*Original Article*

**Journal of Public Health Research**

Journal of Public Health Research
2023, Vol. 12(1), 1–7

DOI: 10.1177/22799036221148989
journals.sagepub.com/home/phj
SAGE

# $PM_{2.5}$ exposure and lung function impairment among fiber-cement industry workers

**Sjahrul Meizar Nasri[1], Fiori Amelia Putri[1], Stevan Sunarno[1], Sifa Fauzia[2] and Doni Hikmat Ramdhan[1]**

**Abstract**

**Introduction:** Numerous studies have reported respiratory impairment by exposure to fine particulate matter ($PM_{2.5}$). However, limited studies investigated its effects on fiber cement roof workers. Thus, our study evaluated the impact of $PM_{2.5}$ on pulmonary impairments among workers and its risk factors.

**Design and Method:** A total of 131 fiber cement roof workers have been chosen based on the inclusive criteria. Size-segregated particles were measured in the workplace of workers. Interview and spirometry tests were obtained to determine the respiratory impairments.

**Result:** The results showed the mean concentrations of $PM_{2.5}$ had exceeded the WHO and US-EPA standards. A quarter of workers had lung restriction, lung obstruction, and mixed. Workers are most likely to have shortness of breath and wheezing. A significant correlation was found between smoking, production workers, and a long work period with abnormal lung function. Fiber cement roof workers are significantly at risk of exposure to $PM_{2.5}$. They are most likely to acquire abnormal lung function due to $PM_{2.5}$ exposure.

**Conclusion:** Our study recommended the industry constantly maintain its programs. The industry should keep using the wet process to prevent dust generation and water suppression from preventing dust spread, as well as to wear respiratory protection for workers to avoid $PM_{2.5}$ exposure. We recommended as well to the industry to implement follow-up programs for workers with abnormal lung function. Further action is needed to protect the workers' occupational health in the fiber cement roof industry.

**Keywords**

Particulate matter, $PM_{2.5}$, lung impairment, workers, fiber cement roof industry

Date received: 9 September 2022; accepted: 14 December 2022

## Introduction

Air pollution by particulate matter (PM) has been considered the five highest contributors to the global burden of disease.[1] Human health effects associated with exposure to PM were significantly affected by the size distribution, concentrations, components, and toxicities.[2,3] Between 2000 and 2019, a large portion of the world's metropolitan populace lived in regions exposed to the high level of PM with a diameter ≤2.5 μm ($PM_{2.5}$), prompting significant numbers of noncommunicable disease burdens.[4] $PM_{2.5}$ is characterized by its small particle size, large surface area, and toxin absorption ability; hence, it can infiltrate the smallest airways, including alveolar tissue, with various toxic substances (such as metals and heavy metal ions, organic and inorganic compounds, allergens, many microbial compounds, and

[1]Department of Occupational Health and Safety, Faculty of Public Health, Universitas Indonesia, Kampus UI, Depok, Indonesia
[2]Department of Environmental Health, Faculty of Public Health, Universitas Indonesia, Kampus UI, Depok, Indonesia

**Corresponding author:**
Sjahrul Meizar Nasri, Department of Occupational Health and Safety, Public Health Faculty, University of Indonesia, Building C, 1st Floor, Depok, West Java, 16424, Indonesia.
Email: sjahrul@ui.ac.id

Polycyclic Aromatic Hydrocarbons).[5,6] Epidemiological studies have consistently linked short-term exposure to gaseous air pollution and ambient particulate matter (PM) with increased hospitalization and mortality from respiratory disease.[7]

Globally, $PM_{2.5}$ has contributed to 7.8% of total deaths and 4.2% of disability-adjusted life years (DALYs).[8] Numerous epidemiological studies have reported morbidity and mortality by respiratory impairments related to inhalation of $PM_{2.5}$, such as pulmonary inflammation,[7,9,10] the decline in pulmonary function, asthma,[11–13] and chronic obstructive pulmonary diseases (COPD).[14,15] In addition, a study has revealed that every 10 μg/m$^3$ increment of $PM_{2.5}$ concentration will increase the mortality by respiratory illness by more than 1.68%.[16]

These particulates come from numerous sources, including traffic, industries, trade activities, and home heating and cooking. Moreover, it is associated with health and well-being, ventilation/air velocity,[17] and improper indoor air quality in an environment, which can severely affect the occupants and workers at the workplace. Increasing industrial activities and urbanization also have consequences, notably in increasing pollution.[18] Inward contamination, reaction products within the indoor environment, and penetration of outdoor pollutants are great examples of sources of indoor air pollutants. $PM_{2.5}$ has been reported as the primary pollutant from industrial sites in many countries such as China,[18–21] Germany,[22] France,[23] Italy,[24] India,[25] and Pakistan.[10] Furthermore, respiratory health effects have also been reported among workers related to exposure to industrial $PM_{2.5}$.[25] In the roofing fiber-cement industry, cement dust is generated in numerous processes, such as blending and pouring, racking and curing, and de-palleting and skid.[26]

To date, there have been limited studies in Indonesia regarding the effect of $PM_{2.5}$ on workers. Specifically, no study has been conducted on fiber cement roof industry workers in Indonesia. In response to this problem, this study investigates the relationship between $PM_{2.5}$ exposure and lung impairment in workers working in the fiber-cement industry in Indonesia.

## Methods

### Study design and data collection

*Study design.* This cross-sectional study determines the relationship between $PM_{2.5}$ and lung impairment among fiber roof industry workers. The collection of data was conducted from April to July 2019.

*Location of study.* The selected industry location is in Cikarang-Karawang, West Java, Indonesia. It is an industrial region area and one of the largest and most important fiber roof industries based on data from the Ministry of Industry of the Republic of Indonesia. The administrative workers are distributed on 8 h work shifts per day. Before the research was carried out, permission was sought from the company of the respective fiber cement roof industry, and ethical clearance was obtained from the Ethical Committee of the Ministry of Health of the Republic of Indonesia. Informed consent was acquired from each respondent in the study. The respondents were explained the measurement and evaluation process before agreeing to participate in this research. All the information and identities used in this study remain classified. based on on-site observation of the industry, the factory uses enclosed ventilation, filtered cabins, and a local exhaust ventilation system. It uses wet processes to prevent dust generation and water suppression from preventing dust spread. In addition, the workers also wear respiratory protection.

*Participants.* We recruited all workers of the selected industry with at least 10 years of seniority and still working when this study was conducted and collected personal data through a questionnaire administered in April−May 2019. A total of 131 respondents participated in this study. Data collection included interviews using a questionnaire, direct observation, and measurement of characteristics (gender, age, height, weight, Body Mass Index (BMI), education level, smoking status, duration of work, type of job, spirometry test), and concentration of PM.

### Measurement of particulate matter

PM concentrations were measured following the previous method[27] in the environmental workplace ($n$ = 14). The particulate matter measurement was collected in the same day. Briefly, four Sioutas cascade impactor (SKC Inc.) stages were attached to the Leland Legacy pump (SKC Inc.) and operated at 9 L/min flow rate for 2 h. Quartz filters (25 and 37 mm) were installed in each impactor stage to catch the PM in different sizes. The first, second, third, and fourth stages of impactor cached the particulate in diameter less than 0.25 μm ($PM_{0.25}$), 0.25–0.5 μm ($PM_{0.5}$), 0.5–1 μm ($PM_{1.0}$), and 1–2.5 μm ($PM_{2.5}$), respectively. The levels of each PM were finally measured by gravimetric analysis using MT5 Microbalance (METTLER TOLEDO Inc.) after being conditioned in the balance room for at least 24 h.

### Identification of respiratory health symptoms

Information on the presence of respiratory health symptoms (coughing, sputum expectoration, shortness of breath, wheezing, and chest-related complaints) within the last 3 months was identified using ST. George's Respiratory Questionnaire[28] by the interview.

### Lung function test (Spirometry)

Lung function tests (spirometry) have been widely used to detect deterioration in respiratory function. The test was performed by a trained researcher using a Portable Spirometer BTL-08 Spiro. The minimum expiration time is 3 s until the flow volume graph peaks. Respondents were given enough time to understand the test procedure and provide the required flows. A pulmonologist's doctor further interpreted the results to identify lung function abnormalities. The lung function abnormalities were classified into lung restriction, obstruction, and mixed symptoms.

### Statistical analysis

The statistical analysis used a chi-square test to analyze the association of lung impairment with respiratory health symptoms and risk factors. The statistical significance was defined as a $p$-value $< 0.05$. The t-test was to analyze the differences of concentration of $PM_{2.5}$. The logistic regression analysis was conducted to determine the significant risk factors.

## Results

### Characteristics of the respondents

The general characteristics of respondents are shown in Table 1. All respondents are male workers. Most workers (81.7%) completed high school or upper level at the education level. Almost half of the respondents (43.5%) were actively smoking based on their smoking status. The workers were predominantly >40 years old, had been working <20 years in the production section, and had BMI < 25. Most workers had normal results in a spirometry test, but 13.7% had lung restrictions.

### Particulate matter distributions

Table 2. shows the concentrations of $PM_{0.25}$, $PM_{0.5}$, $PM_{1.0}$, and $PM_{2.5}$ from eight measurement spots in the workplace divided into production and non-production area. The highest mean concentration both in the production and non-production area was $PM_{2.5}$. There was a significant difference in mean concentrations between the production and non-production area.

### Lung function impairment with respiratory health symptoms

The abnormal group reported more wheezing (66.67% vs 33.33%) and almost the same shortness of breath (43.75% vs 56.25%) than the normal group. It also showed a significant correlation between lung function impairment and respiratory health symptoms (wheezing and shortness of breath), demonstrating an 8.61-times and 3.29-times more significant risk of suffering lung function impairment compared to the respondents with normal lung function (Table 3).

**Table 1.** General characteristics of fiber cement roof workers. Indonesia, 2019.

| Variables | Respondents ($n$ = 131, %) |
|---|---|
| Gender | |
| Male | 131 (100.0) |
| Female | 0 (0.0) |
| Education level | |
| Low (Middle school or lower) | 24 (18.3) |
| High (High school or upper) | 107 (81.7) |
| Smoking status | |
| Yes | 57 (43.5) |
| No | 74 (56.5) |
| Age (years old) | |
| ≤40 | 52 (39.7) |
| >40 | 79 (60.3) |
| Body mass index (BMI) | |
| >25 | 63 (48.09) |
| <25 | 68 (51.91) |
| Job unit | |
| Production | 71 (54.20) |
| Non-production | 60 (45.80) |
| Duration of work | |
| >20 years | 61 (46.6) |
| <20 years | 70 (53.4) |
| Spirometry test | |
| Abnormal | 29 (22.1) |
| Lung restriction | 18 (13.7) |
| Lung obstruction | 9 (6.9) |
| Mixed | 2 (1.5) |
| Normal | 102 (77.9) |

**Table 2.** Concentrations of PM in the environmental workplace of a fiber cement roof factory. Indonesia, 2019.

| Variables | Mean (μg/m³) | SD (μg/m³) | Min–Max (μg/m³) |
|---|---|---|---|
| Production area | | | |
| PM 0.25 | 25.76 | 7.68 | 14.82–34.05 |
| PM 0.5 | 44.52 | 10.74 | 28.70–52.88 |
| PM 1.0 | 73.78 | 6.30 | 63.48–80.06 |
| PM 2.5 | 151.26* | 38.83 | 108.61–199.51 |
| Non-production area | | | |
| PM 0.25 | 28.69 | 8.45 | 12.04–35.34 |
| PM 0.5 | 46.69 | 6.29 | 33.33–52.13 |
| PM 1.0 | 68.20 | 11.52 | 48.38–74.85 |
| PM 2.5 | 91.456 | 11.37 | 66.23–99.95 |

PM: particulate matter.
The fiber cement roof industry has distribution concentrations (mean ± SD) of PM 0.25, PM 0.5, PM 1.0, and PM 2.5.
*Significant at <0.05 for an independent $t$-test.

**Table 3.** Prevalence of respiratory health symptoms by lung impairment group among fiber cement roof workers. Indonesia, 2019.

| Symptoms | Abnormal | Normal | OR | $p$-value |
|---|---|---|---|---|
| | n (%) | n (%) | (95% CI) | |
| Coughing | | | | |
| Yes | 22 (33.33) | 44 (66.67) | 4.143 | 0.004 |
| No | 7 (10.77) | 58 (89.23) | (1.624–10.568) | |
| Sputum expectoration | | | | |
| Yes | 9 (20.93) | 34 (79.07) | 0.900 | 0.993 |
| No | 20 (22.73) | 68 (77.27) | (0.370–2.187) | |
| Chest-related complaints | | | | |
| Yes | 12 (40.0) | 18 (60.0) | 3.294 | 0.015 |
| No | 17 (16.83) | 84 (83.17) | (1.343–8.091) | |
| Shortness of breath | | | | |
| Yes | 7 (43.75) | 9 (56.25) | 3.288 | 0.048* |
| No | 22 (19.13) | 93 (80.87) | (1.104–9.794) | |
| Wheezing | | | | |
| Yes | 6 (66.67) | 3 (33.33) | 8.609 | 0.004* |
| No | 23 (18.85) | 99 (81.15) | (2.003–37.005) | |

Significant differences (*, $p < 0.05$) by chi-square test.

**Table 4.** Prevalence of risk factors by lung impairment group among fiber cement roof workers. Indonesia, 2019.

| Variables | Abnormal | Normal | OR (95% CI) | $p$-value |
|---|---|---|---|---|
| | n (%) | n (%) | | |
| Education | | | | |
| <Junior high school | 7 (29.17) | 17 (70.83) | 0.629 (0.232–1.704) | 0.518 |
| >Senior high school | 22 (20.56) | 85 (79.44) | | |
| Smoking | | | | |
| Yes | 22 (38.60) | 35 (61.40) | 6.016 (2.342–15.458) | <0.001* |
| No | 7 (9.46) | 67 (90.54) | | |
| Age | | | | |
| >40 years | 12 (22.64) | 41 (77.36) | 1.050 (0.454–2.420) | 1.000 |
| ≤40 years | 17 (21.79) | 61 (78.21) | | |
| BMI | | | | |
| 25.0–≥30 | 15 (23.81) | 48 (76.19) | 1.205 (0.528–2.752) | 0.816 |
| <18.5–24.9 | 14 (20.59) | 54 (79.41) | | |
| Job | | | | |
| Production | 21 (29.58) | 50 (70.42) | 2.730 (1.108–6.729) | 0.043* |
| Non-production | 8 (13.33) | 52 (86.67) | | |
| Duration of work | | | | |
| ≥20 years | 14 (35.0) | 26 (65.0) | 2.728 (1.162–6.407) | 0.034* |
| <20 years | 15 (16.48) | 76 (83.52) | | |

Significant differences (*, $p < 0.05$) by chi-square test.

### *Lung function impairment with risk factors*

The workers who were actively smoking worked in the production section, and had been working for more than 20 years, had a significant correlation with lung function impairment, demonstrating a 6.0-times, 2.7-times, and 2.7-times greater risk of suffering lung function impairment (Table 4).

Multiple logistic regression analysis took $PM_{2.5}$ exposure, education, smoking, age, BMI, job, and duration of work. Table 5 confirmed the abnormal lung function associated with smoking of OR 5.83 (95% CI: 2.14–15.87) and duration of work of OR 4.93 (95% CI: 1.20–20.24). However, smoking and $PM_{2.5}$ exposure did not show any interaction.

**Table 5.** Multiple logistic regression analysis among fiber cement roof workers in Indonesia, 2019.

| Variable | B | OR | 95% C.I. for OR | | *p*-value |
|---|---|---|---|---|---|
| | | | Lower | Upper | |
| Education | −0.04 | 0.96 | 0.28 | 3.34 | 0.954 |
| Smoking | 1.76 | 5.83 | 2.14 | 15.87 | 0.001* |
| Age | −1.12 | 0.33 | 0.08 | 1.33 | 0.118 |
| BMI | 0.17 | 1.19 | 0.46 | 3.07 | 0.722 |
| Job | 0.80 | 2.23 | 0.80 | 6.22 | 0.126 |
| Duration of work | 1.60 | 4.93 | 1.20 | 20.24 | 0.027* |

*Statistical significance at $p < 0.05$.

## Discussion

This study figured that 22.1% of the workers acquire abnormal results in detail 13.7% lung restriction, 6.9% obstruction, and 1.5% both. This fraction may correlate with the interview result where the abnormal group reported more wheezing (66.67% vs 33.33%) and almost the same shortness of breath (43.75% vs 56.25%). It is also presented 8.61-times and 3.29-times more significant risk of suffering lung function impairment compared to the respondents with normal lung function. Decreased forced vital capacity (FVC) and FEV1 have also been associated with increasing concentrations of $PM_{2.5}$ (PM with aerodynamic diameter $<2.5\,\mu m$) in chronic obstructive pulmonary disease (COPD) patients who are ex-smokers or sustained quitters. Nonetheless, the effects of elemental components of PM among individuals not selected based on respiratory disease are under-investigated.[29] Similar to our results, the previous study has shown the association between $PM_{2.5}$ exposure and lung function decline.[30]

Our results showed high concentrations of $PM_{2.5}$ in the workplace area. The concentrations of $PM_{2.5}$ (127.46 $\mu g/m^3$) were 8.5-fold higher than the WHO standard for the 24 h mean (15 $\mu g/m^3$). It was 3.6-fold higher than the US-EPA standard[31] for a 24 h mean (35 $\mu g/m^3$). Even though the mean concentrations of $PM_{2.5}$ are the highest, the results still meet the required environmental quality standards of the Ministerial Decree of the Ministry of Health, Republic of Indonesia No. 70/2016 regarding Standards and Requirements for Industrial Work Environment, which is 10 $mg/m^3$. Studies on respiratory symptoms among cement workers showed a higher risk of pulmonary dysfunction, pneumoconiosis, bronchitis, emphysema, and other disorders.[32]

Regarding the smaller fractions ($PM_{0.25}$, $PM_{0.5}$, and $PM_{1.0}$), our results demonstrated that the mean concentrations were not as high as $PM_{2.5.}$ Moreover, $PM_{2.5}$ and heavy metals are found easily on the low-level floor in indoor air environments closer to the ground.[33] A previous study reported that the Brownian diffusion-controlled smaller particles, while the larger particle was affected by the gravitational sedimentation.[34] Since the smaller PM fractions have higher toxicities,[35,36] more interest is needed, although the standards have not been established. Prior research by Mekasha et al. presented that the highest emission level of $PM_{2.5}$ was from production areas (material receiving areas), and the lowest was in non-production areas (administrative units). In addition, employees working in production units, such as raw material receiving unit, cement milling unit, and cement packing unit, were eight, three, and two times more likely to develop chronic respiratory symptoms, respectively, compared to the workers in the non-production unit (administrative unit).[37] High PM concentration may contribute to chronic respiratory problems among workers in these high dust exposure units. As expected, the highest concentrations of fine particles were registered in the production area, as it is the type of location with the highest number of sources of emission. The statistical analysis reveals significant differences between the production and non-production areas. Once again, the non-production area had the lowest mean concentration values of particles in this fraction, while the production area had the highest.

We further examined the respiratory health symptoms by interview based on ST. George's Respiratory Questionnaire.[28] Our results presented that workers are likely to have shortness of breath and wheezing. The result of coughing and chest-related complaints was lower than the symptoms of shortness of breath and wheezing. Exposure to a high concentration of PM, particularly $PM_{2.5}$, has been reported to induce respiratory tract irritation and a higher risk of having a chronic cough, dyspnea, sputum production, wheezing, chest tightness, shortness of breath, phlegm, and nose irritation.[30] A previous animal study reported that high exposure to the fine particulate matter had been known to develop significant pulmonary inflammation, airway hyperresponsiveness, and promote airflow obstruction.[38]

Smoking, production workers, and a long work period are the risk factors in our study. The previous studies also found that smoking, workers in production jobs, and long years of employment correlate with lung impairment.[39] Those studies suggest that the workers had a high risk of respiratory symptoms and impairment of lung functions, potentially caused by increased exposure to not only $PM_{2.5}$ but also smaller PM fractions.

This study has limitations regarding design study and health effect measurement. This cross-sectional study can not show the causa effect relationship, and it only describes the association between PM2.5 exposure and lung impairment among workers. Nevertheless, our results are consistent with the current literature. Instead of its limitation, we believe our study will assist increase awareness about PM among workers and develop suitable occupational health programs.

## Conclusion

This study found that the fiber cement roof industry showed high concentrations of $PM_{2.5}$. The mean concentrations of $PM_{2.5}$ were higher than the WHO and US-EPA standards. Almost a quarter of workers get abnormal results (lung restriction, obstruction, and both). This fraction may correlate with the interview result, where the abnormal group reported more wheezing and shortness of breath. The workers are most likely to have shortness of breath and wheezing. Meanwhile, the symptoms of coughing and chest-related complaints were lower than shortness of breath and wheezing. Smoking, production workers, and long work periods also correlate to abnormal lung function. However, the smoking habit factors have a more significant impact than the job factor (production and non-production) and the duration of work.

Our study recommended the industry constantly maintain its programs, such as using enclosed ventilation, filtered cabins, and local exhaust ventilation. The industry should keep using the wet process to prevent dust generation and water suppression from preventing dust spread, as well as to wear respiratory protection for workers exposed to higher amounts of particulate matter. Furthermore, we recommended the industry implement follow-up programs for workers with abnormal lung function by observing trends based on the results of medical examinations indicating abnormal lung function for further occupational health programs to be implemented for workers. Although the study has some limitations, the results will help improve public awareness of PM in the workplace.

### Acknowledgments

The authors would like to acknowledge Dion Zein Nuridzin and Ema Fiki Munaya for technical help.

### Author contribution

Conceptualization, S.M.N and D.H.R.; methodology, S.M.N and D.H.R.; writing—original draft preparation, S.M.N, D.H.R, F.A.P and S.S.; writing—review and editing, D.H.R, F.A.P, S.S. and S.F; supervision, S.M.N.; All authors have read and agreed to the published version of the manuscript

### Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

### Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This research was supported by the Ministry of Research, Technology and Higher Education, the Republic of Indonesia, grant year 2019 and 2020. Decree Number 8/AMD/E1/KP. PTNBH/2020 and Agreement/Contract Number 332/PKS/R/UI/2020.

### Institutional review board statement

The study will be conducted according to the guidelines of th Declaration of Helsinki, and has been approved by the Health Research Committee, National Institute of Health Research and Development (HREC-NIHRD), Ministry of Health of Republic Indonesia. Ethics clearance number: LB.02.01/KE.68/2019. The ethical approval was valid for a year.

### Significance for public health

This article describes the association between $PM_{2.5}$ exposure and lung impairment among workers. In this study, the $PM_{2.5}$ exposure was higher in production area than non-production area. Regarding the health examination of the workers, almost a quarter of workers had lung restriction, obstruction, and combination of both. The workers are most likely to have shortness of breath and wheezing due to $PM_{2.5}$ exposure.

### Availability of data and materials

All data generated or analyzed during this study are included in this published article.

### References

1. Forouzanfar MH, Alexander L, Anderson HR, et al. Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks in 188 countries, 1990–2013: a systematic analysis for the Global Burden of Disease Study 2013. *Lancet* 2015; 386(10010): 2287–2323.
2. Hieu NT and Lee BK. Characteristics of particulate matter and metals in the ambient air from a residential area in the largest industrial city in Korea. *Atmos Res* 2010; 98(2-4): 526–537.
3. Schraufnagel DE. The health effects of ultrafine particles. *Exp Mol Med* 2020; 52(3): 311–317.
4. WHO. Global air-quality guidelines. 2006.
5. Li PH, Yu J, Bi CL, et al. Health risk assessment for highway toll station workers exposed to PM2.5-bound heavy metals. *Atmos Pollut Res* 2019; 10(4): 1024–1030.
6. Schulze F, Gao X, Virzonis D, et al. Air quality effects on human health and approaches for its assessment through microfluidic chips. *Genes* 2017; 8(10): 244.
7. Habre R, Moshier E, Castro W, et al. The effects of PM2.5 and its components from indoor and outdoor sources on

cough and wheeze symptoms in asthmatic children. *J Expo Sci Environ Epidemiol* 2014; 24(4): 380–387.
8. Cohen AJ, Brauer M, Burnett R, et al. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. *Lancet* 2017; 389(10082): 1907–1918.
9. Fan Z, Pun VC, Chen XC, et al. Personal exposure to fine particles (PM2.5) and respiratory inflammation of common residents in Hong Kong. *Environ Res* 2018; 164: 24–31.
10. Khanum F, Chaudhry MN, Skouteris G, et al. Chemical composition and source characterization of $PM_{10}$ in urban areas of Lahore, Pakistan. *Indoor Built Environ* 2021; 30(7): 924–937.
11. Fan J, Li S, Fan C, et al. The impact of PM2.5 on asthma emergency department visits: a systematic review and meta-analysis. *Environ Sci Pollut Res Int* 2016; 23(1): 843–850.
12. Wang L, Cheng H, Wang D, et al. Airway microbiome is associated with respiratory functions and responses to ambient particulate matter exposure. *Ecotoxicol Environ Saf* 2019; 167: 269–277.
13. Tecer LH, Alagha O, Karaca F, et al. Particulate Matter (PM(2.5), PM(10-2.5), and PM(10)) and Children's hospital admissions for asthma and respiratory diseases: a bidirectional case-crossover study. *J Toxicol Environ Health A* 2008; 71(8): 512–520.
14. Jo YS, Lim MN, Han YJ, et al. Epidemiological study of $PM_{2.5}$ and risk of COPD-related hospital visits in association with particle constituents in Chuncheon, Korea. *Int J Chron Obstruct Pulmon Dis* 2018; 13: 299–307.
15. Han F, Yang X, Xu D, et al. Association between outdoor PM $_{2.5}$ and prevalence of COPD: a systematic review and meta-analysis. *Postgrad Med J* 2019; 95(1129): 612–618.
16. Zanobetti A and Schwartz J. The effect of fine and coarse particulate air pollution on mortality: a national analysis. *Environ Health Perspect* 2009; 117(6): 898–903.
17. Gao J, Wang H, Wu X, et al. Indoor air distribution in a room with underfloor air distribution and chilled ceiling: effect of ceiling surface temperature and supply air velocity. *Indoor Built Environ* 2020; 29(2): 151–162.
18. Santos UP, Arbex MA, Braga ALF, et al. Environmental air pollution: respiratory effects. *J Bras Pneumol* 2021; 47: e20200267.
19. Geng N, Wang J, Xu Y, et al. PM2.5 in an industrial district of Zhengzhou, China: chemical composition and source apportionment. *Particuology* 2013; 11(1): 99–109.
20. Xue W, Zhang J, Zhong C, et al. Spatiotemporal PM2.5 variations and its response to the industrial structure from 2000 to 2018 in the Beijing-Tianjin-Hebei region. *J Clean Prod* 2021; 279: 123742.
21. Wang S, Ji Y, Zhao J, et al. Source apportionment and toxicity assessment of PM2.5-bound PAHs in a typical iron-steel industry city in northeast China by PMF-ILCR. *Sci Total Environ* 2020; 713: 136428.
22. Ehrlich C, Noll G, Kalkoff W, et al. PM10, PM2.5 and PM1.0—Emissions from industrial plants—Results from measurement programmes in Germany. *Atmos Environ* 2007; 41(29): 6236–6254.
23. Sylvestre A, Mizzi A, Mathiot S, et al. Comprehensive chemical characterization of industrial PM2.5 from steel industry activities. *Atmos Environ* 2017; 152: 180–190.
24. Cesari D, Merico E, Grasso FM, et al. Source apportionment of PM2.5 and of its oxidative potential in an industrial suburban site in South Italy. *Atmos* 2019; 10(12): 758.
25. Guo H, Kota SH, Sahu SK, et al. Source apportionment of PM2.5 in North India using source-oriented air quality models. *Environ Pollut* 2017; 231: 426–436.
26. Fu N, Kim MK, Chen B, et al. Investigation of outdoor air pollutant, $PM_{2.5}$ affecting the indoor air quality in a high-rise building. *Indoor Built Environ* 2022; 31(4): 895–912.
27. Neophytou AM, Costello S, Picciotto S, et al. Accelerated lung function decline in an aluminium manufacturing industry cohort exposed to $PM_{2.5}$: an application of the parametric g-formula. *Occup Environ Med* 2019; 76(12): 888–894.
28. Jones PW, Quirk FH and Baveystock CM. The St George's Respiratory Questionnaire. *Respir Med* 1991; 85: 25–31.
29. Baccarelli AA, Zheng Y, Zhang X, et al. Air pollution exposure and lung function in highly exposed subjects in Beijing, China: a repeated-measure study. *Part Fibre Toxicol* 2014; 11(1): 51.
30. Paulin L and Hansel N. Particulate air pollution and impaired lung function. *F1000Res* 2016; 5: 201.
31. US EPA. The National Ambient Air Quality Standards for Particle Matter Revised Air Quality Standards 2012. 2012.
32. Thepaksorn P, Pongpanich S, Siriwong W, et al. Determining occupational health risks at a roofing cement processing factory in Southern Thailand. *J Health Res* 2013; 55: 21–28.
33. Bai L, He Z, Chen W, et al. Distribution characteristics and source analysis of metal elements in indoor $PM_{2.5}$ in high-rise buildings during heating season in Northeast China. *Indoor Built Environ* 2020; 29(8): 1087–1100.
34. Urso P, Cattaneo A, Garramone G, et al. Identification of particulate matter determinants in residential homes. *Build Environ* 2015; 86: 61–69.
35. Hu S, Polidori A, Arhami M, et al. Redox activity and chemical speciation of size fractioned PM in the communities of the Los Angeles-Long Beach harbor. *Atmos Chem Phys* 2008; 8: 6439–6451.
36. Shirmohammadi F, Lovett C, Sowlat MH, et al. Chemical composition and redox activity of PM0.25 near Los Angeles International Airport and comparisons to an urban traffic site. *Sci Total Environ* 2018; 610-611: 1336–1346.
37. Mekasha M, Haddis A, Shaweno T, et al. Emission level of PM2.5 and its association with chronic respiratory symptoms among workers in cement industry: a case of Mugher Cement Industry, Central Ethiopia. *Avicenna J Environ Health Eng* 2018; 5(1): 1–7.
38. Hamatui N and Beynon C. Particulate matter and respiratory symptoms among adults living in Windhoek, Namibia: a cross sectional descriptive study. *Int J Environ Res Public Health* 2017; 14(2): 110.
39. Chen CH, Wu CD, Chiang HC, et al. The effects of fine and coarse particulate matter on lung function among the elderly. *Sci Rep* 2019; 9(1): 14790.