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Environmental Health Risk and Spatial Distribution of $PM_{2.5}$ in The Cement Industry

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ABSTRACT

The proximity of cement factories to residential areas raises concerns about air pollution and health risks associated with particulate matter (PM) emissions, particularly $PM_{2.5}$. This study aims to assess environmental health risks and spatial $PM_{2.5}$ exposure around the cement industry in South Sulawesi, Indonesia. Methods involved descriptive quantitative techniques, with data collected from eight sampling locations using purposive sampling, encompassing 160 individuals. Data analysis included intake calculations and risk quotient assessments. Hazard identification, dose-response analysis, exposure evaluation, and risk characterization were conducted to assess the health risks of $PM_{2.5}$ exposure. Results indicate that $PM_{2.5}$ levels in areas near the cement plant often exceed acceptable safety limits, posing notable health risks, especially among sensitive populations such as children and the elderly. The spatial analysis identifies Taraweang and Mangilu Villages as moderately exposed, Mangilu village is 1.6 km away from the cement factory, while Taraweang village is 1.55 km away, underscoring the necessity for targeted mitigation strategies and policies to safeguard public health in similar industrial settings.

1. INTRODUCTION

Particulate Matter (PM) refers to airborne mixtures of fine solid particles and liquid droplets originating from both anthropogenic and natural processes. Prolonged and repeated exposure to PM is associated with numerous adverse health outcomes, notably affecting respiratory and cardiovascular functions. PM typically comprises chemical constituents such as sulfates, nitrates, ammonia, sodium chloride, black carbon, mineral particles, and water content (WHO, 2023). In the cement manufacturing sector, particulate emissions are considered a major environmental pollutant. These emissions, primarily in the form of dust, can be released during almost every operational phase, including raw material handling, processing, and the distribution of finished cement products (Fitriyanti and Fatimura, 2019).

$PM_{2.5}$ is particulate dust with an aerodynamic diameter of 2.5 µm originating from fuel combustion, vehicle smoke, forest fires, and industry, smaller than PM_{10} (≤10 µm). $PM_{2.5}$ can be inhaled through the nose or mouth, pass through the respiratory tract, and reach the lung alveolus because its small size allows it to escape the body's natural filtration. These pollutants are collected with 50% efficiency by PM sampling collection 2.5 (Liang et al., 2021). $PM_{2.5}$ forming composition consists of sulfates, nitrates, organic compounds, ammonium compounds, metals, acidic materials, and other contaminants, which are believed to harm health.

$PM_{2.5}$ refers to fine particulate matter with an aerodynamic diameter of 2.5 micrometers or less, which is primarily generated from sources such as combustion of fossil fuels, motor vehicle emissions, industrial activities, and biomass burning, and is significantly smaller in size compared to PM_{10}

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particles (≤10 µm). $PM_{2.5}$ can be inhaled through the nose or mouth, pass through the respiratory tract, and reach the lung alveolus because its small size allows it to escape the body's natural filtration.

The generation of $PM_{2.5}$ originates from multiple sources, such as the combustion of biomass and coal, emissions from motor vehicles and industrial processes, as well as the resuspension of particulate dust (Sun et al., 2023). Among the identified sources, the combustion of solid fuels contributes substantially to $PM_{2.5}$ emissions, primarily because of its inherently low thermal efficiency and the high emission rates of pollutants released during the process (Xu et al., 2019; Yun et al., 2020). In the cement industry, $PM_{2.5}$ is produced by processing raw materials, burning limestone into cement, packaging, and storage (Regia et al., 2021).

Rapidly growing industrial activities cause an increase in energy consumption, which can indirectly cause air pollution (Ouyang et al., 2022). The physicochemical characteristics of $PM_{2.5}$ exhibit considerable variability depending on the emission source. Combustion of solid fuels is known to generate $PM_{2.5}$ laden with high concentrations of organic compounds and trace heavy metals. These chemical constituents can potentiate the cytotoxic potential of $PM_{2.5}$ by inducing cellular dysfunction and enhancing oxidative stress upon inhalation and systemic absorption in the human body (Sun et al., 2023). Cytotoxicity is defined as the capacity of a substance, process, or agent to induce toxicity in cells, either by causing cell death or impairing cellular functions (Saroyo and Saputri, 2021). Figure 1 explains the flow or scheme of environmental impacts related to fly ash exposure to human health and ecosystems, with details of sources, exposures and impacts. Wind can transport particulate matter over long distances, leading to its deposition in soil and water bodies.

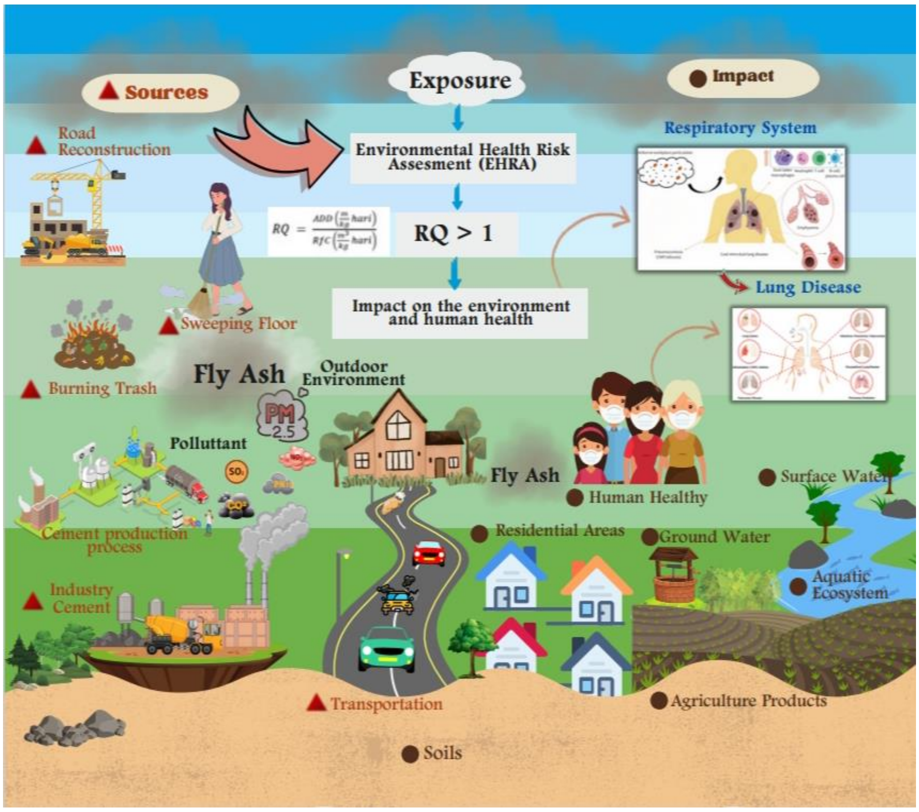


Figure 1. Exposure of $PM_{2.5}$ in the cement industry

Airborne particulate matter (PM) can undergo long-range atmospheric transport via wind and subsequently deposit on terrestrial or aquatic surfaces (United States Environmental Protection Agency, 2022). Air humidity also plays a crucial role in influencing PM behavior, with humid conditions accelerating the deposition of fine particles such as $PM_{2.5}$ (Duppa et al., 2020). Exposure to $PM_{2.5}$ poses substantial public health risks, as it has been epidemiologically associated with cardiovascular and respiratory disorders such as myocardial infarction, arrhythmias, asthma aggravation, reduced pulmonary function, and elevated mortality among individuals with preexisting cardiopulmonary conditions (United States Environmental Protection Agency, 2022). Environmental impacts associated with PM include land degradation, water pollution, solid waste generation, and dust accumulation. In the cement industry, PM emissions are particularly influenced by the use of calcareous materials, primarily derived from natural limestone ($CaCO_3$). Calcium, which constitutes nearly 50% of CO_2 emissions during clinker production, is a key contributor to air pollution in this sector (Abubakar et al., 2022).

Global estimates indicate that $PM_{2.5}$ exposure contributes to approximately 5 million premature deaths annually, with an additional 0.5 million deaths linked specifically to $PM_{2.5}$ pollution exacerbated by climate change (Lin et al., 2018). According to the Global Burden of Disease (GBD) study, outdoor air pollution—primarily from $PM_{2.5}$ and ground-level ozone—was responsible for an estimated 4.5 million premature deaths in 2019 (Roser, 2021). The 2020 World Air Quality Report indicates that Indonesia recorded the highest average $PM_{2.5}$ concentration in Southeast Asia, reaching 40.8 µg/m³, ranking first among countries in the region (Dwi Safira et al., 2022).

Assessing the environmental health risks associated with $PM_{2.5}$ exposure is critical, particularly in communities residing near cement industry zones. Due to its ultrafine size, $PM_{2.5}$ is capable of penetrating deep into the respiratory tract, reaching the alveolar region, and potentially translocating into the bloodstream. Consequently, populations in these areas are at elevated risk for developing cardiopulmonary diseases linked to prolonged $PM_{2.5}$ exposure (Chanda et al., 2024; Wan Mahiyuddin et al., 2023). Research by Novirsa and Achmadi (2012) analyzed the risk of $PM_{2.5}$ in the PT Semen Padang area. Lifetime risk assessment results indicate that three zones—Ring 2 (500-1,000 m), Ring 4 (1,500-2,000 m), and Ring 5 (2,000-2,500 m)—exceed the acceptable Risk Quotient (RQ) threshold of 1, signifying potential health hazards. The RQ, defined as the ratio between estimated exposure and a reference concentration, serves as an index for evaluating the likelihood of adverse effects from chemical exposure. The analysis suggests that residential areas located beyond 2.5 km from the cement industry are considered the safest, with $PM_{2.5}$ concentrations not exceeding 0.028 mg/m³ (Novirsa and Achmadi, 2012).

Environmental health risk analysis (EHRA) is a process used to calculate or estimate risks to human health now or in the future (Fitra et al., 2022; Kasim et al., 2023). Analyzing environmental health risks for people living in cement industrial areas is essential to understanding the community's current and future environmental health risks. In addition, related parties (government) can create policies and risk mitigation efforts to reduce disease due to exposure to $PM_{2.5}$ and PM_{10}. Apart from carrying out risk analysis, it is also essential to determine the spatial pattern of people at risk of exposure to $PM_{2.5}$ and PM_{10} from the cement industrial area. GIS is a technology that can store, manipulate, analyze, and display natural conditions with the help of attribute and spatial data (Devi MLS, 2020).

PT Semen Tonasa, recognized as the largest cement manufacturer in Eastern Indonesia, operates on a 715-hectare site located in Biringere Village, Bungoro District, Pangkep Regency, approximately 68 kilometers from the city of Makassar. The facility comprises four production units, each equipped with key components such as limestone and clay crushers, raw mills, kilns, coal mills, silos, and packing systems. Utilizing a dry processing method, Units II and III have a combined annual production capacity of 590,000 tons, while Unit IV and Unit V produce 2,300,000 and 2,500,000 tons of cement per year, respectively.

$PM_{2.5}$ emissions in cement factory are generated through various stages of production, including raw material crushing, grinding, rotary kiln combustion, clinker cooling, and final grinding. These fine particles originate from material dust, fuel combustion, and the condensation of volatilized compounds. The level of $PM_{2.5}$ emissions is influenced by the efficiency of emission control systems such as bag filters and electrostatic precipitators (ESP). The proximity of the cement plant to residential zones increases the potential for ambient air pollution and associated health risks among the surrounding population due to industrial emissions. Exposure to $PM_{2.5}$ in industrial environments often becomes a primary concern in public health risk management.

The novelty of this study resides in the integration of environmental health risk assessment with geospatial analysis to characterize the spatial distribution patterns of $PM_{2.5}$ exposure in the vicinity of the PT Semen Tonasa industrial complex. The implication of this study underscores the importance of integrating spatial information in environmental health risk management to identify the most vulnerable zones to the negative impacts of $PM_{2.5}$ exposure. These findings provide a strong foundation for developing more effective mitigation strategies and environmental protection policies in similar industrial areas.

2. METHODOLOGY

2.1 Study area

PT Semen Tonasa represents the largest cement production facility in Eastern Indonesia. Production Units II and III are situated in Mangilu Village, whereas Unit IV is located in Biring Ere Village, Bungoro District, Pangkep Regency, within the province of South Sulawesi. The activities of the cement factory include mining exploration activities, especially blasting and storing coal fuel, factory operations from Biring Ere to Biringkassi, and supporting raw materials. Figure 2 illustrates the sampling points of respondents and research locations within the PT Semen Tonasa industrial area.

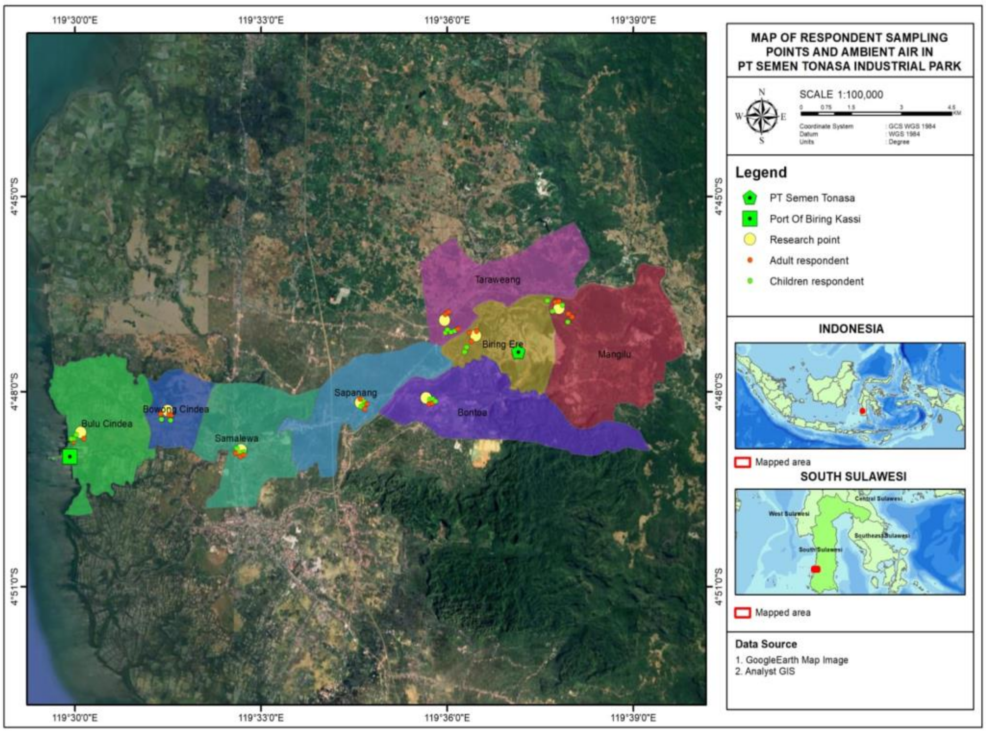


Figure 2. Sampling location

2.2 Sampling method

This study employs a descriptive quantitative approach, with observational findings analyzed using spatial mapping techniques to identify regions with varying levels of $PM_{2.5}$ exposure risk. The samples in this study are human samples and environmental samples used to analyze environmental health risks. The data used in the study all come from primary data. Sampling was conducted at eight sites surrounding the PT Semen Tonasa cement industrial area using a purposive sampling technique. A total of 160 human subjects, comprising both adults and children, were included alongside eight environmental sampling points focused on measuring ambient $PM_{2.5}$ concentrationsAmbient air samples were obtained from eight villages in the vicinity of the PT Semen Tonasa cement industrial complex, specifically Mangilu, Biring Ere, Sapanang, Samalewa, Bulu Cindea, Bowong Cindea, Bontoa, and Taraweang. One air quality sampling point was selected in each village to evaluate the ambient air quality in residential areas near PT Semen Tonasa.

2.3 Environmental health risk assessment

2.3.1 Hazard identification

Hazard identification aims to determine the concentration of specific hazardous agents that may pose health risks upon short- or long-term exposure (Fitra et al., 2022). The risk agents analyzed in this research are particulate matter ($PM_{2.5}$).

2.3.2 Dose-response analysis

The dose-response assessment was conducted using the Reference Concentration (RfC) for $PM_{2.5}$ established by the United States Environmental

Protection Agency (US-EPA), which is set at 0.0012 milligrams per kilogram per day (mg/kg/day).

2.3.3 Exposure analysis (exposure assessment)

Exposure analysis is intended to quantify the exposed population and determine the duration of exposure to the hazardous agent (Paustenbach et al., 2024). Exposure to airborne pollutants is quantified by estimating the intake dose absorbed into the human body (Regia et al., 2021). Exposure assessment is conducted by inputting anthropometric parameters and activity patterns into a standardized computational formula, typically processed using Microsoft Excel (Novirsa and Achmadi, 2012).

In this study, the environmental health risk assessment (EHRA) was carried out through the following sequential stages:

1) Hazard identification

This stage involves identifying the types of particulate matter generated from combustion processes during cement raw material processing that contribute to ambient air pollution.

2) Dose-response analysis

The dose-response analysis was conducted in accordance with the Reference Concentration (RfC) for $PM_{2.5}$ established by the U.S. Environmental Protection Agency (US-EPA), set at 0.0012 mg/kg/day.

3) Exposure analysis

$$\mathrm{ADD} = \frac{\mathrm{C \times InhR \times ET \times EF \times ED}}{\mathrm{BW \times AT}}$$

Where; ADD=average daily dose (mg/kg/day); C=concentration of contaminant in air (mg/m^3); InhR=inhalation rate (m^3/hour); ET=exposure time (hour/day); EF=frequency of exposure (day/year); ED=duration (year); BW=body weight (kg); AT=averaging time (day).

4) Risk characterization

Non-carcinogenic risk characterization was performed by calculating the ratio of estimated intake to the reference dose or concentration of the hazardous agent. The resulting Risk Quotient (RQ) is used to assess the potential for adverse health effects based on established non-carcinogenic exposure guidelines.

$$\mathrm{RQ} = \frac{\mathrm{ADD}}{\mathrm{RfC}}$$

Where; RQ=risk characterization; RfC= reference concentration.

5) Risk management

Upon completion of the environmental health risk assessment, if the Risk Quotient (RQ) is found to be ≥1, mitigation measures must be initiated. As part of the risk management process, appropriate strategies should be implemented, including the establishment of safe exposure thresholds.

The Environmental Health Risk Analysis by the US EPA estimates human health risks from ambient air pollution. The equation for the non-carcinogenic risk analysis of the inhalation route is shown in Figure 3:

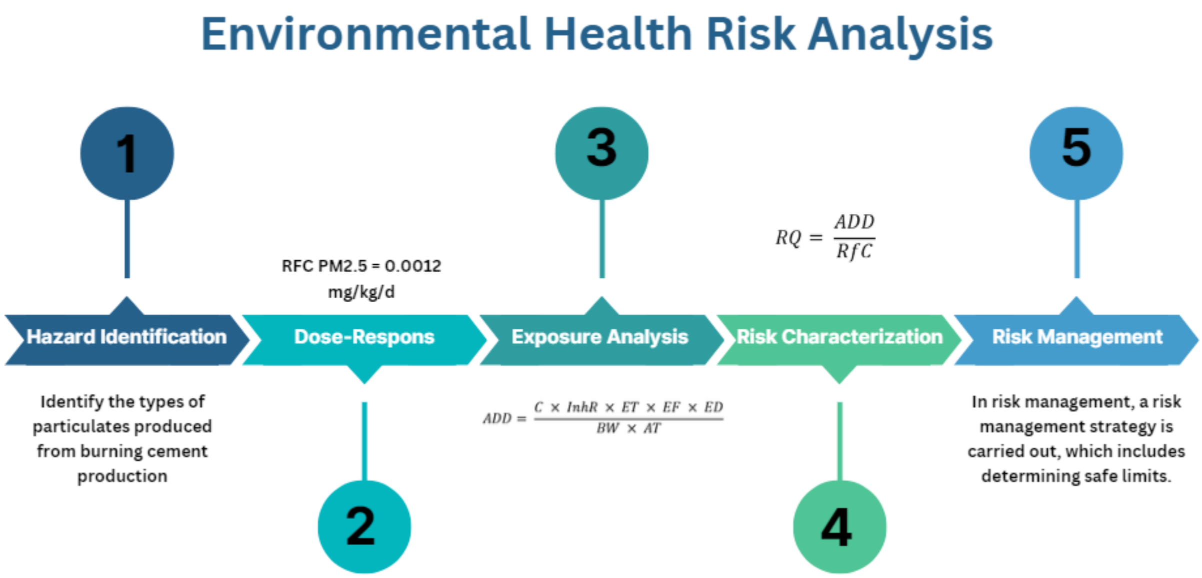


Figure 3. Environmental health risk analysis

3. RESULTS AND DISCUSSION

The environmental sample in this study consists of ambient air quality measurements of $PM_{2.5}$ collected by the researchers at eight locations, with one air quality monitoring point established in each village. Meteorological parameters—such as temperature, relative humidity, and wind speed—were sourced from the Meteorology, Climatology, and Geophysics Agency (BMKG) to ensure data reliability and consistency in representing standardized environmental conditions throughout the study.

Figure 4 The data illustrate ambient $PM_{2.5}$ concentrations along with temperature, humidity, and wind speed in the vicinity of PT Semen Tonasa, Pangkajene Islands Regency. The highest $PM_{2.5}$ level was recorded in Bontoa Village at 20.8 µg/m³, while the lowest was observed in Mangilu Village at 8.3 µg/m³. Two locations exceed the PM concentration quality standards$_{2.5}$ (15 µg/m³), namely Bontoa Village as much as 20.8 µg/m³ and Samalewa Village by 16.1 µg/m³. The temperature at the eight research locations ranged from 32.3-36.5ºC, humidity from 42.9-64.8%, and wind speed from 1.1-2.3 (m/s). A high concentration of $PM_{2.5}$ is influenced by temperature, humidity and wind speed. The higher the temperature, the higher the PM concentration$_{2.5}$, while the higher the humidity, the lower the PM concentration$_{2.5}$. (Keyvani et al., 2020).

High $PM_{2.5}$ concentrations in Bontoa Village are due to the distance from the PT Semen Tonasa industry which is less than 1 km. People complained about scattered dust because of the mobilization of factory production in Biring Ere to Biringkassi. The elevated $PM_{2.5}$ concentration observed in Samalewa Subdistrict is attributed to heavy traffic conditions, particularly from frequent truck movement transporting cement, which contributes to the resuspension of dust particles into the ambient air.

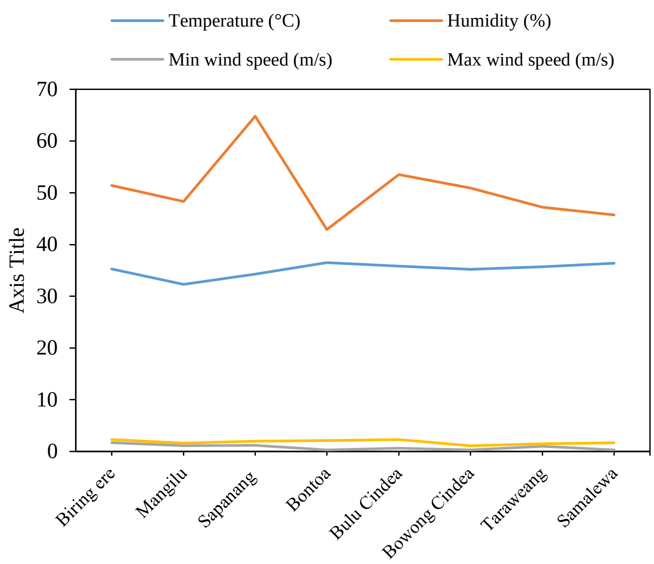
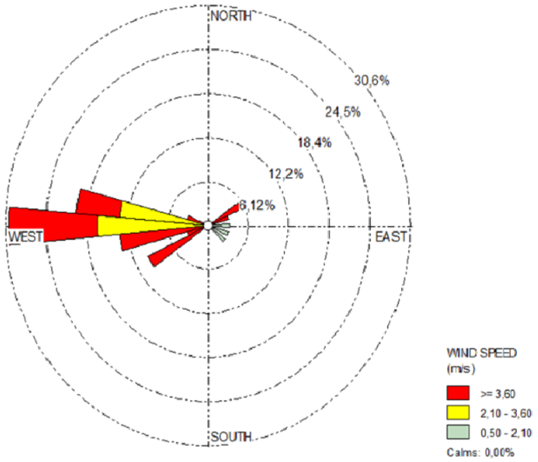


Figure 4. Ambient air quality parameters, $PM_{2.5}$ concentrations and meteorological data in Pangkajene Islands Regency, Indonesia

Meteorological variables such as wind direction, relative humidity, and temperature significantly influence ambient PM concentrations. Wind, in particular, plays a crucial role in the dispersion and transport of atmospheric pollutants. Measurement data indicate wind speeds ranging from 1.1 to 2.3 m/s. Prior research suggests that low wind velocities contribute to pollutant accumulation near emission sources, whereas higher wind speeds facilitate the dispersion of contaminants to more distant locations (Abbasi et al., 2019).

Figure 5 shows the wind direction for 6 months around the cement industry, where the dominant wind direction at the study site is towards the west and shows the frequency distribution of wind classes, where most are in the wind class 2.10-3.60 m/s. Wind serves as a primary driver in the atmospheric dispersion of pollutants, directing the movement of particulate matter along its flow. Wind velocity also determines the rate at which these pollutants are transported away from their emission sources (Istiqomah et al., 2023).



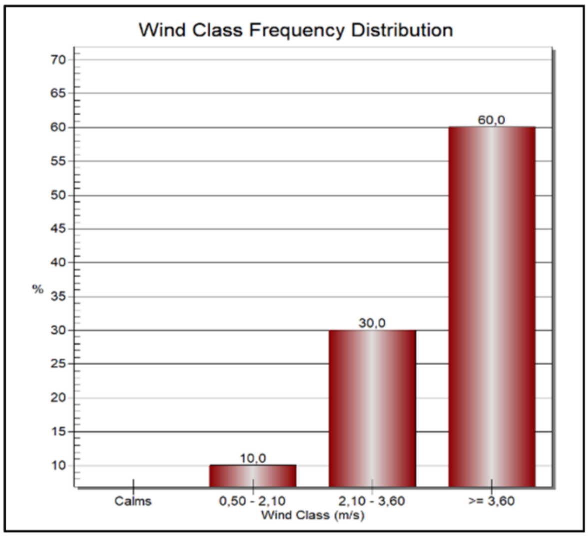


Figure 5. Wind rose and frequency distribution of wind classes

Table 1 shows the data indicate that respondents were aged between 6 and 45 years, with a mean age of 23 years. Body weight ranged from 11 to 92 kilograms, averaging 43 kg. The inhalation rate was recorded at 0.5 m^3/hour for children and 0.83 m^3/hour for adults. Annual exposure frequency varied from 317 to 365 days, with a mean of 358 days/year.

Intake values represent the level of exposure, and respondent characteristics are analyzed to identify the specific risk agents present in ambient air within Pangkajene Islands Regency. The real-time projected intake (Dt) values—minimum, maximum, and mean—are summarized in the following Table 2.

Based on Table 2. ADD intake value *real-time* non-carcinogenic $PM_{2.5}$ From 160 respondents, the result was showed that the mean real-time ADD for adults was 0.0047 mg/kg/day, exceeding that of children, which was 0.0016 mg/kg/day. For the lifetime exposure projection of non-carcinogenic $PM_{2.5}$ over a 5-30 year period, children's mean ADD ranged from 0.0009 to 4.6679 mg/kg/day, higher than adults whose values ranged from 0.0006 to 4.1989 mg/kg/day. Notably, the projected mean ADD in the 5th year remained below the Reference Concentration (RfC) for PM2.5 of 0.0012 mg/kg/day, indicating compliance with safety thresholds at that stage.

Table 1. Characteristics of respondents based on body weight and community activity patterns in Pangkep Regency 2023

Variabel	Min	Max	Mean	Total respondents
Age (years)	6	45	23	160
Body Weight (kg)	11	92	43	
Inhalation Rate (inhR) (m^3/jam) (USEPA, 2022)	0.5	0.83	0.665	
Exposure Frequency (EF) (hari/tahun)	317	365	358	

Table 2. Min, max and mean values of respondents' non-carcinogenic ADD for duration of PM exposure$_{2.5}$ around the PT industrial area. Tonasa Cement Pangkajene Islands District

Duration Time	ADD (mg/kg/day)							
	Min		Max		Mean		Is	
	Children	Mature	Children	Mature	Children	Mature	Children	Mature
Realtime	0.0005	0.0014	0.0043	0.0132	0.0016	0.0047	TMS	TMS
Lifetime								
5	0.0004	0.0002	0.0023	0.0015	0.0009	0.0006	MS	MS
10	0.0013	1.0150	9.8910	9.8520	2.7194	4.1989	TMS	TMS
15	1.0510	1.0380	7.0390	9.5360	2.7435	2.4284	TMS	TMS
20	1.4010	1.0640	9.3850	8.5020	3.6443	2.7060	TMS	TMS
25	1.0250	1.0620	9.6480	7.5670	4.2082	3.2630	TMS	TMS
30	1.1190	1.2750	9.9270	9.0810	4.6679	3.9157	TMS	TMS

3.1 Risk level characteristics

The Risk Quotient (RQ) serves as an indicator for assessing non-carcinogenic health risks. An RQ value exceeding 1 signifies the need for risk management interventions, whereas values below 1 indicate an acceptable risk level. Nonetheless, RQ values should consistently be maintained below the threshold of 1 to ensure continued protection of human health. The non-carcinogenic risk level is presented in Table 3 as follows.

Based on the results of Table 3 shows that the value of the real-time non-carcinogenic risk level or RQ $PM_{2.5}$ of 160 respondents (children and adults) is the average value for adult respondents 3.9845 higher than children, namely 1.4036, which means that the average community around the PT. Semen Tonasa industrial area is at risk of respiratory problems and decreased lung function in children's respondents because the RQ value >1. While the lifetime RQ projection for years 5-30 for children's respondents is 0.7631 to 4.5811 and adult respondents are 0.5342 to 3.2630. The projected mean RQ in the 5th year of the community living around the PT. Semen Tonasa industry is not at risk because the RQ value is <1, while the projected average RQ in the 10th-30th years increases, meaning that people are at risk of premature death, especially in people suffering from chronic heart or lung disease because the RQ value is >1.

Table 3. Min, max and average risk quotient (RQ) PM values$_{2.5}$ around the Industrial Area PT. Semen Tonasa Regency Pangkajene Islands

Duration time	RQ (mg/kg/day)							
	Min		Max		Average		Is	
	Children	Mature	Children	Mature	Children	Mature	Children	Mature
Realtime	0.4260	1.1330	3.6490	11.0000	1.4036	3.9845	Risk	Risk
Lifetime								
5	0.2600	0.1770	1.8600	1.2610	0.7631	0.5342	No risk	No risk
10	0.5840	0.3540	3.9100	2.5220	1.5268	1.0873	Risk	Risk
15	0.8760	0.5310	5.8660	3.7830	2.2904	1.6313	Risk	Risk
20	1.1680	0.7080	7.8210	5.0450	3.0540	2.1752	Risk	Risk
25	9.7770	0.8850	1.4600	6.3060	3.8177	2.7191	Risk	Risk
30	1.7520	1.0620	11.7300	7.5670	4.5811	3.2630	Risk	Risk

In developing countries, PM concentration$_{2.5}$ around cement factories is often above exposure limits, causing an increase in the number and severity of disease (Kholodov et al., 2020). In addition to air pollution, the cement industry contributes to various environmental and societal challenges, including land degradation, water pollution, and adverse health effects associated with particulate emissions (Rasmi and Türkay, 2023). Populations residing in proximity to cement manufacturing facilities are at risk of exposure to airborne pollutants emitted during production processes (Kholodov et al., 2020).

Health risks increase with the duration of exposure (Palacio et al., 2023). Elevated rates of illness among children residing near cement production facilities have been documented even in developed nations, despite ambient PM concentrations remaining within established regulatory limits (Kholodov et al., 2020). Individuals exposed to $PM_{2.5}$ face an elevated risk of developing pulmonary disorders and impaired cardiovascular function. Vulnerable populations, such as children and the elderly, are particularly susceptible to exacerbated respiratory symptoms, including airway irritation and dyspnea (He, 2021).

3.2 Risk management

In the context of Environmental Health Risk Analysis, risk management involves establishing protective exposure thresholds by regulating the duration, frequency, and timing of exposure to ensure population safety. The primary objective of risk management is to ensure that individuals or populations at risk of exposure to hazardous agents remain protected from associated health effects. This is achieved by adjusting relevant exposure parameters to maintain the Risk Quotient (RQ) below 1. The risk management thresholds for $PM_{2.5}$ are detailed in Table 4.

Risk reduction at the research location can be carried out by implementing scenario three, which shows that $PM_{2.5}$ exposure times are safe, around 5-7 hours daily obtained from the interview results. If respondents are exposed to more than the safe limit, there will be a risk to their health. This scenario can apply to research sites; determining the exact timing of exposure can help identify the health risks associated with a particular exposure. Reducing exposure times is an essential preventive strategy in environmental health risk management. People can time their outdoor activities to avoid exposure to high levels of air pollution. Avoid outdoor activities when the cement factory operates, or the air conditions are particularly poor.

Table 4. $PM_{2.5}$ risk management

$PM_{2.5}$ risk management	Children	Mature
Scenario 1 EDaman (year)	7,2	9,4
Scenario 2 EFaman (days/year)	86,5	112
Scenario 3 ETaman (hours/days)	5,8	7,5

3.3 Spatial patterns

The following is the distribution of respondents' real-time RQ at each research location.

Figure 6 illustrates the risk of PM exposure$_{2.5}$ real-time projection of 5-30 years for respondents (children and adults) living around the PT Tonasa Cement industrial area. The study findings indicate that Samalewa, Sapanang, and Bontoa Villages fall within the moderate-risk category for $PM_{2.5}$ exposure, whereas Mangilu, Biring Ere, Taraweang, Bulu Cindea, and Bowong Cindea Villages are classified as low-risk areas.

This study shows that communities in Samalewa, Sapanang, and Bontoa villages are at moderate risk of environmental and health impacts due to proximity to the Semen Tonasa plant, including operational sites and raw material transportation routes. While the relationship between proximity to the plant and increased risk is clear, this study provides quantitative evidence by measuring $PM_{2.5}$ levels and documenting health complaints, such as coughing and shortness of breath in children based on interviews. In addition, the study also examined whether more remote villages were affected by cement-containing winds by analyzing $PM_{2.5}$ dispersion patterns and meteorological data, including wind direction and speed. The findings show that particulate matter can disperse beyond the immediate area of the plant under certain meteorological conditions, potentially impacting more remote areas, albeit to a lesser extent. These results emphasize the broader environmental and public health implications of plant operations, particularly regarding the dispersion of airborne particulates.

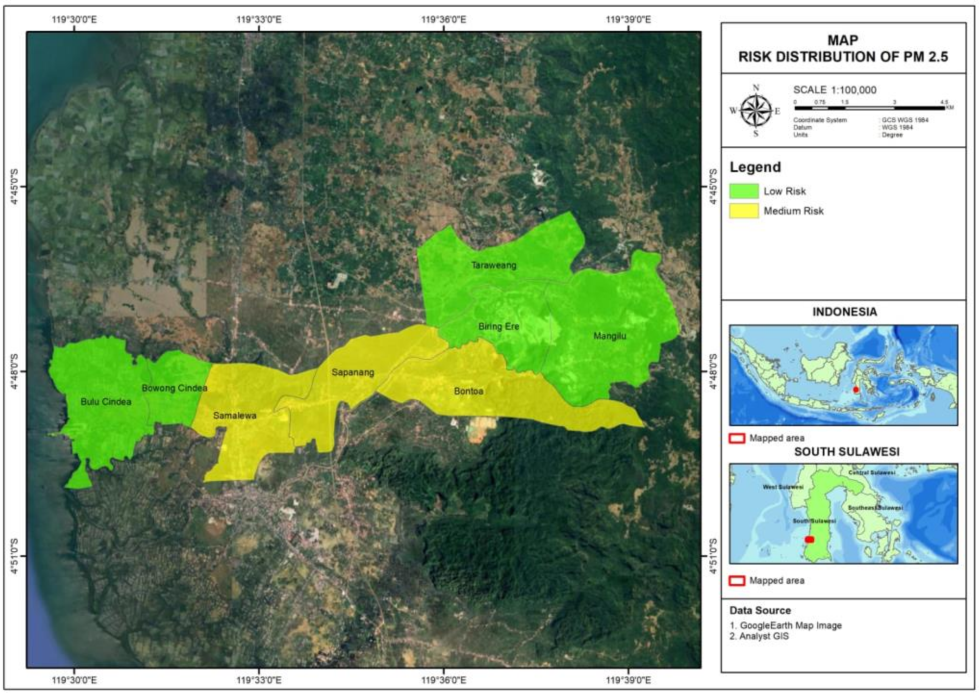


Figure 6. Distribution of PM real-time risk levels$_{2.5}$ respondent

The moderate risk classification for Taraweang and Mangilu Villages reflects the complex interplay of factors influencing $PM_{2.5}$ concentration, not just proximity to the cement factory. While the villages are near the factory, wind direction plays a significant role in dispersing or concentrating particulate matter, with specific patterns leading to localized accumulation of $PM_{2.5}$. Other contributing factors include emissions from blasting operations, transportation of raw materials, and dust released during material handling. Meteorological factors—such as wind velocity, temperature inversions, and relative humidity—significantly influence the dispersion dynamics of particulate matter, while local topographic features may contribute to the accumulation of pollutants in specific areas. This multifaceted assessment highlights that risk levels are shaped by a combination of environmental and operational influences, rather than proximity alone.

4. CONCLUSION

Ambient air monitoring around the PT Semen Tonasa industrial complex in Pangkajene Kepulauan Regency identified two locations—Bontoa Village and Samalewa Village—where $PM_{2.5}$ concentrations exceeded the permissible air quality standard of 15 µg/m³. The environmental health risk assessment indicates that residents living in proximity to the PT Semen Tonasa industrial area are exposed to $PM_{2.5}$ levels resulting in a Risk Quotient (RQ) greater than 1, which means that on average people are at risk of non-carcinogenic diseases. The spatial pattern shows that Samalewa, Sapanang, and Bontoa villages are at moderate risk of $PM_{2.5}$ exposure.

REFERENCES

Abbasi SA, Ponni G, Tauseef SM. Potential of joyweed Alternanthera sessilis for rapid treatment of domestic sewage in SHEFROL® bioreactor. International Journal of Phytoremediation 2019;21(2):160-9.

Abubakar IR, Maniruzzaman KM, Dano UL, AlShihri FS, AlShammari MS, Ahmed SMS, et al. Environmental sustainability impacts of solid waste management practices in the global South. International Journal of Environmental Research and Public Health 2022;19(19):Article No. 12717.

Chanda F, Lin Kai-Xuan, Chaurembo AI, Huang Jian-Yuan, Zhang Hui-Juan, Deng Wen-Hui, et al. $PM_{2.5}$-mediated cardiovascular disease in aging: Cardiometabolic risks, molecular mechanisms and potential interventions. Science of The Total Environment 2024;954:Article No. 176255.

Devi MLS WP. Distribution of Tsp (Total Suspended Particulate) dust to public health in Pt Semen Padang Industrial Area. Buana 2020;4(6):1245-61 (in Indonesian).

Duppa A, Daud A, Bahar B. Ambient air quality around Bosowa Cement Industry in Maros Regency. Journal of Maritime Public Health 2020;3(1):86-92 (in Indonesian).

Dwi Safira M, Syafiuddin A, Hakim A, Fasya Z, Setianto B, S1 PS, et al. Literature review: Air quality in industrial estates in various locations in Indonesia. Jurnal Public Health 2022;9(2):38-47 (in Indonesian).

Fitra M, Awaluddin S, Sejati, Elanda Fikri. Environmental Health Risk Analysis Revised Edition. Miladil Fitra; 2022 (in Indonesian).

Fitriyanti R, Fatimura M. Cleaner production applications in the cement industry. Jurnal Redoks 2019;3(1):10-5 (in Indonesian).

He B. A risk and decision analysis framework to evaluate future $PM_{2.5}$ risk: A case study in Los Angeles-Long Beach Metro Area. International Journal of Environmental Research and Public Health. 2021;18(9):Article No. 4905.

Istiqomah Q, Irsan R, Satria A. Analysis of distribution of NO_2 pollutants in PT. X Sanggau Regency, West Kalimantan. Journal of Civil Engineering 2023;23(3):359-62.

Kasim S, Daud A, Birawida AB, Mallongi A, Arundhana AI, Rasul A, et al. Analysis of environmental health risks from exposure to polyethylene terephthalate microplastics in refilled drinking. Global Journal of Environmental Science and Management 2023;9:301-18.

Keyvani S, Mohammadyan M, Chimehi E. Effect of the meteorological parameters on the indoor $PM_{2.5}$ and PM_{10} concentrations in a hospital. Scientific Research Publishing House 2020;2(4):1-7.

Kholodov A, Zakharenko A, Drozd V, Chernyshev V, Kirichenko K, Seryodkin I, et al. Identification of cement in atmospheric particulate matter using the hybrid method of laser diffraction analysis and Raman spectroscopy. Heliyon 2020;6(2):e03299.

Liang Y, Sengupta D, Campmier MJ, Lunderberg DM, Apte JS, Goldstein AH. Wildfire smoke impacts on indoor air quality assessed using crowdsourced data in California. Proceedings of the National Academy of Sciences 2021;118(36): e2106478118.

Lin C, Huang RJ, Ceburnis D, Buckley P, Preissler J, Wenger J, et al. Extreme air pollution from residential solid fuel burning. Nature Sustainability 2018;1(9):512-7.

Novirsa R, Achmadi UF. Risk analysis of exposure to $PM_{2.5}$ in daytime ambient air to people in the cement industry area. Public Health: National Public Health Journal 2012;7(4):Article No. 173 (in Indonesian).

World Health Organization (WHO). WHO Ambient Air Quality Database, 2022 Update: Status Report. World Health Organization; 2023.

Ouyang H, Tang X, Kumar R, Zhang R, Brasseur G, Churchill B, et al. Toward better and healthier air quality: Implementation of WHO 2021 global air quality guidelines in Asia. Bulletin of the American Meteorological Society 2022;103(7):1696-703.

Palacio LC, Durango-Giraldo G, Zapata-Hernandez C, Santa-González GA, Uribe D, Saiz J, et al. Characterization of airborne particulate matter and its toxic and proarrhythmic effects: A case study in Aburrá Valley, Colombia. Environmental Pollution 2023;336:Article No. 122475.

Paustenbach DJ, Madl AK, Massarsky A. Exposure assessment. Human and Ecological Risk Assessment: Theory and Practice 2024;1:157-261.

Rasmi SAB, Türkay M. Sustainability analysis of cement supply chains considering economic, environmental and social effects. Cleaner Logistics and Supply Chain 2023;8:Article No. 100112.

Regia RA, Bachtiar VS, Solihin R. Analysis of health risks due to exposure to particulate Matter 2.5 ($PM_{2.5}$) in residential homes in housing X Cement Industrial Area. Journal of Environmental Science 2021;19(3):531-40 (in Indonesian).

Roser M. Data Review: How Many People Die from Air Pollution? Our World in Data; 2021.

Saroyo H, Saputri NFM. Cytotoxicity of mangrove leaves (rhizophora) ethanolic extract on cancer cells. Journal of Nutraceuticals and Herbal Medicine 2021;4(1):43-52.

Sun J, Yu J, Niu X, Zhang X, Zhou L, Liu X, et al. Solid fuel derived $PM_{2.5}$ induced oxidative stress and according cytotoxicity in A549 cells: The evidence and potential neutralization by green tea. Environment International 2023;171:Article No. 107674.

United States Environmental Protection Agency. Applying or Implementing Particulate Matter (PM) Standards. USEPA; 2022.

Wan Mahiyuddin WR, Ismail R, Mohammad Sham N, Ahmad NI, Nik Hassan NMN. Cardiovascular and respiratory health effects of fine particulate matters ($PM_{2.5}$): A review on time series studies. Atmosphere 2023;14(5):Article No. 856.

Xu H, Léon JF, Liousse C, Guinot B, Yoboué V, Akpo AB, et al. Personal exposure to $PM_{2.5}$ emitted from typical anthropogenic sources in southern West Africa: Chemical characteristics and associated health risks. Atmospheric Chemistry and Physics 2019;19(10):6637-57.

Yun X, Shen G, Shen H, Meng W, Chen Y, Xu H, et al. Residential solid fuel emissions contribute significantly to air pollution and associated health impacts in China. Science Advances 2020;6(44):eaba7621.