Unified Health Critical Research

Journal homepage: https://journal.uin-alauddin.ac.id/index.php/ucr

Research Article

Environmental Health Risk Analysis of SO_2 and NO_2 Exposure in Communities Near Cement Industrial Areas: A Case Study of PT. Semen Tonasa, Pangkajene Kepulauan Regency

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ARTICLE INFO

Keywords:
cement industry; EHRA; nitrogen dioxide; spatial pattern; sulfur dioxide

History:
Submitted : 17 June 2026
Reviewed : 30 July 2026
Accepted : 7 August 2026

Competing Interests:
The authors declare no conflicts of interest related to this work.

ABSTRACT

Background: The cement industry is a major source of Sulfur Dioxide (SO_2) and Nitrogen Dioxide (NO_2) emissions that potentially pose health risks to surrounding communities. PT. Semen Tonasa, located in Pangkajene Kepulauan (Pangkep) Regency, is one of the largest cement industries in Eastern Indonesia. Objective: This study aimed to analyze environmental health risks from SO_2 and NO_2 exposure and map the spatial distribution of risk among communities residing near PT. Semen Tonasa industrial area. Methods: A descriptive observational study was conducted using the Environmental Health Risk Analysis (EHRA) approach. Ambient air quality was measured at 8 locations (Ring 1 villages) using Volume Air Sampler with Impinger. A total of 160 respondents (80 adults aged 26–45 years and 80 children aged 6–12 years) were recruited through purposive sampling. Exposure parameters included SO_2 and NO_2 concentrations, inhalation rate, body weight, exposure frequency, and real-time and lifetime exposure durations. Spatial patterns were analyzed using ArcGIS with overlay and buffer methods. Results: The highest SO_2 concentration was found in Bontoa Village (51.3 µg/m³) and the highest NO_2 in Samalewa Village (46.2 µg/m³), both below national standards. Real-time Risk Quotient (RQ) values indicated that all child respondents were not at risk (RQ<1), while some adult respondents in Bontoa and Samalewa showed risk for SO_2 and NO_2 exposure. Lifetime projections showed increasing risk with exposure duration. Spatial patterns revealed risk concentration within 1–3 km from the industrial center. Conclusion: Although ambient SO_2 and NO_2 concentrations have not exceeded quality standards, there are indications of long-term health risks for adults residing in the zone closest to emission sources. Regular monitoring and implementation of community-based risk management are needed.

e-ISSN: 3109-0478 p-ISSN: 3109-0486

1. Introduction

Air pollution resulting from industrial activities has become an increasingly pressing environmental and public health problem in the era of global industrialization. The cement industry, as an energy-intensive manufacturing sector, is known to generate large quantities of hazardous gas emissions, including Sulfur Dioxide (SO_2) and Nitrogen Dioxide (NO_2) (Ciobanu et al., 2021). Both pollutants are generated through the combustion of high-sulfur fossil fuels and the oxidation of nitrogen at kiln combustion temperatures exceeding 1,200°C (Xinghan et al., 2022).

Short- and long-term exposure to SO_2 and NO_2 is known to cause various serious health disorders, particularly affecting the respiratory system. SO_2 can trigger airway irritation, decreased lung function, and exacerbate asthma and bronchitis (Mukono, 2019). Meanwhile, NO_2 can cause pulmonary edema, airway inflammation, and increased susceptibility to bacterial infection (Nugroho, 2022). Vulnerable groups such as children, the elderly, and individuals with chronic lung disease face higher risks (He, 2021).

According to the World Health Organization (2020), 92% of the world's population lives in areas with air quality exceeding WHO-recommended thresholds. In Indonesia, the impact of air pollution is estimated to cause more than 60,000 deaths per year, with an average reduction in life expectancy of approximately 1.2 years (Lee & Greenstone, 2021). This condition is increasingly concerning in areas surrounding heavy industry, where communities are chronically exposed to air pollutants at concentrations higher than the urban average.

PT. Semen Tonasa is one of the largest cement producers in Eastern Indonesia, located in Biringere Village, Bungoro Subdistrict, Pangkajene Kepulauan Regency (Pangkep), South Sulawesi. The industry occupies an area of 715 hectares and is surrounded by relatively dense residential settlements (Mallongi, 2021). The dominant emissions from the cement production process include particulate dust, SO_2, and NO_2, primarily originating from the raw mill and rotary kiln units that use coal as the main fuel (Kurniati et al., 2020).

Although various EHRA studies related to cement industry emissions have been conducted in various regions of Indonesia and abroad, comprehensive studies integrating non-carcinogenic health risk analysis with Geographic Information System (GIS)-based spatial mapping in the Pangkep cement industrial area remain very limited. A spatial approach is highly important for identifying risk distribution based on distance and wind direction from emission sources, thereby supporting more accurate decision-making in environmental risk management (Devi MLS, 2020).

This study aims to: (1) analyze SO_2 and NO_2 concentrations in ambient air around the PT. Semen Tonasa industrial area; (2) calculate the Risk Quotient (RQ) of SO_2 and NO_2 exposure among adult and child respondents in real-time and lifetime scenarios; and (3) map the spatial distribution pattern of environmental health risk based on GIS.

2. Methods

2.1 Design and Research Location

This study constitutes a descriptive observational study using an Environmental Health Risk Analysis (EHRA) approach, conducted in October–November 2023. The research location encompassed 8 villages/sub-districts classified as Ring 1 of the PT. Semen Tonasa industrial area, namely: Biringere Village, Taraweang Village, Bontoa Village, Sapanang Sub-district, Bulu Cindea Village, Bowong

Cindea Village, Samalewa Sub-district, and Mangilu Village, Pangkajene Kepulauan Regency, South Sulawesi Province (see Figure 1).

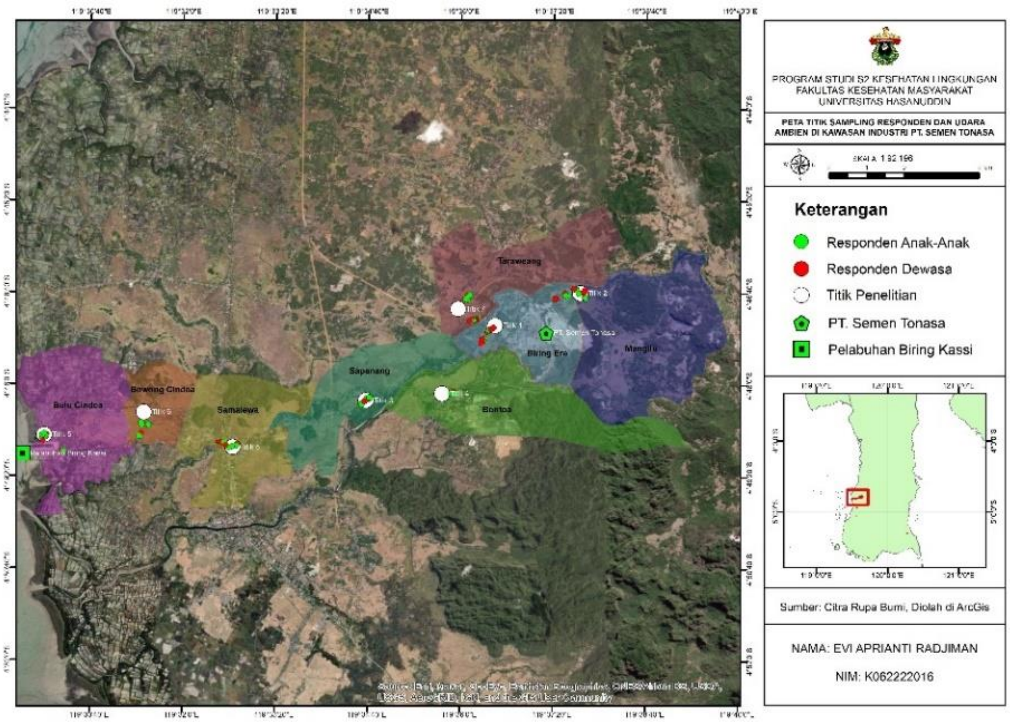

Figure 1. Sampling Location

2.2 Population and Sample

The study population comprised community members aged 6–12 years (children) and 26–45 years (adults) residing in the Ring 1 area of PT. Semen Tonasa. Sampling was conducted through purposive sampling with inclusion criteria of: residence located 1–5 km from the industrial area, minimum residency duration of 3 years, and presence at the research location for a minimum of 12 hours per day. The total sample involved was 160 respondents (80 adults and 80 children), with 10 respondents per age group at each location.

2.3 Air Quality Measurement

Ambient air sampling was conducted at 1 point per village using a Volume Air Sampler with Impinger. Meteorological data (temperature, humidity, and wind speed) were measured concurrently with air sampling. Laboratory analysis results were used as the concentration (C) values in the EHRA calculations.

2.4 Environmental Health Risk Analysis (EHRA)

EHRA was conducted with reference to the 2012 Technical Guidelines for EHRA issued by the Directorate General of P2PL, Ministry of Health of the Republic of Indonesia, which comprises four stages: (1) hazard identification, (2) dose-response analysis, (3) exposure analysis, and (4) risk characterization. The Acceptable Daily Dose (ADD) was calculated using the formula:

$$ADD = (C \times R \times tE \times fE \times Dt) / (Wb \times tavg)$$

Where: C = concentration of risk agent (μg/m³), R = inhalation intake rate (0.83 m^3/hour for adults; 0.05 m^3/hour for children, US-EPA default), tE = daily exposure time (hours/day), fE = annual exposure frequency (days/year), Dt = exposure duration (years), Wb = body weight (kg), tavg = average time period (30 years × 365 days for non-carcinogenic effects). The risk level is expressed as Risk Quotient (RQ) = ADD / RfC. The RfC value for SO_2 = 0.05 mg/m^3 and NO_2 = 0.04 mg/m^3 (US-EPA, 2020). A condition is considered at risk when RQ ≥ 1.

2.5 Spatial Pattern Analysis

Location coordinate data were obtained through geotagging using the GPS Essentials application. The data were then processed using ArcGIS software with overlay and buffer methods to produce a health risk distribution map based on respondents' RQ values.

2.6 Research Ethics

This study obtained ethical approval from the Research Ethics Commission of the Faculty of Public Health, Universitas Hasanuddin, with Number: 5779/UN4.14.1/TP.01.02/2023.

3. Results

3.1 Respondent Characteristics

Table 1 summarizes the characteristics of the adult respondents (n=80). The majority of respondents were female (72.5%), with the 40–45-year age group predominating (47.5%). The most common education level was senior high school (50.0%), and the main occupation was housewife (58.8%). The average body weight of adult respondents fell within the ≥61 kg range (48.8%).

Table 1. Distribution of Adult Respondent Characteristics (N=80)

Variable	Frequency (n)	Percentage (%)
Sex: Female	58	72.5
Sex: Male	22	27.5
Age 26–32 years	33	41.3
Age 33–39 years	9	11.3
Age 40–45 years	38	47.5
Education: Senior High School	40	50.0
Occupation: Housewife	47	58.8
Body Weight ≥61 kg	39	48.8

3.2 Ambient SO_2 and NO_2 Concentrations

The results of ambient air quality measurements at the eight study locations are presented in Table 2. The highest SO_2 concentration was found in Bontoa Village (51.3 µg/m³) and the lowest in Bulu Cindea Village (16.1 µg/m³) (see Table 2). For the NO_2 parameter, the highest concentration was recorded in Samalewa Sub-district (46.2 µg/m³) and the lowest in Biring Ere Village (16.9 µg/m³). All SO_2 and NO_2 concentration values remained below the national quality standards, namely 150 µg/m³ for SO_2 and 200 µg/m³ for NO_2 (Government Regulation No. 22 of 2021).

Table 2. Ambient SO_2 and NO_2 Concentrations Around PT. Semen Tonasa (2023)

Location	SO_2 (µg/m³)	NO_2 (µg/m³)	Temp. (°C)	Wind Speed (m/s)
Biringere Village	32.4	28.5	34.2	1.8
Taraweang Village	28.7	31.2	33.8	1.5
Bontoa Village	51.3	38.7	36.5	1.1
Sapanang Sub-district	24.6	29.8	34.0	1.9
Bulu Cindea Village	16.1	22.4	32.3	2.1
Bowong Cindea Village	29.5	34.6	33.5	1.7
Samalewa Sub-district	44.8	46.2	35.1	1.4
Mangilu Village	21.3	16.9	33.9	2.3
National Quality Standard	**150**	**200**	–	–

3.3 Health Risk Analysis (Risk Quotient)

The results of the real-time and lifetime RQ calculations for SO_2 and NO_2 exposure among adult and child respondents are presented in Table 3. Overall, all child respondents (aged 6–12 years) showed real-time RQ values < 1, indicating no current risk. However, lifetime projections show that if the exposure duration reaches 30 years, there is a significant increase in RQ values, particularly for the SO_2 agent (see Table 3).

Among adult respondents, several individuals residing in Bontoa Sub-district and Samalewa showed real-time RQ values ≥ 1 for SO_2 exposure (3 and 3 respondents, respectively) and NO_2 exposure (2 and 2 respondents, respectively). Differences in RQ values across locations were influenced by ambient concentration, body weight, and respondents' length of residence.

Table 3. Real-time and Lifetime RQ Values for SO_2 and NO_2 Exposure by Respondent Group

Group	**RQ SO_2**		**RQ NO_2**	
	Realtime	**Lifetime (30 yr)**	**Realtime**	**Lifetime (30 yr)**
Adults (Mean)	0.82	**1.24***	0.71	**1.08***
Adults (Min)	0.31	0.47	0.27	0.41
Adults (Max)	**1.38***	**2.08***	**1.19***	**1.79***
Children (Mean)	0.43	0.65	0.37	0.56
Children (Min)	0.16	0.24	0.14	0.21
Children (Max)	0.72	**1.09***	0.62	0.94

** RQ ≥ 1 (at risk); Source: Primary Data, 2023*

3.4 Spatial Risk Pattern

The spatial mapping results using ArcGIS showed that the distribution of environmental health risk was not uniform across the Ring 1 area. The majority of respondents showing real-time RQ values ≥ 1 resided in Bontoa and Samalewa Sub-districts, located within a radius of 1–3 km from the industrial center, in a direction aligned with the dominant wind. Buffer analysis showed that zones with higher risk were concentrated in areas directly exposed to wind from the southwest direction, where the kiln operates. Bulu Cindea and Mangilu Villages, located farther from the emission source, showed lower real-time RQ values in both age groups (Figure 2).

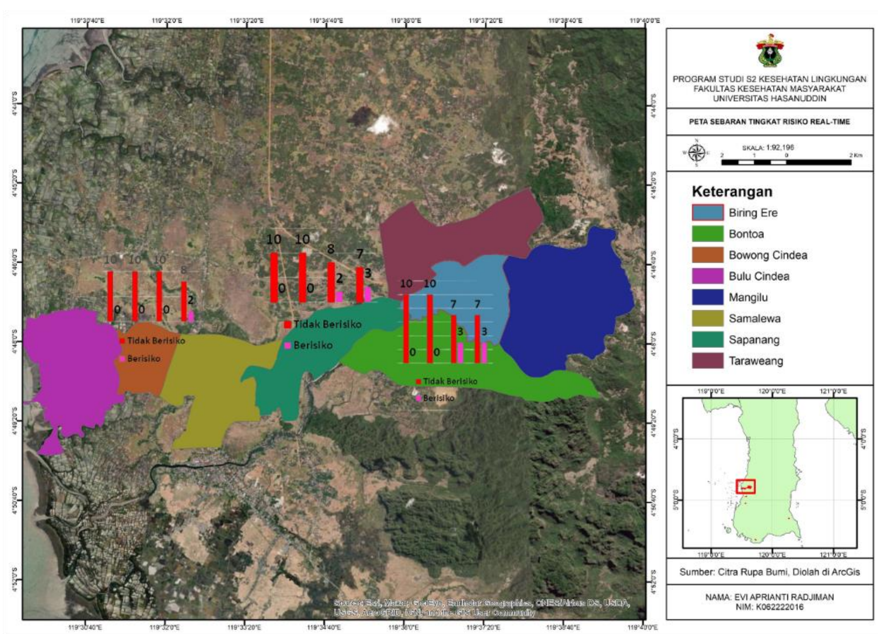

Figure 2 Distribution of Real-Time PM2.5 Risk Levels Among Respondents

3.5 SO_2 and NO_2 Concentrations in Ambient Air

The measurement results showed that all SO_2 and NO_2 concentration values at the eight study locations remained below the national ambient air quality standard (Government Regulation No. 22 of 2021). This finding is consistent with the study by Al Rabadi et al. (2023), which reported SO_2 concentrations in cement industrial areas in Jordan ranging from 35–70 µg/m³, with values at certain locations such as Bontoa Village approaching the lower end of that range. The considerable variation in concentrations across locations (SO_2: 16.1–51.3 µg/m³; NO_2: 16.9–46.2 µg/m³) indicates a significant influence of meteorological factors, particularly wind speed and direction.

Meteorological factors play an important role in air pollutant dispersion. The lower wind speed in Bontoa Village (1.1 m/s) contributed to the accumulation of pollutants in that area, while the higher wind speed in Mangilu Village (2.3 m/s) facilitated pollutant dispersion away from residential areas (Elizbath et al., 2023). This study reaffirms that meteorological factors need to be incorporated as routine monitoring parameters in cement industrial areas, particularly under wind stagnation conditions that may exacerbate community exposure.

3.6 Health Risk from SO_2 and NO_2 Exposure

The results of the real-time RQ calculation showed that the majority of respondents in this study were in a non-risk condition (RQ < 1), although several adult individuals in Bontoa and Samalewa Sub-districts already showed RQ values ≥ 1. This condition indicates that health risk among the population around PT. Semen Tonasa, while not exceeding the risk threshold on average, has already begun to accumulate among individuals with longer exposure durations and higher inhalation rates.

Lifetime risk projections showed a concerning increase in RQ values, particularly among adult respondents. The mean lifetime RQ value for SO_2 reached 1.24, exceeding the non-carcinogenic risk threshold (RQ ≥ 1). This finding is consistent with the studies by Nugroho (2022) and Wenas et al. (2020), which also reported significant lifetime risk among communities around industrial areas, despite ambient concentrations remaining below quality standards. This indicates that the ambient quality standard approach alone is insufficient to protect the health of populations exposed chronically.

Child respondents generally did not show real-time risk; however, lifetime projections for the child group with the highest exposure concentration already approached a critical value (maximum lifetime SO_2 RQ: 1.09). Children are more vulnerable to air pollutants due to their higher inhalation rate per kilogram of body weight compared to adults, their immature immune systems, and the potential long-term impact on lung development (He, 2021; Kholodov et al., 2020).

3.7 Spatial Pattern and Risk Management Implications

Spatial pattern analysis provides important added value in understanding risk distribution at the regional level. The finding that risk is concentrated within a 1–3 km zone downwind of the emission source provides a scientific basis for establishing a more effective buffer zone. This approach supports recommendations for the implementation of health risk-based spatial planning policy, in which the development of new settlements in high-risk zones needs to be assessed more rigorously.

The recommended risk management comprises three approaches: (1) technological – implementation of more efficient emission filtration systems at the source, including upgrading flue gas desulfurization systems; (2) administrative – real-time and periodic air quality monitoring throughout the Ring 1 zone as well as the development of an early warning system; and (3) community-based – education on the use of protective masks, particularly among vulnerable groups, as well as the development of green open spaces as natural pollutant absorbers (Suhaib et al., 2023; Palacio et al., 2023).

4. Conclusion

This study concludes that: (1) SO_2 and NO_2 concentrations in ambient air around the PT. Semen Tonasa industrial area have not exceeded the national quality standard, but show significant variation across locations influenced by meteorological factors; (2) Real-time RQ values indicate that some adult respondents in Bontoa and Samalewa Sub-districts are already at risk, while children are generally not yet at risk; (3) Lifetime risk projections reveal a significant potential long-term risk, particularly among adults with an exposure duration ≥ 30 years; (4) The spatial risk pattern shows the highest exposure concentration within a 1–3 km radius from the industrial center, in the direction of the dominant wind.

The implications of these findings are the need for a more comprehensive and sustainable air quality monitoring system in the Ring 1 area, as well as the implementation of community-based risk management involving PT. Semen Tonasa, local government, and the local community. Further research using a longitudinal cohort design and exposure biomarker measurements is strongly recommended to more precisely quantify long-term health impacts.

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