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Original Research

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 are notably higher during the early and late parts of the year, especially in the dry season. Selecting an appropriate face mask is crucial for respiratory protection. To ensure that the mask used provides adequate filtration efficiency, it is essential to have an accessible, cost-effective, and reliable method for performance assessment. This quasi-experimental study developed testing equipment to evaluate the filtration efficiency of particulate matter under simulated breathing conditions, focusing on the performance of materials used in face mask production. The primary objective was to design and develop testing equipment for comparing the effectiveness of commercial face masks in filtering $PM_{2.5}$ and PM_{10}. The study also evaluated and compared the filtration efficiency 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 particulate matter across various size ranges. The calibration process employed a reference gravimetric method (NIOSH 0500) to ensure accuracy (±5% deviation) and sampling pump air-flow rates of 1-2 L/min. The results revealed that the KN95 mask exhibited the highest filtration efficiency, with an average particle concentration of 0.489 mg/m³ (SD=0.067), followed by surgical masks (0.572 mg/m³, SD=0.127) and fabric masks (0.944 mg/m³, SD=0.167). Wearing a mask significantly reduced particulate matter concentrations compared to not wearing a mask ($p < 0.001$). Addressing Thailand's severe particulate pollution requires an accessible, cost-effective device for evaluating mask filtration efficiency. This study's equipment, while not industrial grade, effectively simulates inhalation conditions. The developed equipment achieved laboratory-grade accuracy, making it suitable for rapid, low-resource settings. Its simplified design ensures compliance with NIOSH Method 0500 standards.

1. INTRODUCTION

Air pollution has emerged as the leading global environmental health threat, particularly affecting tropical regions. Asian countries contribute significantly to this problem, accounting for 40% to 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. While global air quality monitoring has improved, significant gaps remain. This is especially true in Africa, where monitoring density is critically low. Causing 32,300 deaths annually, it disproportionately affects outdoor workers, with $PM_{2.5}$ exposure exceeding WHO and national standards. The 2022

World Air Quality Report revealed that only 13 out of 131 countries met the WHO $PM_{2.5}$ guideline of 5 µg/m³, 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 activities 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 specific seasons. In Bangkok, $PM_{2.5}$ levels have been recorded exceeding 43.94 µg/m³ (Archer et al., 2024), in Chiang Mai, particularly during the dry season, with varying concentrations across altitudes due to the city's topography. This study found average $PM_{2.5}$ and PM_{10} concentrations of 23±13 µg/m³ and 47±18 µg/m³, respectively, in urban areas, and 14±9 µg/m³ and 29±14 µg/m³ outside urban areas. The ambient dose equivalent rate averaged 95±12 nSv/h, showing no significant altitude-related differences (Kranrod et al., 2024), far above the WHO's recommended 24-hour mean of 15 µg/m³ (Sooktawee et al. 2022). This trend underscores the urgent need for effective personal protection measures.

Recent epidemiological studies have clearly demonstrated the severe health impacts of PM exposure. Long-term exposure to fine $PM_{2.5}$ is associated with increased mortality risks 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 µg/m³ increase) significantly elevated mortality risks, with risk ratios ranging from 1.10 to 1.33, depending on exposure duration. Longer moving averages of $PM_{2.5}$ exposure showed 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, while $PM_{2.5}$ 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 exceeding recommended quality limits, with $PM_{2.5}$ identified as particularly dangerous due to 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 usage. While 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 involve high costs and complex setups, limiting their practical applicability, particularly in developing countries.

There remains a critical need for comprehensive yet practical testing equipment for face mask filtration efficiency. This research 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. The development is particularly timely given the growing global demand for reliable face mask testing methods and increasing awareness of air pollution's health impacts.

This study aims 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 face masks. Furthermore, the proposed system can serve as a model for future standardization efforts, ultimately contributing to improved public health protection in high-pollution regions.

2. MATERIALS AND METHODS

A quasi-experimental study was conducted to evaluate the filtration efficiency of various commercial face masks against particulate matter. The data collection period spanned from 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 measurement accuracy. 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, humidity and temperature were regulated by placing the filtration paper in a desiccator before testing.

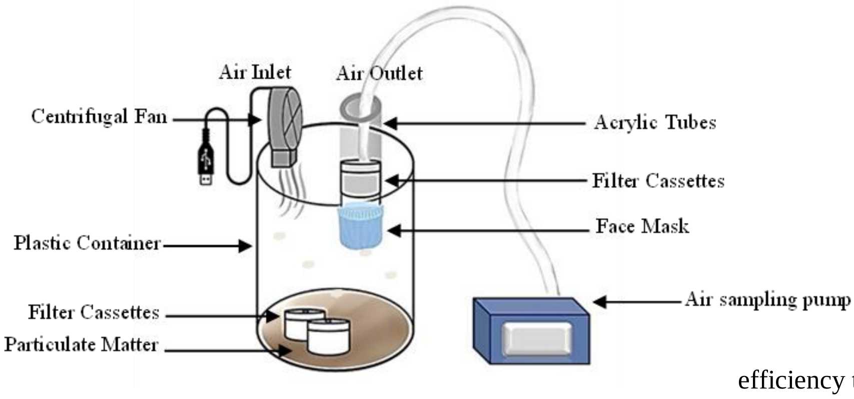


Fig 1: Schematic diagram of particulate matter filtration efficiency testing equipment

2.1 Materials and Instruments

Testing System Configuration

The experimental setup consisted of a sealed containment chamber (dimensions: 13 × 20 cm) fabricated from high-grade transparent plastic and sealed with rubber gaskets to ensure airtightness. Particle circulation was facilitated by a calibrated 12V centrifugal fan (dimensions: 97 × 95 × 33 mm) operating at an airflow velocity of 10.19 m/min, validated using a TSI velocity measurement system. The sample mounting system included heat-resistant acrylic tubing (dimensions: 6 × 13 cm), designed to securely accommodate both filter and test masks (Fig 2).

Analytical Equipment

Aerosol sampling was cassettes conducted using a GilAir Plus high-flow pump integrated with a TSI calibration system. Gravimetric analysis was performed using a Mettler Toledo analytical balance with a precision of 0.001 g. Sample conditioning was conducted in a vacuum desiccator to maintain 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, while flexible tubing ensured proper and secure flow connectivity.

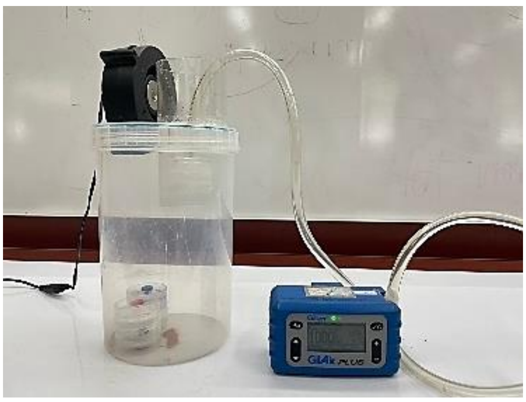


Fig 2: Particulate matter filtration efficiency testing equipment

Experimental Design and Setting

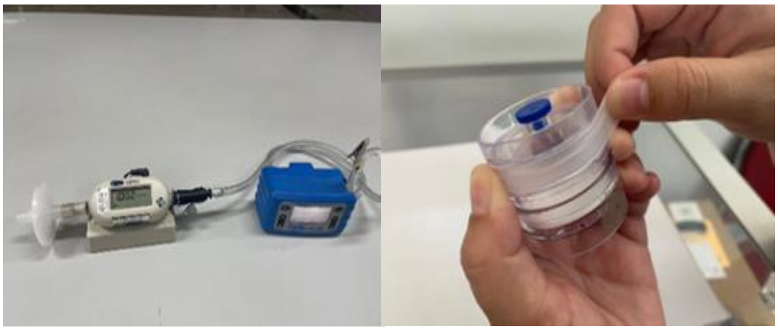
The experimental design process consisted of several key steps, including particulate sample collection, calibration methodology, sample preparation and analysis, dust sample preparation, setup and experimental protocol, and post-experimental procedures.

Particulate Sample Collection

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

Calibration Methodology

The calibration process adhered to NIOSH Method 0500 protocols (NIOSH, 1994). The high-flow air sampling pump was stabilized for 5 minutes 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 by flexible tubing with cassette adapters. The calibration configuration connected the filter cassette inlet to a flow calibrator and the outlet to the air sampling pump. The flow rate was adjusted to 1.0 L/min and verified using a digital calibration display (Fig 4).



Sample Preparation and Analysis

Filter papers were conditioned in a vacuum desiccator for 2 hours to achieve humidity equilibrium. Initial weights ($m1$) were measured using a calibrated analytical balance, with triplicate measurements averaged for precision. Control filter papers were similarly weighed (mb_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 into 12 individual cassettes for testing. 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 experiments.

Experimental Protocol

Humidity within the testing equipment was monitored using an air velocity meter. Test facial masks were securely attached to the acrylic tube interface, and filter cassettes were installed at the equipment apex. 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 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 wiped thoroughly with tissue. Filter papers were conditioned in a vacuum desiccator for 2 hours before being weighed to determine final weights (m2). Calculate the dust concentration C using the formula (Fig 8):

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

where V is the air volume sampled.

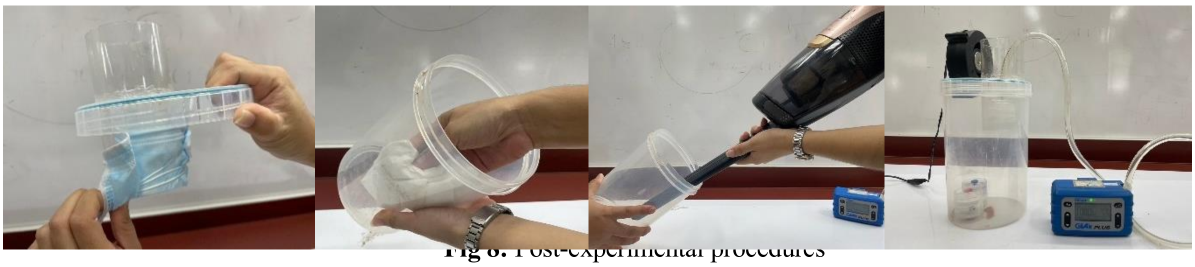


Fig 8. Post-experimental procedures

2.2 Statistical Analysis

The analysis incorporated both descriptive statistics (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 established at $p < 0.05$.

3. RESULTS AND DISCUSSION

Gravimetric analysis of filter papers

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/m³, 13.585 mg/m³, 13.931 mg/m³, 15.981 mg/m³, and 13.076 mg/m³ 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/m³, 13.597 mg/m³, 13.942 mg/m³, 16.031 mg/m³, and 13.077 mg/m³, respectively (Table 1).

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/m³)			
	Pre-sampling	Post-sampling	Mass difference	Filtration efficiency*
	$\bar{x}$	$\bar{x}$	$\bar{x}$	%
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 - [mask mass difference / no-mask mass difference]) × 100%
Test conditions: Temperature: 22±2°C, Relative humidity: 50±5%, Flow rate: 10.19 m/s, Sampling duration: 20 minutes

Comparative Filtration Performance

The analysis of particulate matter concentrations identified statistically significant differences in the filtration efficiency of three commercially available face masks. The KN95 mask achieved the lowest particulate matter concentration (0.489 ± 0.489 mg/m³), followed by surgical masks (0.572 ± 0.127 mg/m³) and fabric masks (0.944 ± 0.167 mg/m³). By contrast, the no-mask condition displayed substantially elevated particulate matter concentrations (2.438 ± 0.305 mg/m³), indicating the effectiveness of masks in minimizing particulate exposure (Table 2).

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

Mask types	Particulate matter concentrations (mg/m³)		
	$\bar{x}$	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 - [mask mass difference / no-mask mass difference]) × 100%
Test conditions: Temperature: 22±2°C, Relative humidity: 50±5%, Flow rate: 10.19 m/s, Sampling duration: 20 minutes

Comparison of filtration efficiency among fabric masks, surgical masks, KN95 masks, and no mask condition

The analysis of particulate matter concentrations during filtration performance testing across fabric masks, surgical masks, KN95 masks, and the no-mask condition 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).

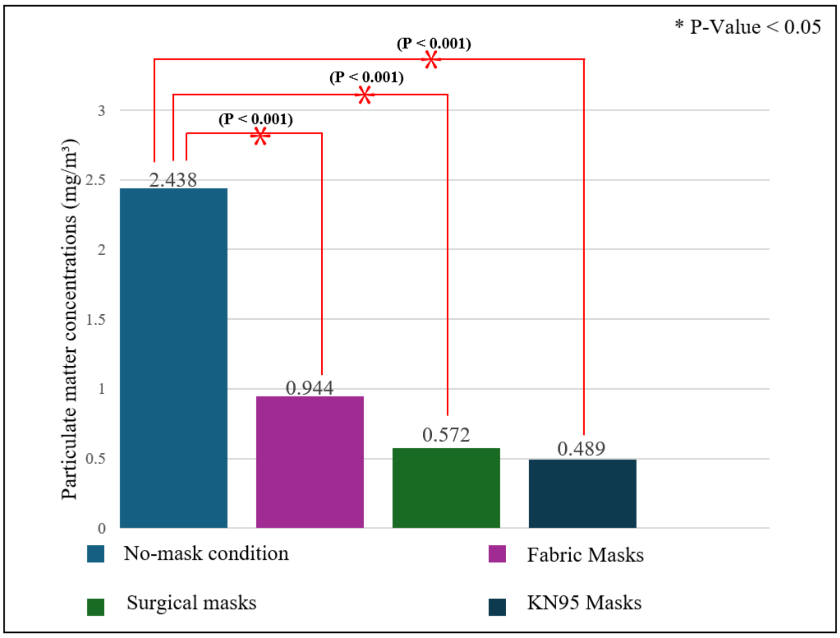


Fig 9: Comparison of filtration efficiency among fabric masks, surgical masks, KN95 masks, and no mask condition.

4. CONCLUSIONS

This study 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 particulate matter samples across all size ranges. 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 does not meet industrial-grade standards, it effectively simulates inhalation conditions. This design enables a practical comparison of filtration efficiency among different types of dust masks, providing valuable insights into their performance under controlled experimental settings.

The results showed that fabric masks had an average pre-sampling filter paper mass of 12.932 mg/m³ and a post-sampling mass of 12.952 mg/m³, resulting in a particulate matter concentration of 0.944 mg/m³. Surgical masks exhibited a lower particulate matter concentration of 0.572 mg/m³ (pre-sampling: 13.585 mg/m³; post-sampling: 13.597 mg/m³). The KN95 mask demonstrated the highest filtration efficiency, with a particulate matter concentration of 0.489 mg/m³ (pre-sampling: 13.931 mg/m³; post-sampling: 13.942 mg/m³). These findings highlight the variability in filtration performance among different mask types.

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. This finding aligns with 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 mg/m³ (pre-sampling: 15.981 mg/m³; post-sampling: 16.031 mg/m³). 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 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 KN95 masks and carbon filters in particulate matter filtration.

In conclusion, the KN95 mask demonstrated the highest dust filtration efficiency, followed by surgical masks 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 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 severely affected by air pollution.

Limitations

This study did not include quality control measures such as blank cassette testing, and the range of masks tested was relatively limited. Furthermore, the findings are based on a laboratory setting and may not fully reflect real-world conditions.

Author Contributions: Rittikorn Sompan: conception and design of the work, data collection, data analysis, interpretation of the data, writing of the article, revision of the article; Nutthaphong Mated: design of the work, data analysis, interpretation of the data, revision of the article. All author approval of the article.

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