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Environmental health risk analysis of exposure to airborne particulate matter (PM10 and PM2.5) in residential areas surrounding a nickel smelter

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ABSTRACT

Comunities surrounding nickel smelters may be exposed to particulate emissions, yet evidence from Indonesia remains limited, particularly studies integrating measured PM_{10} and $PM_{2.5}$ concentrations with individual exposure characteristics. This study estimated non-carcinogenic inhalation risks among residents of Borongloe Village, which was selected because its settlements are located close to a nickel smelter industrial area in Bantaeng Regency. A descriptive study using Environmental Health Risk Assessment (EHRA) included 40 adult residents, with 10 representing the area surrounding each of four sampling points. Ambient concentrations were measured gravimetrically using a high-volume air sampler. EHRA integrated the measured concentrations with individual exposure time, frequency, duration, and body weight to estimate inhalation intake and risk quotients (RQs). Mean concentrations were 30.65 μg/m³ for PM_{10} and 11.57 μg/m³ for $PM_{2.5}$. The corresponding mean RQs were 0.0546 and 0.0287, while the maximum RQs were 0.2035 and 0.1169. All RQs were below one, although residents exposed for more than four hours per day had the highest estimates. Because measurements lasted only 90–120 minutes and the smelter was not operating at full capacity, these values indicate no appreciable non-carcinogenic risk only under the observed exposure scenario and do not demonstrate long-term safety. The results provide a practical basis for prioritizing air-quality monitoring, emission control, risk communication, and protection of residents with longer outdoor exposure. By integrating environmental measurements with individual exposure parameters, this study provides a site-specific baseline EHRA for an understudied community near an Indonesian nickel smelter. Repeated 24-hour and long-term monitoring during normal operations is required to determine risks under representative operating conditions.

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1. INTRODUCTION

Ambient air pollution remains one of the leading environmental threats to public health. The World Health Organization estimated that outdoor air pollution caused approximately 4.2 million premature deaths worldwide in 2019, with most of the burden occurring in low and middle income countries (World Health Organization, 2024). Particulate matter is one of the most widely used indicators of air pollution because of its established effects on respiratory and cardiovascular health. PM_{10} consists of inhalable particles with an aerodynamic diameter of 10 µm or less, while $PM_{2.5}$ consists of finer particles with a diameter of 2.5 µm or less. PM_{10} can penetrate the lower respiratory tract, whereas $PM_{2.5}$ can reach the alveolar region and enter the bloodstream. Short and long-term exposure to these pollutants has been associated with respiratory infections, impaired lung function, asthma exacerbation, chronic obstructive pulmonary disease, cardiovascular disease, lung cancer, and premature mortality (World Health Organization, 2021, 2024).

Industrial activities are important sources of particulate pollution, particularly when production involves high temperature combustion, solid fuel use, and the handling of mineral materials. Nickel processing through the rotary kiln electric furnace method involves ore drying, calcination, reduction, smelting, material transfer, and energi intensive operations (Keskinkilic, 2019; Wang et al., 2023). These processes can release coarse and fine particulate matter through stacks, fugitive dust, fuel combustion, and material handling activities. Particulate characterization at a nickel smelter has demonstrated that dust emissions may originate from multiple stages of the production process, highlighting the importance of continuous monitoring to protect workers and surrounding communities (Kelvin et al., 2022). A life cycle assessment of nickel production also identified primary nickel extraction as an important contributor to $PM_{2.5}$ and PM_{10} emissions, particularly when energy and processing systems remain dependent on fossil fuels (Golroudbary et al., 2022).

The rapid development of nickel processing industries in Indonesia has increased the need for environmental health protection in communities located near industrial areas (M. G. Y. Lo et al., 2024; Nasution et al., 2024). The Government of Indonesia regulates ambient PM_{10} and $PM_{2.5}$ concentrations through Government Regulation Number 22 of 2021 concerning environmental protection and management. However, compliance with ambient air quality standards alone does not fully describe the health risks experienced by a population (Goshua et al., 2022; Hoffmann et al., 2021). Measured concentrations must be interpreted according to their averaging periods, while the amount inhaled by individuals is also influenced by inhalation rate, body weight, daily exposure time, exposure frequency, and duration of residence. Therefore, population specific exposure assessment is required to complement environmental monitoring.

The nickel smelter industrial area in Pajukukang District, Bantaeng Regency, is located close to residential settlements, including Borongloe Village. Residents may experience particulate exposure during daily activities around their homes, although exposure levels can vary according to industrial operations, local activities, and meteorological conditions (Alhajeri et al., 2024; Maung et al., 2022). Respiratory infections have also remained among the commonly reported health problems in Bantaeng Regency during recent years. Nevertheless, these health records cannot establish that industrial particulate exposure is the cause of respiratory illness because respiratory outcomes may be influenced by various environmental, behavioral, and individual factors (Vardoulakis et al., 2020; Zhang et al., 2021). Direct measurement and systematic exposure assessment are therefore needed to provide an objective estimate of the potential health risks faced by nearby residents.

The use of Environmental Health Risk Assessment is urgent in this setting because particulate concentrations alone cannot describe the dose received by residents or the resulting level of health concern. Individual intake is also influenced by body weight, daily exposure time, exposure frequency, and duration of residence. EHRA integrates these parameters through hazard identification, dose-response assessment, exposure assessment, and risk characterization, allowing measured concentrations to be translated into individual intake and risk quotients. This approach is particularly important around nickel smelters because emissions may vary according to production intensity, fuel use, meteorological conditions, and emission-control performance. An RQ above one indicates that the estimated intake exceeds the reference value and requires risk-management attention, whereas an RQ at or below one indicates no appreciable non-carcinogenic risk only under the evaluated assumptions and exposure scenario (Kemenkes, 2012; Republic of Indonesia Government, 2021). Thus, EHRA complements ambient monitoring by providing a population specific basis for preventive management and risk communication.

Previous studies have several limitations in addressing community risks surrounding Indonesian nickel smelters. Indonesian Environmental Health Risk Assessment studies have primarily examined cement industries, concrete-industry workers, or residential areas affected by other pollution sources (Abidin et al., 2025; Fikri et al., 2025; Taha et al., 2025). These exposure settings differ from nickel smelters in production technology, emission characteristics, particulate composition, settlement patterns, and population activity. Meanwhile, studies of nickel smelter particulate matter have mainly characterized emissions from production processes rather than integrating ambient PM_{10} and $PM_{2.5}$ measurements with resident specific exposure parameters (Kelvin et al., 2022). Consequently, evidence remains limited regarding how particulate concentrations around Indonesian nickel smelters translate into inhaled doses and non-carcinogenic risks among nearby communities. This gap limits the development of site specific monitoring, risk communication, and preventive environmental health policies.

Accordingly, this study aimed to analyze the environmental health risks associated with inhalation exposure to PM_{10} and $PM_{2.5}$ among residents living around a nickel smelter industrial area in Bantaeng Regency. Specifically, the study measured ambient particulate concentrations at four residential sampling points, estimated inhalation intake using individual exposure characteristics, and characterized non carcinogenic risks under average and maximum exposure scenarios. The findings are expected to provide a baseline for periodic air quality monitoring, risk communication, and preventive environmental health management in communities surrounding the industrial area.

2. RESEARCH METHOD

Study Design and Setting

This study used a descriptive quantitative design (Siregar et al., 2022) with an Environmental Health Risk Assessment approach to estimate non carcinogenic risks associated with inhalation exposure to PM_{10} and $PM_{2.5}$. The assessment followed four stages: hazard identification, dose response assessment, exposure assessment, and risk characterization (Kemenkes, 2012). The study was conducted in residential areas of Borongloe Village, Pajukukang District, Bantaeng Regency, Indonesia, located near a nickel smelter industrial area. Field data were collected in December 2025. Ambient air sampling was conducted on December 17, 2025.

Study participants

The study included 40 adult residents, comprising 10 eligible participants from the residential area surrounding each of the four sampling points. This balanced allocation was used to obtain individual exposure information for every monitored area and to link participants' body weight and activity patterns with the particulate concentration measured at the corresponding point. Because the study aimed to conduct a descriptive, site specific EHRA rather than estimate population prevalence or test statistical associations, the sample was not determined through an inferential power calculation. Therefore, the participants represented the exposure scenarios surrounding the four monitoring points but should not be considered a probability based representation of all residents in Bantaeng Regency.

Participant characteristics and exposure patterns were collected using a structured questionnaire. The information included age, sex, duration of residence, average time spent outdoors each day, and the number of days per week spent undertaking activities around the residential environment. Body weight was measured directly using a calibrated weighing scale. Weekly exposure frequency was converted into days per year by multiplying the reported number of exposed days per week by 52 weeks.

Ambient particulate matter measurement

Ambient PM_{10} and $PM_{2.5}$ concentrations were measured at four sampling points selected according to their proximity to the industrial area and the distribution of surrounding settlements. The approximate distance between sampling points was 200 m. Sampling locations were determined with reference to SNI 19-7119.6-2005 concerning the selection of ambient air quality monitoring locations. Air samples were collected sequentially using a High Volume Air Sampler and analyzed gravimetrically by an accredited environmental laboratory. PM_{10} measurement followed SNI 7119.15:2016, while $PM_{2.5}$ measurement followed SNI 7119.14:2016. Sampling was conducted between 08:30 and 17:10 Central Indonesian Time. Measurements lasted 120 minutes at Points 1, 3, and 4 and 90 minutes at Point 2. Temperature, relative humidity, wind speed, wind direction, and weather conditions were recorded during sampling using a thermohygrometer and anemometer.

The particulate concentrations were expressed in $\mu g/m^3$ and converted into mg/m^3 for the exposure calculations. Each participant was assigned the PM_{10} and $PM_{2.5}$ concentration measured at the sampling point representing the participant's residential area. Because the measurements lasted only 90–120 minutes, they were treated as short-duration measurements representing conditions during the sampling period. They were not considered equivalent to the 24 hour or annual averaging periods specified in Indonesia's ambient air quality standards under Government Regulation Number 22 of 2021 (Republic of Indonesia Government, 2021).

Dose response assessment and risk characterization

Pollutant specific inhalation reference concentrations for undifferentiated PM_{10} and $PM_{2.5}$ are not available in the United States Environmental Protection Agency's Integrated Risk Information System. Therefore, this study adopted dose equivalent reference values commonly applied in Indonesian Environmental Health Risk Assessment studies: 0.014 mg/kg/day for PM_{10} and 0.010 mg/kg/day for $PM_{2.5}$ (Gusti et al., 2018; Novirsa & Achmadi, 2012). These values were selected because they are expressed in units consistent with the calculated inhalation intake, allowing the risk quotient to be determined by dividing intake by the corresponding reference value. An RQ above one indicates that estimated intake exceeds the reference level, whereas an RQ at or below one indicates no appreciable non-carcinogenic risk under the evaluated assumptions (Kemenkes, 2012). These reference values are intended for risk characterization and should not be interpreted as ambient air quality standards or definitive thresholds below which health effects cannot occur.

Data Analysis

Data were processed using Microsoft Excel and analyzed descriptively. Categorical variables were summarized as frequencies and percentages. Continuous variables were presented as means and standard deviations or medians and ranges, according to their distributions. PM_{10} and $PM_{2.5}$ concentrations, participant specific intake values, and risk quotients were summarized using minimum, maximum, and average values. No inferential statistical tests were used to establish associations or causal relationships between particulate exposure and health outcomes.

3. RESULTS AND DISCUSSIONS

The study involved 40 adult residents, with 10 participants representing the residential area around each sampling point. Table 1 showed that most participants were women (77.5%), and the largest age group was 31–45 years (42.5%). Three quarters of the participants had lived in the study area for more than 10 years. The participants had a mean age of 42.7 years and a mean body weight of 58.0 kg. The median daily outdoor exposure time was 2 hours, while the median exposure frequency was 208 days per year.

Table 1. Characteristics of the study participants

Characteristic	Category/statistic	n (%) or value
Sex	Male	9 (22.5)
	Female	31 (77.5)
Age group	18–30 years	6 (15.0)
	31–45 years	17 (42.5)

Characteristic	Category/statistic	n (%) or value
Duration of residence	46–60 years	14 (35.0)
	>60 years	3 (7.5)
	<5 years	2 (5.0)
	6–10 years	8 (20.0)
	>10 years	30 (75.0)
Age	Mean ± SD, years	42.7 ± 12.3
Body weight	Mean ± SD, kg	58.0 ± 5.3
Daily outdoor exposure	Median (range), hours/day	2 (1–8)
Exposure frequency	Median (range), days/year	208 (104–364)

The predominance of long term residents indicates that the participants represented a relatively stable population around the industrial area. However, duration of residence should not be interpreted as equivalent to duration of exposure to emissions from the nickel smelter because industrial activity may have changed over time. Similarly, the demographic distribution was used to characterize the exposed population rather than to test whether sex or age was independently associated with particulate exposure or health risk.

Daily outdoor exposure time and annual exposure frequency varied considerably among participants. These variations are important in Environmental Health Risk Assessment because estimated intake is influenced not only by ambient concentration but also by the amount of time an individual spends in the exposed environment. Consequently, residents living in the same area may have different intake and RQ values even when assigned the same ambient particulate concentration.

Ambient PM_{10} and $PM_{2.5}$ concentrations and risk estimates

PM_{10} concentrations ranged from 26.51 to 38.52 μg/m³, with an average of 30.65 μg/m³. The highest PM_{10} concentration was recorded at Point 1, while the lowest was recorded at Point 2. $PM_{2.5}$ concentrations ranged from 10.98 to 12.36 μg/m³, with an average of 11.57 μg/m³. The highest $PM_{2.5}$ concentration occurred at Point 3, whereas the lowest was measured at Point 2 (Table 2).

Table 2. Ambient concentrations, inhalation intake, and risk quotients by sampling point

Sampling point	PM_{10} concentration (μg/m³)	PM_{10} intake (mg/kg/day)	PM_{10} RQ	$PM_{2.5}$ concentration (μg/m³)	$PM_{2.5}$ intake (mg/kg/day)	$PM_{2.5}$ RQ
Point 1	38.52	0.0010	0.0710	11.24	0.0003	0.0290
Point 2	26.51	0.0007	0.0507	10.98	0.0003	0.0294
Point 3	30.12	0.0009	0.0614	12.36	0.0004	0.0353
Point 4	27.45	0.0005	0.0353	11.69	0.0002	0.0211
Overall average	30.65	0.0008	0.0546	11.57	0.0003	0.0287

Note: Intake and RQ values for each point represent the average of 10 participants. RQ was calculated using reference values of 0.014 mg/kg/day for PM_{10} and 0.010 mg/kg/day for $PM_{2.5}$.

Differences between the sampling points were observed for both particulate fractions. PM_{10} was highest at Point 1, whereas $PM_{2.5}$ was highest at Point 3. These differences may reflect the combined influence of proximity to local emission sources, material handling activities, wind conditions, and measurement time. Because sampling was conducted sequentially at different locations during a single day, the study could not separate spatial differences from temporal and meteorological variations. Therefore, the results should not be interpreted as a permanent ranking of air quality among the four locations.

The recorded concentrations were numerically lower than Indonesia's 24-hour ambient standards of 75 μg/m³ for PM_{10} and 55 μg/m³ for $PM_{2.5}$ under Government Regulation Number 22 of 2021. However, the measurements lasted only 90–120 minutes and therefore cannot be used to establish regulatory compliance with 24-hour or annual standards. The WHO air quality guideline values are also defined using specific 24-hour and annual averaging periods (World Health Organization, 2021). Accordingly, the present concentrations represent short duration conditions during the field measurement and should not be interpreted as daily or long term average exposure.

The average intake was 0.0008 mg/kg/day for PM_{10} and 0.0003 mg/kg/day for $PM_{2.5}$. The corresponding average RQ values were 0.0546 and 0.0287, respectively. The maximum observed participant specific intake was 0.0028 mg/kg/day for PM_{10} and 0.0012 mg/kg/day for $PM_{2.5}$, producing maximum observed RQ values of 0.2035 and 0.1169. All calculated RQ values were below one, indicating that the estimated intake did not exceed the reference values under the exposure conditions evaluated in this study.

All RQ values were below one because the calculated intakes remained substantially lower than the adopted reference values. The maximum intake was 0.0028 mg/kg/day for PM_{10} and 0.0012 mg/kg/day for $PM_{2.5}$, compared with reference values of 0.014 and 0.010 mg/kg/day, respectively. These estimates were influenced by the relatively low particulate concentrations measured during sampling, the median outdoor exposure time of 2 hours per day, the median exposure frequency of 208 days per year, and the mean body weight of 58.0 kg. Most smelter units were inactive during sampling, while the remaining active unit was experiencing an operational disruption, which may have reduced emissions compared with normal or peak production. Meteorological dispersion and contributions from non industrial sources may also have affected the measured concentrations. Therefore, proximity to the smelter did not automatically produce an RQ above one because risk was determined by the combined effects of concentration and individual exposure parameters. The findings indicate no appreciable risk only under the observed reduced activity scenario and may underestimate exposure during normal operations. They should not be interpreted as evidence of long term safety or regulatory compliance.

These estimates were lower than those reported in several Indonesian industrial and residential settings. Abidin et al. (2025) recorded residential $PM_{2.5}$ concentrations of 50.7–61.9 µg/m^3 in Bantul Regency and reported RQ values above one. Among concrete-industry workers, Fikri et al. (2025) found average concentrations of 71.25 µg/m^3 for $PM_{2.5}$ and 217.25 µg/m^3 for PM_{10}, with a maximum RQ of 2.08. The differences from the present study are likely related to substantially higher pollutant concentrations, occupational exposure patterns, and longer time spent in contaminated work environments.

The relatively low risk estimates in the present study should also be interpreted in relation to field conditions. During sampling, most smelter units were reportedly not operating, while the active production unit was experiencing an operational disruption. The measured concentrations and calculated RQ values therefore provide a baseline estimate for a period of reduced industrial activity and cannot be generalized to full production conditions. Previous research has demonstrated that particulate emissions from nickel smelting activities may vary according to production stage, operational intensity, fuel use, and emission control performance (Kelvin et al., 2022).

An RQ below one does not mean that the air is completely free from health hazards. It only indicates that the estimated dose was below the reference value used in the calculation. WHO has reported that adverse health effects can occur at particulate concentrations lower than previously recognized, particularly after repeated or long term exposure (World Health Organization, 2021). Furthermore, the present assessment was based on particulate mass and did not determine chemical or metal composition. Nickel smelter particles may contain mineral and metal components with different toxicological properties; therefore, equal mass concentrations do not necessarily indicate equal health hazards (Kelvin et al., 2022).

Variation in risk quotient according to daily exposure time

The RQ values increased across the daily exposure time categories for both particulate fractions. Participants exposed for less than 2 hours per day had the lowest average RQ values. The highest averages were observed among participants exposed for more than 4 hours per day, reaching 0.1401 for PM_{10} and 0.0758 for $PM_{2.5}$.

Although all calculated RQ values were below one, this finding should be interpreted as indicating no appreciable non carcinogenic risk under the exposure assumptions applied in this study, rather than the complete absence of health effects. The mining and processing of critical minerals in Indonesia may release pollutants into the air and contribute to adverse human health impacts, particularly when industrial activities depend heavily on fuel combustion and electricity generation (Wahyono et al., 2024). Airborne particles originating from mining and mineral processing activities may also contain metals whose toxicity cannot be adequately represented by particulate mass concentration alone (Kasongo et al., 2024). Moreover, a nationwide cohort study demonstrated that long-term exposure to $PM_{2.5}$ was associated with cardiopulmonary diseases and lung cancer (W. C. Lo et al., 2022), while a recent systematic review found that ambient $PM_{2.5}$ exposure may increase the incidence of asthma among adults (Lee et al., 2024). Evidence from low and middle income countries further indicates that prolonged exposure to both $PM_{2.5}$ and PM_{10} is associated with increased cardiovascular and respiratory morbidity and mortality (Guo et al., 2023). Therefore, the current RQ values should be regarded as a baseline risk estimate. Repeated measurements across different seasons, meteorological conditions, and levels of smelter production, accompanied by an analysis of the metal composition of particulate matter, are required to provide a more comprehensive assessment of long-term community health risks.

Table 3. Risk quotients according to daily exposure time

Daily exposure time	n	Mean PM_{10} RQ	Maximum PM_{10} RQ	Mean $PM_{2.5}$ RQ	Maximum $PM_{2.5}$ RQ
<2 hours/day	7	0.0135	0.0231	0.0079	0.0133
2–4 hours/day	27	0.0463	0.1122	0.0236	0.0585
>4 hours/day	6	0.1401	0.2035	0.0758	0.1169

In the table 3 show the higher RQ values among participants with longer daily exposure are consistent with the structure of the intake equation, in which exposure time is included directly in the numerator. Thus, this pattern should not be interpreted as an independently tested association or causal effect. Rather, it demonstrates how individual activity patterns modify estimated dose when ambient concentration and other exposure parameters are considered. Similar Environmental Health Risk Assessment studies have shown that daily exposure time, exposure frequency, body weight, and pollutant concentration contribute jointly to variation in intake and risk estimates (Novirsa & Achmadi, 2012; Taha et al., 2025).

Although none of the exposure time groups had an average or maximum RQ exceeding one, participants who spent more than 4 hours per day outdoors had approximately ten times the average PM_{10} RQ and $PM_{2.5}$ RQ of those exposed for less than 2 hours. This finding identifies residents with longer outdoor activity as a priority group for risk communication and preventive measures, particularly when industrial production increases or visible dust episodes occur. Preventive actions may include access to timely air-quality information, reducing non-essential outdoor activity during high emission periods, and appropriate respiratory protection when particulate concentrations increase.

Environmental health implications and study limitations

The findings support the need for continued environmental management even though all calculated RQ values were below one. Monitoring should be repeated when the smelter is operating at normal capacity and should use measurement periods consistent with national 24-hour standards. Monitoring at different seasons and times of day, combined with upwind and downwind sampling, would provide a more representative description of particulate dispersion. Source level measures should include routine maintenance of bag filters and scrubbers, control of fugitive dust from material handling and transport, and evaluation of stack emissions. Continued monitoring of particulate sources is important for reducing environmental impacts on workers and surrounding communities (Kelvin et al., 2022).

The operating condition of the smelter has important implications for interpreting these findings. During sampling, most smelter units were inactive, while the remaining active unit was experiencing an operational disruption. Reduced production may have resulted in lower industrial emissions and consequently lower particulate concentrations and RQs than those occurring during normal or peak operations. Moreover, the measured particulate matter may have included contributions from background conditions, traffic, domestic activities, and other local sources. Therefore, the findings cannot establish the smelter as the sole emission source and should not be generalized to full capacity operations or interpreted as evidence of regulatory compliance and long-term safety. Instead, they provide a baseline for the observed reduced-activity scenario. Repeated 24-hour measurements during different production levels and seasons, supported by operational records and upwind downwind sampling, are needed to determine how normal smelter activity affects community exposure and risk.

This study has several limitations. First, ambient measurements were conducted at only four points during one day and lasted 90–120 minutes at each location. Second, measurements were conducted sequentially, so differences between points may partly reflect changes in measurement time and meteorological conditions. Third, the industry was not operating at full capacity during data collection, potentially producing lower concentrations than would occur during normal operations. Fourth, ambient concentrations were assigned to residents according to sampling area rather than measured using personal monitoring devices. Fifth, the risk estimates relied on dose-equivalent reference values used in Indonesian Environmental Health Risk Assessment studies rather than pollutant-specific inhalation reference concentrations established for generic PM_{10} and $PM_{2.5}$. Finally, the study did not analyze particulate composition, identify emission sources, estimate lifetime risk, or test relationships with diagnosed health outcomes. These limitations mean that the results should be considered a baseline assessment of the observed exposure scenario rather than definitive evidence of long-term safety or direct attribution of particulate pollution to the nickel smelter.

4. CONCLUSION

This main contribution of this study is the establishment of a site specific baseline EHRA that integrates ambient PM_{10} and $PM_{2.5}$ measurements with individual exposure characteristics in a residential community surrounding an Indonesian nickel smelter. Mean concentrations were 30.65 µg/m³ for PM_{10} and 11.57 µg/m³ for $PM_{2.5}$, with corresponding mean RQs of 0.0546 and 0.0287. All RQs were below one, although residents exposed for more than four hours per day had the highest estimated risks. These results indicate no appreciable non-carcinogenic risk only under the observed short duration and reduced operational scenario.

Local authorities and industry managers should implement repeated 24-hour monitoring during normal and peak operations, strengthen stack emission and fugitive dust controls, routinely evaluate filtration systems, publicly communicate air quality information, and establish community respiratory health surveillance. Particular attention should be given to residents with prolonged outdoor exposure and other vulnerable groups. Further studies should use larger probability based samples, repeated seasonal and upwind downwind measurements, personal exposure monitoring, particulate chemical and metal analysis, and industrial operating records. Longitudinal studies incorporating respiratory symptoms, lung function, and other health indicators are also needed to provide more comprehensive estimates of cumulative and long term health risks.

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REFERENCES

Abidin, A. U., Munawaroh, A. L., Rosinta, A., Sulistiyani, A. T., Ardianta, I., & Iresha, F. M. (2025). Environmental health risks and impacts of PM2.5 exposure on human health in residential areas, Bantul, Yogyakarta, Indonesia. *Toxicology Reports*, *14*. https://doi.org/10.1016/j.toxrep.2025.101949

Alhajeri, N. S., Alrashidi, A. M., Yassin, M. F., & Al-Awadi, L. (2024). Optimizing indoor air quality: Investigating particulate matter exposure in household kitchens and source identification. *Environmental Quality Management*, *34*(1). https://doi.org/10.1002/tqem.22198

Fikri, E., Dewi, D. R., & Juariah, L. (2025). Analisis Risiko Kesehatan Lingkungan (ARKL) Pajanan PM2.5 dan PM10 Pada Pekerja PT. Beton Elemenindo Perkasa Tahun 2024. *Jurnal Kesehatan Lingkungan Indonesia*, *24*(1). https://doi.org/10.14710/jkli.67628

Golroudbary, S. R., Kraslawski, A., Wilson, B. P., & Lundström, M. (2022). Assessment of environmental sustainability of nickel required for mobility transition. *Frontiers in Chemical Engineering*, *4*. https://doi.org/10.3389/fceng.2022.978842

Goshua, A., Akdis, C. A., & Nadeau, K. C. (2022). World Health Organization global air quality guideline recommendations: Executive summary. *Allergy: European Journal of Allergy and Clinical Immunology*, *77*(7). https://doi.org/10.1111/all.15224

Guo, J., Chai, G., Song, X., Hui, X., Li, Z., Feng, X., & Yang, K. (2023). Long-term exposure to particulate matter on cardiovascular and respiratory diseases in low- and middle-income countries: A systematic review and meta-analysis. *Frontiers in Public Health*, *11*. https://doi.org/10.3389/fpubh.2023.1134341

Gusti, A., Arlesia, A., & Anshari, L. H. (2018). Penurunan Derajat Kesehatan Pedagang Akibat Pajanan Debu PM10 di Kawasan Pasar Siteba Kota Padang. *Media Kesehatan Masyarakat Indonesia*, *14*(3). https://doi.org/10.30597/mkmi.v14i3.4260

Hoffmann, B., Boogaard, H., de Nazelle, A., Andersen, Z. J., Abramson, M., Brauer, M., Brunekreef, B., Forastiere, F., Huang, W., Kan, H., Kaufman, J. D., Katsouyanni, K., Krzyzanowski, M., Kuenzli, N., Laden, F., Nieuwenhuijsen, M., Mustapha, A., Powell, P., Rice, M., … Thurston, G. (2021). WHO Air Quality Guidelines 2021–Aiming for Healthier Air for all: A Joint Statement by Medical, Public Health, Scientific Societies and Patient Representative Organisations. *International Journal of Public Health*, *66*. https://doi.org/10.3389/ijph.2021.1604465

Kasongo, J., Alleman, L. Y., Kanda, J. M., Kaniki, A., & Riffault, V. (2024). Metal-bearing airborne particles from mining activities: A review on their characteristics, impacts and research perspectives. In *Science of the Total Environment* (Vol. 951). https://doi.org/10.1016/j.scitotenv.2024.175426

Kelvin, M., Whiteman, E., & Leybourne, M. (2022). Characterization of Particulate Matter Generated at a Nickel Smelter Using Quantitative Mineralogy. *Frontiers in Earth Science*, *10*. https://doi.org/10.3389/feart.2022.817759

Kemenkes, R. I. (2012). Pedoman Analisis Risiko Kesehatan Lingkungan. *Ditjen P2P. Ditjen P2P*.

Keskinkilic, E. (2019). Nickel laterite smelting processes and some examples of recent possible modifications to the conventional route. In *Metals* (Vol. 9, Number 9). https://doi.org/10.3390/met9090974

Lee, S., Tian, D., He, R., Cragg, J. J., Carlsten, C., Giang, A., Gill, P. K., Johnson, K. M., & Brigham, E. (2024). Ambient air pollution exposure and adult asthma incidence: a systematic review and meta-analysis. *The Lancet Planetary Health*, *8*(12). https://doi.org/10.1016/S2542-5196(24)00279-1

Lo, M. G. Y., Morgans, C. L., Santika, T., Mumbunan, S., Winarni, N., Supriatna, J., Voigt, M., Davies, Z. G., & Struebig, M. J. (2024). Nickel mining reduced forest cover in Indonesia but had mixed outcomes for well-being. *One Earth*, *7*(11). https://doi.org/10.1016/j.oneear.2024.10.010

Lo, W. C., Ho, C. C., Tseng, E., Hwang, J. S., Chan, C. C., & Lin, H. H. (2022). Long-term exposure to ambient fine particulate matter (PM2.5) and associations with cardiopulmonary diseases and lung cancer in Taiwan: A nationwide longitudinal cohort study. *International Journal of Epidemiology*, *51*(4). https://doi.org/10.1093/ije/dyac082

Maung, T. Z., Bishop, J. E., Holt, E., Turner, A. M., & Pfrang, C. (2022). Indoor Air Pollution and the Health of Vulnerable Groups: A Systematic Review Focused on Particulate Matter (PM), Volatile Organic Compounds (VOCs) and Their Effects on Children and People with Pre-Existing Lung Disease. In *International Journal of Environmental Research and Public Health* (Vol. 19, Number 14). https://doi.org/10.3390/ijerph19148752

Nasution, M. J., Tugiyono, Bakri, S., Setiawan, A., Murhadi, Wulandari, C., & Wahono, E. P. (2024). The Impact of Increasing Nickel Production on Forest and Environment in Indonesia: A Review. In *Jurnal Sylva Lestari* (Vol. 12, Number 3). https://doi.org/10.23960/jsl.v12i3.847

Novirsa, R., & Achmadi, U. F. (2012). Analisis Risiko Pajanan PM2,5 di Udara Ambien Siang Hari terhadap Masyarakat di Kawasan Industri Semen. *Kesmas: National Public Health Journal*, *7*(4). https://doi.org/10.21109/kesmas.v7i4.52

Republic of Indonesia Government. (2021). Government Regulation [PP] Number 22 of 2021 concerning the Implementation of Environmental Protection and Management. In *Legal Documentation and Information Network [JDIH]*.

Siregar, M. H., Susanti, R., Indriawati, R., Panma, Y., Hanaruddin, D. Y., Adhiwijaya, A., Akbar, H., Nugraha, D. P., & Renaldi, R. (2022). *Metodologi penelitian kesehatan*. Yayasan Penerbit Muhammad Zaini.

Taha, S. S., Idoudi, S., Alhamdan, N., Ibrahim, R. H., Surkatti, R., Amhamed, A., & Alrebei, O. F. (2025). Comprehensive review of health impacts of the exposure to nitrogen oxides (NOx), carbon dioxide (CO2), and particulate matter (PM). In *Journal of Hazardous Materials Advances* (Vol. 19). https://doi.org/10.1016/j.hazadv.2025.100771

Vardoulakis, S., Giagloglou, E., Steinle, S., Davis, A., Sleeuwenhoek, A., Galea, K. S., Dixon, K., & Crawford, J. O. (2020). Indoor exposure to selected air pollutants in the home environment: A systematic review. In *International Journal of Environmental Research and Public Health* (Vol. 17, Number 23). https://doi.org/10.3390/ijerph17238972

Wahyono, Y., Sasongko, N. A., Trench, A., Anda, M., Hadiyanto, H., Aisyah, N., Anisah, A., Ariyanto, N., Kumalasari, I., Putri, V. Z. E., Lestari, M. C., Panggabean, L. P., Ridlo, R., Sundari, S., Suryaningtyas, A. D., Novianti, E. D., Hakim, M. R. F., Prihatin, A. L., & Matin, H. H. A. (2024). Evaluating the impacts of environmental and human health of the critical minerals mining and processing industries in Indonesia using life cycle assessment. *Case Studies in Chemical and Environmental Engineering*, *10*. https://doi.org/10.1016/j.cscee.2024.100944

Wang, X., Zhu, D., Guo, Z., Pan, J., Lv, T., Yang, C., & Li, S. (2023). Efficient Utilization of Limonite Nickel Laterite to Prepare Ferronickel by the Selective Reduction Smelting Process. *Sustainability (Switzerland)*, *15*(9). https://doi.org/10.3390/su15097147

World Health Organization. (2021). *WHO global air quality guidelines: particulate matter (PM2. 5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide: executive summary*. World Health Organization.

World Health Organization. (2024). *Ambient (outdoor) air pollution*. https://www.who.int/news-room/fact-sheets/detail/ambient-%28outdoor%29-air-quality-and-health?utm_source=chatgpt.com

Zhang, L., Ou, C., Magana-Arachchi, D., Vithanage, M., Vanka, K. S., Palanisami, T., Masakorala, K., Wijesekara, H., Yan, Y., Bolan, N., & Kirkham, M. B. (2021). Indoor particulate matter in urban households: Sources, pathways, characteristics, health effects, and exposure mitigation. In *International Journal of Environmental Research and Public Health* (Vol. 18, Number 21). https://doi.org/10.3390/ijerph182111055