 0500 protocols throughout all experimental phases. This study addresses the challenges associated with accessing laboratory-grade particulate filtration testing equipment, particularly in regions that are severely affected by air pollution.

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