Media Kesehatan Masyarakat Indonesia
Volume 21 Issue 1 2025
DOI : 10.30597/mkmi.v21i1.42224
Website : http://journal.unhas.ac.id/index.php/mkmi

Multiple Path Particle Dosimetry (MPPD) Model Total Dust Among Mineral Ore Processing Workers

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ARTICLE INFO

Article History:
Received Jan, 6th, 2025
Accepted Mar, 15th, 2025
Published online Mar, 31st, 2025

Keywords:
Health Risk Assessment;
Mineral Ore Processing Industry;
MPPD;
PEL;
Respirable Dust Exposure;

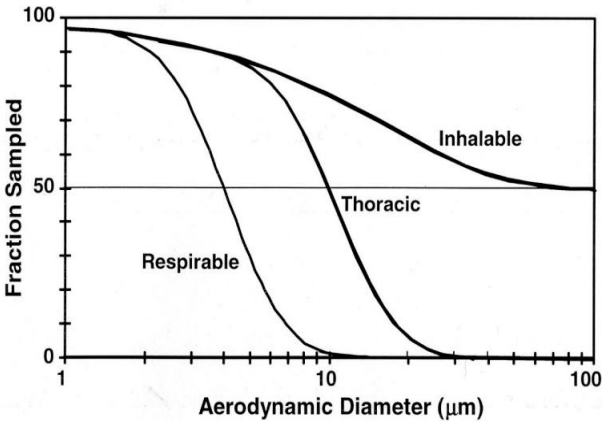
ABSTRACT

Mineral ore processing generates dust, which poses a significant health risk to workers due to prolonged exposure. The aerodynamic properties of this dust allow it to be inhaled and deposited deep within the respiratory tract, increasing the risk of impaired respiratory function. This study aimed to quantify and assess the health risk associated with respirable dust exposure among workers in mineral ore processing areas using the Multiple Path Particle Dosimetry (MPPD) Model. The MPPD model was used to estimate the deposition of dust particles in various regions of the respiratory tract. A constant scenario with the average respirable dust concentration values was used. The values of breathing parameters, such as upper respiratory tract volume, functional residual capacity, breathing frequency, and tidal volume, refer to The International Commission on Radiological Protection (ICRP). Personal respirable dust monitoring data from 2021 to 2024 were analyzed to calculate the total deposition, regional deposition, and deposition fraction for each generation of airways. A cross sectional analysis was conducted on a cohort of 30 male laborers, designated as the directly exposed group. Instruments and procedures used for assessing personal exposure to respirable dust were executed by the NIOSH 0600 standard methodology, employing an SKC Cyclone in conjunction with a personal air sampler, characterized by an airflow rate of approximately 1.9 to 2.0 lpm. The average personal respirable monitoring concentration over the past four years (2021 -2024) was 0,2391 mg/m^3, with annual averages of 0,2835 mg/m^3, 0,2626 mg/m^3, 0,1441 mg/m^3, and 0,2661 mg/m^3, generally within the permissible exposure limit (PEL). The MPPD model simulation results for 2021 showed a maximum mass deposition rate of 2,74 x 10^{-3} µg/min and a maximum mass deposition per area of 7,374 x 10^{-3} µg/m^2. Particle size, shape, density, and airflow velocity were identified as the key factors influencing dust deposition. Understanding dust distribution within the respiratory tract can provide more effective recommendations for controlling dust exposure and implementing a respiratory protection program (RPP) for workers in the mineral ore processing industry.

INTRODUCTION

Mineral ore processing is an integral part of the mining industry, playing a crucial role in extracting valuable minerals from earth and contributing to the national economy. However, this process is accompanied by various hazards and risks due to dangerous activities and the use of hazardous materials.[1] Hazards in the mining industry include landslides, collisions, falls, and dust exposure.[2] The main risk for workers in the mineral ore processing industry is exposure to dust generated during processing activities. Dust is defined as the mass fraction of airborne particles ranging from 1 to 100 micrometers in size, and is called the total suspended particulate (TSP). Due to its aerodynamic properties, dust can be inhaled into the respiratory system and deposited deep within the lungs.[3] Based on size, dust is classified into three categories: respirable dust, inhalable dust, and total dust.

Inhalable dust is less than 100 micrometers in size and can be retained by the upper respiratory tract, such as the mouth or nose, as well as by the bronchial tree, which includes cilia and mucus. As shown in Figure 1, respirable dust is a mass fraction of inhalable particles with a 50% cut-point size of approximately 4 micrometers. The particles will penetrate deeper into the tracheobronchial region and enter the alveolar region, eventually entering the bloods tream. Total dust is the combination of inhalable and respirable dust.[4–6] Therefore, it is essential in industrial hygiene to evaluate dust concentrations in various size fractions.[4]



Source: ACGIH, 2024

Figure 1. Presentation of Respirable Dust Inhaled and Reaching the Thorax, Relative to Total Airborne Dust

Workers in mineral ore processing environments are frequently exposed to dust. This exposure occurs primarily during the crushing, grinding, and flotation processes. The crushing process aims to reduce the mineral ore to particles approximately 210 micrometers in size. This process generates dust that disperses in the work environment and becomes a source of pollution.[7,8] Long-term exposure to dust can lead to a decline in respiratory health among workers.[9] Exposure to dust during work in mining environments, especially respirable dust, is correlated with an increased prevalence of respiratory disorders such as silicosis, pneumoconiosis, and Chronic Obstructive Pulmonary Disease (COPD).[10]

Pneumoconiosis is one of the most prevalent occupational ailments worldwide, particularly in developing nations. From 1990 to 2017, there was a remarkable 81.1% increase in the incidence of cases across both genders. The age-adjusted prevalence rate was markedly elevated among males.[11] Moreover, the incidence demonstrated an upward trend with advancing age, and this increase was significantly more pronounced in males. According to the Global Burden of Disease report published in 2010, pneumoconiosis was responsible for 125,000 fatalities. The Global Burden of Disease assessment conducted in 2016 estimated that asbestosis was responsible for 3,495 deaths.[12] The prevalence of pneumoconiosis exhibited an upward trajectory among individuals exposed to occupational dust. In Jiangsu Province, China, a total of 9,243 cases were documented between 2006 and 2017, with silicosis and coal workers' pneumoconiosis constituting the majority of these cases. In contrast, in developed nations such as the United Kingdom, asbestosis accounts for the predominant cases.[13]

Regrettably, the prevalence data pertaining COPD within the mining sector are not available in Indonesia; hence, it is imperative to conduct a thorough investigation of COPD to facilitate its effective prevention.[14] These pathological conditions have the potential to culminate in other severe health complications. For example, exposure to silica significantly elevates the risk of developing tuberculosis, malignancies, and emphysema.[15] The Indonesian Ministry of Manpower Regulation No. 5 of 2018 sets exposure

limits for inhalable dust at 5 mg/m^3 and respirable dust at 3 mg/m^3 for an 8-hour time-weighted average. Therefore, the mineral ore processing industry needs to implement interventions to ensure that working conditions do not exceed these limits. When inhaled, dust particles can deposit in various parts of the respiratory system, including the alveoli. Different parts of the lungs serve as attachment sites for dust particles. Therefore, it is essential to understand how dust particles are distributed within the respiratory system to assess the associated health risks.[16] By conducting real-time measurements under actual working conditions, we can gain a better understanding of dust characteristics and their impact on occupational health and safety. Advances in measurement technology have allowed for more accurate risk assessments, effective monitoring strategies, and appropriate controls to mitigate dust-related issues in the mineral ore processing industry.

The primary objective of this study was to evaluate the health risks associated with total dust exposure among workers in the mineral ore processing area. To achieve this, we used Multiple Path Particle Dosimetry (MPPD) to estimate the amount of total dust deposited in various parts of the human respiratory system. The MPPD model allows us to calculate total deposition, regional deposition, and the fraction of deposition in each generation of the airway.[17] We used retrospective data on personal exposure concentrations of respirable dust from 2021 to 2024 to analyze the deposition of size-segregated respirable dust in the human respiratory tract. The results of this study are expected to be used in health risk analysis of workers and provide recommendations for controlling dust exposure.

MATERIAL AND METHOD

The site of the study was meticulously selected at various locations within the mineral ore processing area, specifically at the Cooper-gold mining operation in Mimika Regency, situated in the Central Papua Province of Indonesia. This epidemiological investigation represents a cross sectional analysis conducted on a cohort of 30 male laborers within the mineral ore processing sector, designated as the directly exposed group, were systematically chosen utilizing a simple random sampling methodology. The directly exposed cohort consisted of individuals subjected to respirable dust exposure during their occupational activities within the mineral ore processing environment, and exclusion of workers with preexisting respiratory disease.

Instruments and procedures involved in the assessment of personal exposure to respirable dust were executed by the NIOSH 0600 standard methodology, employing an SKC Cyclone in conjunction with a personal air sampler (Gilian, GiliAir Plus), characterized by an airflow rate of approximately 1.9 to 2.0 liters per minute (lpm). The sampling process was conducted in the breathing zone over a duration of six hours during working hours. For the purpose of dust sampling, Mixed Cellulose Ester (MCE) filters, having a pore size of 0.8 μm and a diameter of 25 mm, were utilized. Initially, the filter was positioned in a disposable petri dish that was duly labeled with the respondent's identification code and subsequently stored in a desiccator for a period of 24 hours prior to being weighed using a four-digit electronic microscale. Samples were collected occurred over a time frame extending from 2021 to 2024. During the sampling phase, the physical parameters of the working environment were quantified, with the temperature fluctuating between a minimum of 11°C and a maximum of 19°C.

This method provides a Time-Weighted Average (TWA) concentration of respirable dust for the entire work shift.[18] The MPPD modelling in this study utilized the MPPD v2.11 software, developed by Applied Research Associates, Inc. This research analysed respirable dust concentration data from various locations to estimate dust deposition in different anatomical regions of the worker's respiratory system. The MPPD used accounts for factors such as particle size distribution, shape, density, and individual breathing parameters. This modelling offers options to simulate human lungs, including specific age options, Yeh-Schum airway modelling, Weibel lung modelling, and other stochastic modelling.[19] This modelling can be categorized into single-path and multi-path approaches, where the single-path method estimates dust deposition in a representative pathway, while the multi-path method is the only method that

provides inter-lobar and intra-lobar deposition patterns.

At the simulation stage, a five-lobe lung model with age-specific parameters was selected. This model allows us to analyse dust deposition in the lung and tracheobronchial regions and provides inter and intra-lobar deposition patterns. Table 1 details the input parameter values used in the modelling, including the Functional Residual Capacity (FRC), Upper Respiratory Tract (URT), and Geometric Standard Deviation (GSD) in the model. The MPPD model classifies dust exposure conditions into two scenarios: constant and variable. In the constant scenario, the breathing frequency and tidal volume were assumed to be constant for each specific respirable dust concentration. Whereas in the variable scenario, both parameters can vary according to activity or time of day.[21]

In this study, a constant scenario with average respirable dust concentration values was used. The values of breathing parameters such as upper respiratory tract volume, functional residual capacity, breathing frequency, and tidal volume refer to The International Commission on Radiological Protection (ICRP). Additionally, the model also considers various other breathing conditions such as mouth breathing, nose breathing, or both. However, in this study, we assumed that all particles entered through the nose.

This research has received an ethical certificate from the ethics committee from The Research and Community Engagement Ethical Committee of Concentrating Division of PTFI and the number of the ethics certificate is Ket-02/Conc.09/2024.

RESULTS

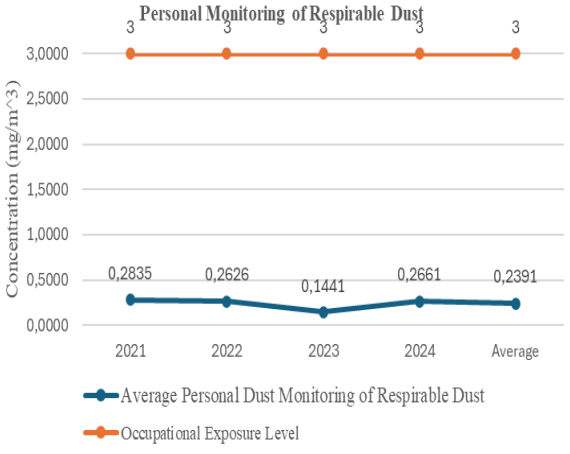
This study utilizes individual respirable dust exposure monitoring data from 2021 to 2024, sourced from a mineral ore processing operation. This is because respirable dust is known to penetrate deep into the lungs, reaching the alveoli.[20] Computational deposition modelling is employed to further understand the transport of dust particles within the respiratory system.

As shown in Figure 2, the average individual respirable dust concentration monitored over the past four years (2021 to 2024) is 0.2391 mg/m^3, and the average annual measured dust concentrations are 0.2835 mg/m^3, 0.2626 mg/m^3, 0.1441 mg/m^3, and 0.2661 mg/m^3, respectively.

Table 1. Parameters Used in MPPD Modelling

Morphometry Airways	Particles Characteristics	Exposure Scenario
Species: Human	**Density**: 1 g/cm	**Dust concentration at the study site**: Constant, dependent on the average personal respirable dust exposure concentration from 2021 to 2024
Model: Age-Specific 5 Lobe **Age selected**: 21 Years	**Aspect Ratio**: 1	**Tidal Volume**: 477,2 mL (Model Value)
FRC: 2123,75 mL (Model Value)	**Diameter**: CMD	**Inspiration fraction**: 0.5 **Breathing Frequency**: 14 Per Minutes
URT Volume: 42,27 mL (Default Value)	**Particle Distribution**: Multiple Particle Size **Range**: 0,01-10 µm	**Body Orientation**: Upright
	Inability Adjustment: GSD (Diameter): 1 GSD (Length): 1	**Breathing Scenario**: Nasal

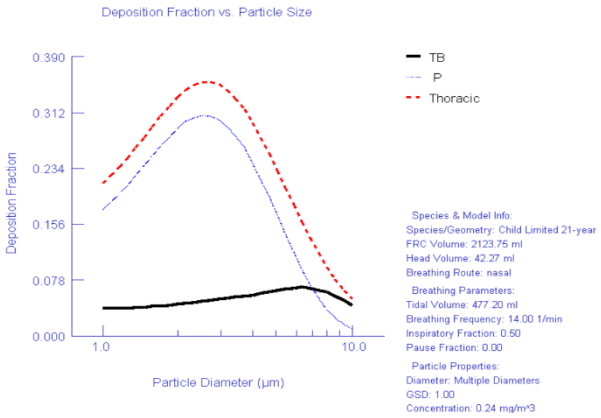
Sources: MPPD, 2024



Sources: Primary Data, 2024

Figure 2. Average Respirable Dust Exposure Concentration in the Mineral Ore Processing Industry

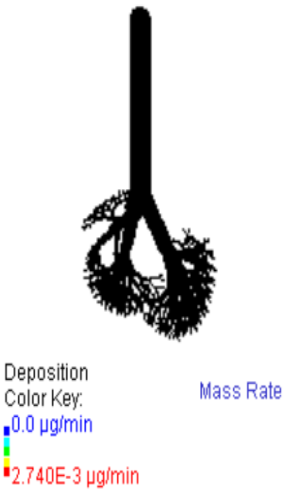
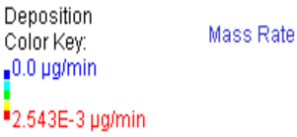
Figure 3 presents the results of the MPPD model simulation designed to predict particle deposition in the respiratory tract of workers, based on an average exposure concentration of 0.2391 mg/m^3 over the past four years. Table 2 visualizes the simulation results of the MPPD model, designed to predict how inhaled dust particles will be distributed and deposited in various parts of the worker's respiratory tract. Table 3 presents a visualization of the MPPD model simulation results, aiming to demonstrate the distribution of dust particle mass per unit area on a surface. Mass deposition per area refers to the amount of particle mass deposited on each unit area of the surface (µg/m^2).



Sources: Primary Data, 2024

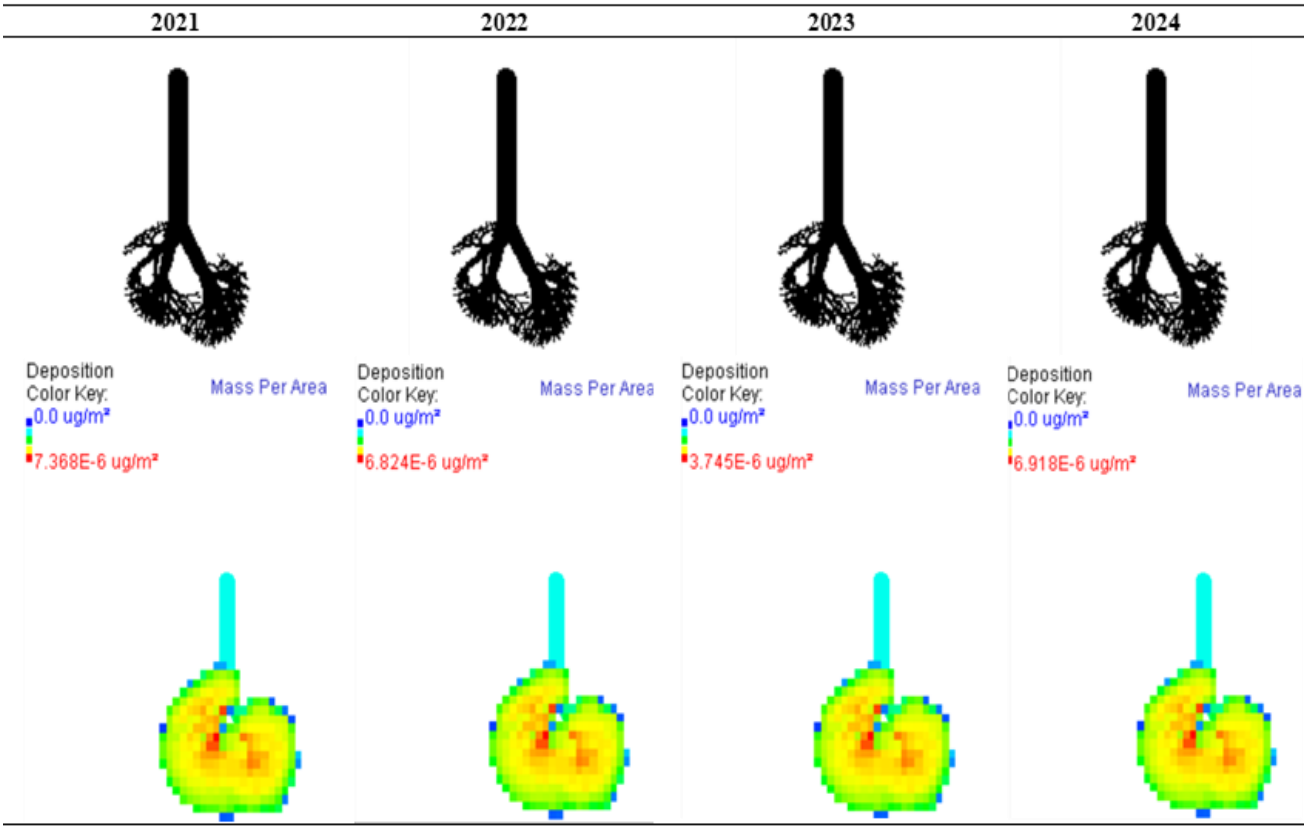
Figure 3. Fraction Deposition vs. Particle Size Curve in the MPPD Model

Table 2. Visualization of Mass Rate of Deposition Per Unit Area in The Human Tracheobronchial (TB) Airway for Respirable Dust

2021	2022	2023	2024
			
			
			

Sources: Primary Data, 2024

Table 3. Visualization of Mass Deposition Per Unit Area in The Human Tracheobronchial (TB) Airways for Respirable Dust



Sources: Primary Data, 2024

DISCUSSION

These monitoring results indicate that respirable dust concentrations generally fall below the permissible exposure limit (PEL) of 3 mg/m^3 according to the ACGIH standard.[3] Figure 3 presents the fraction deposition vs. particle size graph compares the proportion of particles of different sizes deposited in three main regions: upper respiratory tract (TB), lung (P), and entire respiratory tract (Thoracic). The x-axis represents the particle size in micrometers (µm), while the y-axis shows the percentage of deposition. The analysis results indicated that particles with an average diameter of approximately 4 µm had the highest mass deposition fraction, especially in the thoracic region. This suggests that particles of this size are mostly deposited in the lower respiratory tract. With a multiple-particle size range of 1.0-10.0 µm, 4 µm diameter particles dominate in the thoracic area.

The model demonstrates that particle size is a primary determinant of deposition location. Larger dust particles tend to be retained in the upper respiratory tract, while smaller particles can reach the alveoli. This information is useful for understanding the mechanism of dust particle deposition and its impact on respiratory function.[21] Factors affecting the deposition of dust particles in the respiratory tract include Particle size, particles sized 1-3 µm are generally retained in the upper respiratory tract due to greater inertial forces. Particles sized 3-10 µm had a more even deposition distribution, in both the upper respiratory tract and lungs. Particles sized <1 µm tend to reach the alveolar region in the lungs due to following airflow;[22] Particle shape, irregularly shaped particles tend to deposit faster than spherical particles due to increased aerodynamic deposition;[23] Particle density, denser particles have a greater gravitational force and are therefore easier to settle; airflow velocity within the respiratory tract can affect particle travel distance. The higher the airflow velocity, the farther the particles can be carried.[21,24]

Table 2 presents the mass deposition rate is defined as the speed at which the mass of dust particles accumulates at a point in the

respiratory tract, expressed in micrograms per minute (μg/min). The colors in the visualization represent different levels of mass deposition rate. Blue indicates areas with the lowest deposition rate (0 μg/min), while red indicates areas with the highest deposition rate. Thus, the visualization image shows that inhaled dust particles tended to accumulate in certain areas of the respiratory tract at different rates. Areas with bright colors indicate regions that are at the highest risk of dust particle accumulation, which can lead to health problems.[19,25] The results of the MPPD model simulation in 2021 showed that the mass deposition rate of respirable dust was 2.74 x 10-3 μg/min (highest value) and 1.39 x 10-3 μg/min (lowest value) in 2023. The highest deposition rate of dust particles in the thoracic region, which is deposited in large quantities, can clog the bronchi and bronchioles, thus reducing airflow as indicated by a decrease in the value of the first-second forced expiratory volume (FEV1) leading to wheezing and difficulty breathing.[26]

As presented in Table 3, in the visualization, blue indicates areas with the lowest mass deposition (0 μg/m^2), while yellow to red indicate the highest mass deposition.[19,27] This visualization provides information on the distribution of dust particles that accumulate the most and where the concentration is low, thus indicating the areas of the respiratory system that are most exposed to dust particles. The results of the MPPD model simulation in 2021 showed that the mass deposition of respirable dust per area was 7.374 x 10-3 μg/m^2 (*highest value*) and 3.75 x 10-3 μg/m^2 (*lowest value*) in 2023. High particle deposition in the thoracic area generally triggers an immune response. Inhaled dust particles can be cleared by the immune system, primarily by alveolar macrophages.[28] When activated, alveolar macrophages, airway epithelial cells, and other cells will produce various cytokines such as tumor necrosis factor alpha (TNF-α). These cytokines willattract other immune cells to the lungs, triggering a further inflammatory response and damaging lung tissue. Additionally, they activate fibroblasts, thus increasing collagen production and causing pulmonary fibrosis, which is the formation of scar tissue in the lungs.[29,30] This reduces the integrity of the lungs to expand fully or is called restriction.[31]

CONCLUSION AND RECOMMENDATION

Respirable dust deposition in the workers' respiratory tract has been proven to cause decreased respiratory function and induce various Occupational Diseases (OD), including pneumoconiosis, Chronic Obstructive Pulmonary Disease (COPD), and cancer. To assess the associated health risks, this study quantified respirable dust deposition in workers in the mineral ore processing industry. The MPPD version 2.11 model was used to analyze deposition data, considering individual exposure history and adopting a five-lobed adult lung model (21 years). Respirable dust monitoring was conducted for 8 working hours at various stages of the production process.

The mean concentration of respirable dust recorded over the preceding four-year period (2021-2024) is quantified at 0.2391 mg/m^3, with the annual averages of measured dust concentrations being 0.2835 mg/m^3, 0.2626 mg/m^3, 0.1441 mg/m^3, and 0.2661 mg/m^3, respectively. The outcomes derived from the MPPD model simulation, which is specifically formulated to forecast the deposition of particles within the respiratory system of workers, are based on an average exposure concentration of 0.2391 mg/m^3 across the previous four years. The findings from the MPPD model simulation in 2021 indicate that the mass deposition rate of respirable dust reached a peak value of 2.74 x 10-3 μg/min while the lowest recorded value was 1.39 x 10-3 μg/min in 2023.

The maximal deposition rate of particulate matter within the thoracic region, which accumulates in substantial volumes, has the potential to obstruct the bronchi and bronchioles, thereby diminishing airflow as evidenced by a reduction in the first-second Forced Expiratory Volume (FEV1), which may lead to symptoms such as wheezing and respiratory distress. The findings from the MPPD model simulation in 2021 further revealed that the mass deposition of respirable dust per unit area was measured at 7.374 x 10-3 μg/m^2 (highest value) and 3.75 x 10-3 μg/m^2 (lowest value) in 2023. Elevated deposition of particles within the thoracic region typically elicits an immunological response. The inhaled particulate matter is predominantly cleared by the immune system, chiefly through

the action of alveolar macrophages.

This study not only measured total deposition but also the deposition fraction in various lung regions. These findings can serve as a basis for further research on the toxicity of respirable dust and the development of control and prevention strategies for dust exposure in the mineral ore processing industry.

AUTHOR CONTRIBUTIONS

All authors declare that they are participating actively in research and article writing and partly responsible for the content of writing, including in the preparation and writing of concepts, designs, analysis, or revision of the article. Conceptualization: AS, AAM, MRY; Methodology: AS, AAM, MRY; Software: AS, MRY; Data curation: MRY, EKP, PK; Writing original draft preparation: AS, AAM, MRY, NH; Visualization: AS, AAM, MRY; Investigation: AS, MRY, PK; Validation: AS, AAM, MRY; Writing, reviewing and editing: AS, AAM, MRY, EKP, NH; Supervision: AS, AAM, EKP; Project administration: MRY, PK. AS = Arif Susanto; AAM = Anthony Andorful Manuel; MRY = Muhamad Rizky Yudhiantara; EKP = Edi Karyono Putro; PK = Prayoga Kara; NH = Nurulia Hidayah.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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