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Environmental Health Risk of Air Dispersion from Cement Plant Port Operations: A Coastal Case Study in Pangkajene

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Abstract

Introduction: The intensification of industrial and transportation activities has significantly contributed to air pollution, particularly in cement industrial zones.

Methods: This study aimed to model the dispersion of sulfur dioxide (SO_2) and carbon monoxide (CO) pollutants around the dedicated port of a cement factory using the AERMOD dispersion model and to assess the associated health risks. A quantitative descriptive approach was employed, involving data collection, field data analysis, and geospatial mapping. The AERMOD software was utilized to simulate the spatial distribution of SO_2 and CO emissions, followed by an environmental health risk assessment for the surrounding population.

Results: The modeling results showed that the highest concentrations of SO_2 and CO reached 196 and 24,407 μg/m³, respectively. Pollutant dispersion predominantly occurred toward the northeast, influenced by wind patterns and emission source characteristics. Environmental health risk assessment results indicated that long-term exposure to CO—particularly beyond 15 years—results in a Risk Quotient (RQ) greater than 1, signifying potential non-carcinogenic health risks. Conversely, SO_2 exposure remains below the risk threshold (RQ < 1) for the general population.

Conclusion: These findings highlight the urgent need for enhanced emission control measures and focused protection for vulnerable groups. Moreover, they underscore the importance of implementing stricter environmental regulations to mitigate the health impacts of industrial port operations.

Keywords: Environmental pollutants, Air pollution, Cardiovascular system, Respiratory tract disease, Cement plant

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Introduction

The rise in industrial activities, vehicle traffic, and energy demand has created complex pollutant interactions, posing significant threats to public health (1). More than 90% of the population in developing countries is exposed to unhealthy air, and air pollution has been associated with one in three deaths from stroke, lung cancer, and chronic respiratory diseases (2). Physiologically, humans inhale a substantial volume of air each day, with an estimated average of approximately 20 m³ per individual. Therefore, when the inhaled air contains harmful pollutants, whether in the form of fine particulate matter or gaseous contaminants, the risk of adverse health effects consequently increases, ranging from respiratory tract irritation to the development of chronic diseases (3). Industrial activities involving various manufacturing processes release significant amounts of pollutants into the atmosphere. This also increases reliance on fossil fuel combustion, a major source of hazardous emissions. Therefore, developing effective mitigation strategies is crucial to minimizing the environmental impact and reducing risks to public health (4). This trend is further driven by technological advancements, leading to a growing number of industrial factories, power plants, and motor vehicles, all of which emit pollutants daily (5).

One of the industries that generates significant air pollution, including particulate matter and gaseous emissions, is the cement industry (6). This industry is one of the world's largest contributors to air pollution, primarily due to its high energy consumption and significant dust emissions (7).

SO_2 emissions in the air primarily originate from diesel-fueled vehicle transportation and stationary sources, including coal combustion, petroleum residues, and palm shell burning (8). Exposure to high doses of SO_2 can irritate the eyes, nose, throat, and sinuses, as well as cause pulmonary edema and, in severe cases, death. When inhaled, SO_2 accumulates in the body, leading to lung function impairment, respiratory tract irritation, and asthma (9).

In contrast, carbon monoxide (CO) gas is produced by the incomplete combustion of carbon-containing materials. Most CO emissions originate from the combustion of fossil fuels in the presence of air, primarily as exhaust gases. High CO concentrations contribute to greenhouse gas accumulation, which results in rising air temperatures and humidity on Earth (10). Based on the five components that make up the standard air pollution index, carbon monoxide (CO) concentration is the most dominant. CO emissions are primarily generated by motor vehicles, waste burning, industrial activities, and other sources. Long-term exposure to carbon monoxide poses serious health risks, including heart damage (11).

The special port for cement factories along the coast of the Regency of Pangkajene and the Islands is a significant source of SO_2 and CO pollutants, primarily due to Electric Steam Power Plant (ESPP) and land transportation activities. The dispersion of these pollutants into residential areas depends on wind patterns and the direction of dispersion. Therefore, to mitigate potential adverse effects caused by port activities, it is essential to gain early knowledge of pollutant dispersion patterns and model the distribution of hazardous emissions from port operations (12). The port functions as a dedicated terminal for handling cement and related commodities such as coal, clinker, and fuel, making it an essential component of the regional cement supply chain. Its operations are primarily focused on the loading and unloading of cement, both in bulk and bagged forms. Geographically, the port is located approximately one kilometer from the Bowong Cindea and Bulu Cindea areas. The majority of the local population in these villages relies on fisheries, particularly aquaculture and capture fishing, as their main source of livelihood, supplemented by rice farming activities (13)

The pollutant distribution pattern modeled using AERMOD serves as the basis for conducting an environmental health risk analysis (EHRA) at each level. EHRA is a method for assessing and predicting human health risks, which involves identifying uncertainty factors, tracing specific exposures, and considering both the inherent characteristics of the pollutant and the susceptibility of the exposed population (12).

Materials and Methods

This study adopted a quantitative descriptive approach, involving data collection, field data processing, and spatial mapping. The AERMOD software was employed to model the dispersion of SO_2 and CO emissions and to assess related health risks in the surrounding area. The research was conducted at a dedicated cement port in the Regency of Pangkajene and the Islands, South Sulawesi, located near the Makassar Strait (4°50' S, 119°30' E), which experiences a humid tropical climate with distinct rainy (November–April) and dry (May–October) seasons.

As stated by Budyningrum (14), emission rate refers to the mass of pollutants released by a source (chimney) per unit of time (seconds). The measurement of sulfur dioxide (SO_2) emissions in this study was conducted using EPA Method 6, in which flue gas was absorbed into a hydrogen peroxide (H_2O_2) solution via an impinger system. The concentration of SO_2 was then analyzed using a titrimetric method, and the results were converted into concentrations expressed in mg/Nm^3. Additionally, real-time measurements were performed using a non-dispersive infrared (NDIR) gas analyzer to verify field data. The calculation of carbon monoxide (CO) emissions from the stack was carried out using the non-dispersive infrared (NDIR) analyzer method based on USEPA Method 10, where infrared radiation was emitted, and the absorption of the radiation by CO molecules was detected. The emission rates of SO_2 and CO can be calculated using the following equation:

$$E = \frac{L \times v \times C}{1{,}000}$$

where E is emission rate (g/s), L is chimney area (m^2), v is exhaust gas velocity (m/s), and C is pollutant emission concentration (mg/m^3).

The calculation of vehicle emissions at the entrance to the port area is influenced by three factors: The total volume of motor vehicles, the characteristics of the motor vehicles, and the prevailing traffic conditions at that time (15). For arterial roads of a length L, where traffic characteristics are assumed to be constant, the emission intensity of the line source is calculated using the following formula:

$$E_p = \sum \frac{n}{i = l} L \times Ni \times Fpi$$

where L is the length of the road under study (km), Ni is the number of type I motor vehicles passing through the road section (vehicles/hour), Fpi is the type I motor vehicle emission factor (g/km), I is the type of motor vehicle, Ep is the emission intensity of a unit segment (g/hour), and P is the type of pollutant estimated.

The meteorological data collected included wind speed, wind direction, solar radiation, cloud cover, dry bulb temperature, lowest cloud height, rainfall, pressure, and humidity. Additionally, upper air data in FSL format obtained from NASA was used to generate PFL and SFL input data. An elevation map of the research area, acquired from WEBGIS using AERMAP, was utilized for contour mapping, in addition to other supporting maps. Air quality data were derived from emissions measurements of the ESPP chimney at the port and vehicle emission calculations at the port entrance.

Environmental health risk analysis (EHRA) was conducted at two locations, Bowong Cindea and Bulu Cindea, using a purposive sampling technique with a sample of 136. Data collection from the sample was conducted using a questionnaire through interview methods to obtain information on the body weight, length of residence, age, and gender of the respondents. The environmental health risk analysis (EHRA) was carried out in the following stages (16):

a. hazard identification
b. dose-response analysis
c. exposure analysis
d. risk characterization

Results

SO_2 and CO emissions generated from port activities were calculated using emission factors derived from the stacks of steam power plants and vehicular traffic. The calculated emission rate and chimney discharge of the cement factory special port ESPP chimney are presented in Table 1:

Based on the specifications presented in Table 1, the existing conditions of the port, along with the presence of chimneys at the Steam Power Plant (PLTU), can be described in greater detail to provide a comprehensive overview of the infrastructure and potential emission sources within the area. Figure 1 presents a 3D visualization of the special port.

The vehicular emissions were calculated using emission factors on the Biringkassi road section, which serves as the main access route to the port, by taking into account the number of vehicle trips. Traffic data collection was conducted between 08:00 and 09:00. The estimated results of vehicular emissions on the main Biringkassi road section are subsequently presented in Table 2:

The concentrations of SO_2 and CO emitted from two pollution sources—the ESPP Chimney (STCK1) and vehicle emissions along the Biringkassi main road, which served as the port entry route (ARLN1)—were analyzed along with hourly meteorological data collected over one year, divided into two semesters or six-month periods.

Based on Figure 2, the dispersion pattern of sulfur dioxide (SO_2) pollutants followed the characteristics of the emission source, meteorological conditions, and topographic factors influencing the area. On the map, areas with the highest concentrations are marked in red and orange, indicating significant SO_2 emission impacts.

The highest hourly average concentration recorded was 196 $\mu g/m^3$ in semester 2, with SO_2 pollutants predominantly spreading from the east to the northeast from the emission source. This suggests that meteorological factors, particularly wind direction and atmospheric conditions, played a crucial role in determining pollutant dispersion patterns. This value exceeded the maximum one-hour average concentration of semester 1, which reached only 128 $\mu g/m^3$, despite a wider distribution and larger high-concentration areas.

As shown in Figure 3, the distribution pattern for the one-hour projection in semester 1 indicated that the highest concentration occurred near the emission source (marked in red and orange), which gradually decreased with increasing distance. Pollutants primarily dispersed

Table 1. Calculation of Emission Rate and Chimney Specifications

Pollutant	Concentration (mg/m^3)	Chimney Height (m)	Chimney Diameter (m)	Flow Lane (m^3/s)	Emission Rate (g/s)
SO_2 (Sulfur Dioxide)	7.5	70	4.1	28.17	0.2112
CO (Carbon Monoxide)	562.9				15.856893

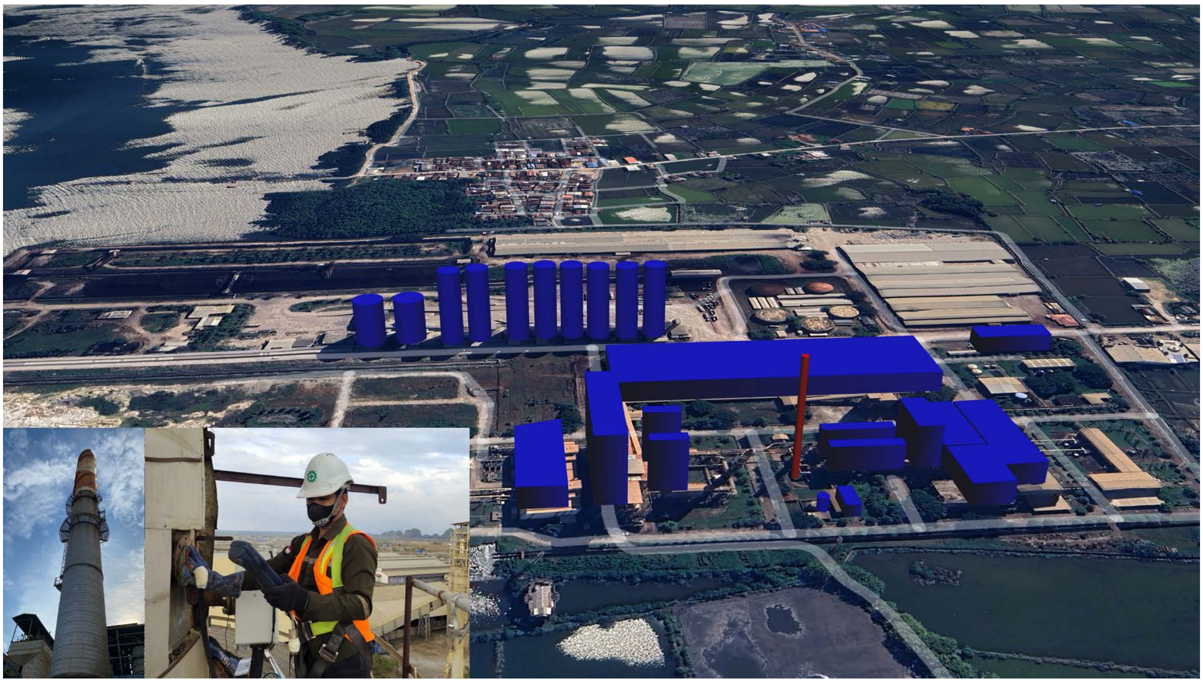

Figure 1. 3D Visualization of the Special Port

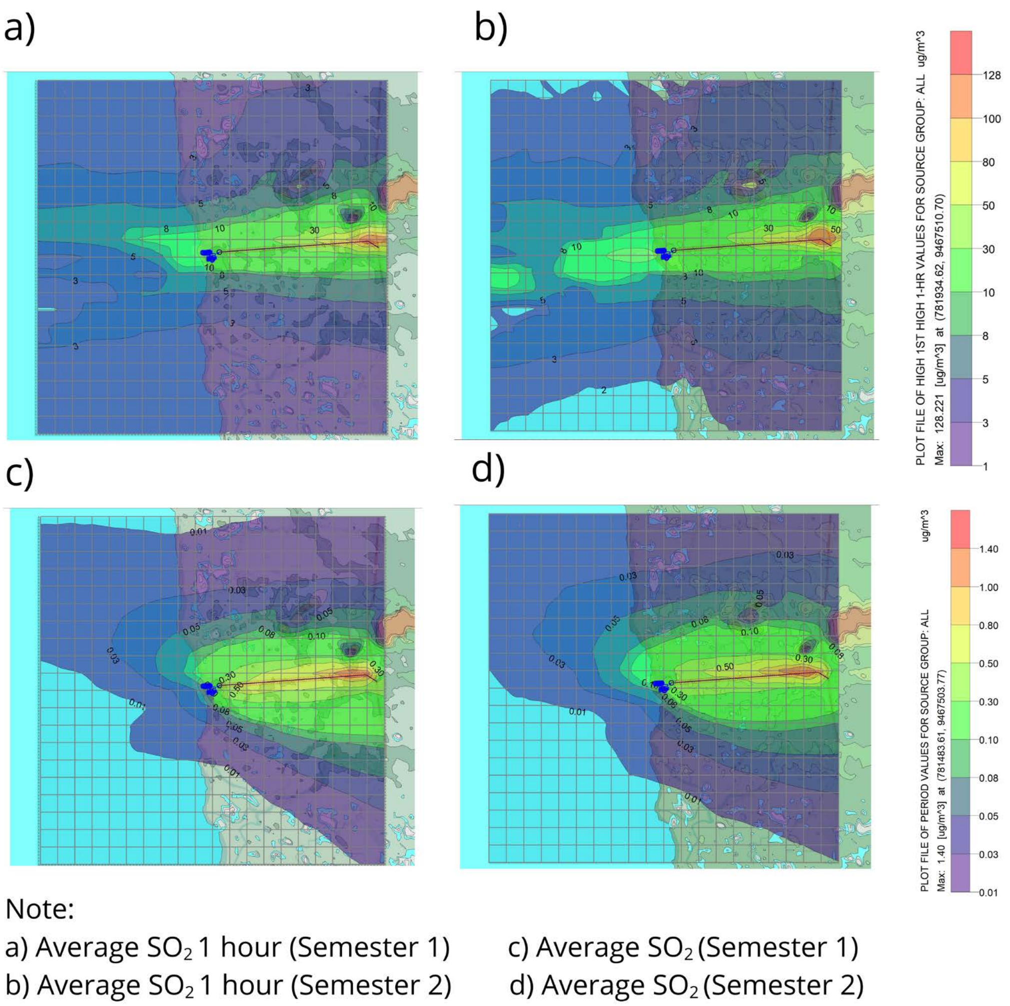

Figure 2. AERMOD Modeling Results of Sulfur Dioxide (SO_2) Parameters

Table 2. Vehicle Emission Calculation

Vehicle Type	Pollutant (g/s)		Road Description	
	SO_2	CO	Road Length (m)	Road Width (m)
Car	0.038225	11,259	4954.9	6
Motorcycle	0.00503	8.8025		
Bus	0.0081375	0.09625		
Truck	0.1886	1,932		
Average	0.05999813	5.5224375		

from the east to the northeast, while concentrations decreased gradually toward the west and northwest, with a peak concentration of 13,584 μg/m^3. In contrast, the one-hour projection for semester 2 showed a significant increase, with the maximum CO concentration reaching 24,407 μg/m^3. High-concentration areas (orange-red) were concentrated in the eastern part of the emission source, suggesting pollutant accumulation in that region. The distribution contour pattern revealed that CO dispersed from the southwest to the northeast, indicating that the prevailing wind direction was from the southwest to the northeast.

Risk characterization involved evaluating whether exposure to a specific concentration of pollutants posed a potential health threat. This was quantified using the risk quotient (RQ), which assesses non-carcinogenic health risks based on established guidelines such as the minimal risk level (MRL), reference dose (RfD), and reference concentration (RfC). RQ was calculated by dividing the estimated intake by the corresponding RfD or RfC value (17).

Risk quotient (RQ) is the ratio of exposure dose to reference dose that is used to evaluate the health risks associated with air pollutants. Figure 4 presents the RQ values for SO_2 and CO across various exposure periods in lifetime (5, 10, 15, 20, 25, and 30 years). Throughout the entire exposure period (5–30 years), the RQ value for SO_2 consistently remains below 1 ($RQ > 1 = 0$, $RQ < 1 = 116$). For carbon monoxide (CO), for a five-year exposure period, only two individuals have an $RQ > 1$, while 114 individuals remain within the safe threshold ($RQ < 1$). After 10 years, the number of individuals with an $RQ > 1$ increases to 74, leaving 42 individuals with an $RQ < 1$. In 15 years, the number rises to 111, with only five individuals remaining in the safe range. At 20 years and beyond (up to 30 years), the entire population (116 individuals) has an $RQ > 1$.

Discussion

The maximum concentration, as shown in Figure 1, was

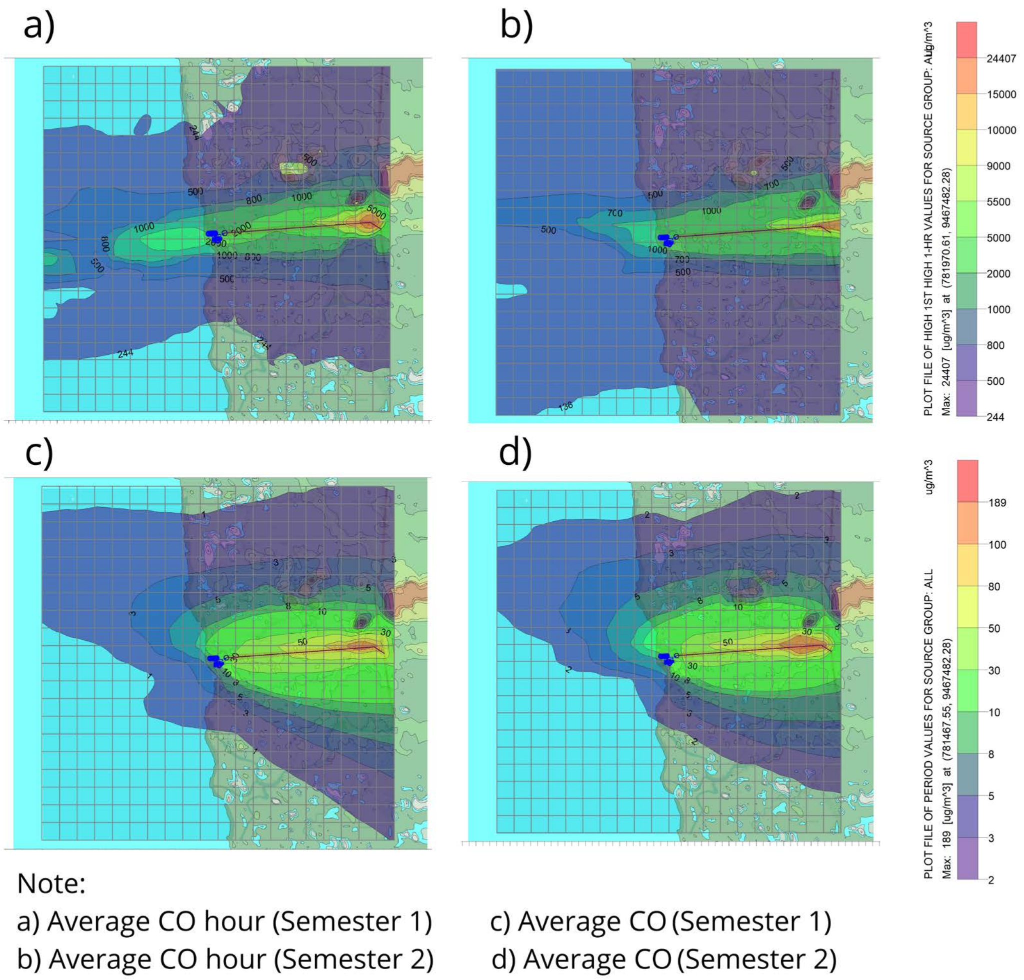

Figure 3. AERMOD Modeling Results of Carbon Monoxide (CO) Parameters

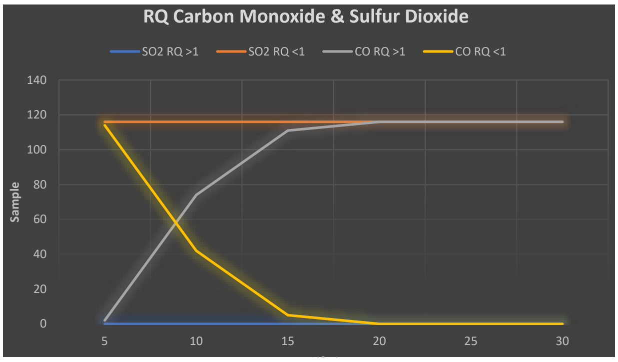

Figure 4. RQ Lifetime around the Special Port Area of the Cement Factory

196 µg/m³, suggesting that certain locations experienced relatively high SO_2 exposure, although it remained within the regulatory threshold set under Government Regulation of the Republic of Indonesia No. 22 of 2021 on Environmental Protection and Management, which stipulates a maximum concentration of 262 µg/m³ for one hour. Additionally, the World Health Organization (WHO) set a one-hour exposure limit at 500 µg/m³.

This pattern was consistent with semester averages, peaking at 1.40 µg/m³ in semester 2 as wind direction shifted from the southwest to the northeast. Semester 1 showed a slightly lower average of 1.28 µg/m³. Variations in concentration are mainly influenced by key meteorological factors such as temperature, pressure, and humidity. Additionally, solar radiation plays a crucial role in atmospheric chemical reactions, influencing the transformation processes of SO_2 and CO (18). This finding is consistent with the findings of previous research (19), where the simulation results demonstrated the dispersion of SO_2, NO_x, and particulate matter westward from the emission source/chimney, following the prevailing wind direction. The dispersion of these pollutants predominantly moved westward in alignment with the dominant wind pattern. When compared to ambient air quality standards, the modeled simulation results remained within permissible limits.

The minimum concentration of SO_2 in Bowong Cindea was recorded at 10 µg/m³, while it was 8 µg/m³ in Bulu Cindea. Meanwhile, the maximum concentration of SO_2 in Bowong Cindea was significantly higher, reaching 30 µg/m³, compared to only 10 µg/m³ in Bulu Cindea. Wind speed significantly influences the dispersion of pollutants. Higher wind speeds facilitate the horizontal and perpendicular spread of contaminants, leading to a reduction in their concentration. However, strong winds can also carry pollutants over long distances, contributing to air pollution in other areas. Conversely, when wind speeds are low, pollutants tend to accumulate, increasing the risk of air pollution in residential areas near the pollution source (20). The results of both modeling studies remained below the standard set under Government Regulation of the Republic of Indonesia No. 22 of 2021, which establishes a limit of 30,000 μg/m³ for one hour. On a per-semester basis, the projection results aligned proportionally with the one-hour findings, with the highest concentration recorded in semester 2 at 189 μg/m³, compared to 130 μg/m³ in semester 1, despite differences in distribution patterns. At high wind speeds, building downwash commonly occurs, highlighting the key role of meteorological factors in determining peak pollutant levels. Downwash is minimal when wind is low and buildings are distant, but it increases significantly with stronger winds and closely spaced structures (21).

Hazard identification is the initial step in EHRA. It is used to identify specific risk agents that may cause health problems upon short-term or long-term exposure (22). Dose-response analysis, the next step, is conducted based on the standardization issued by the U.S. Environmental Protection Agency (US EPA) for reference concentration (RfC) values, with SO_2 set at 0.0026 milligrams per kilogram per day (mg/kg/day) and CO at 0.1 milligrams per kilogram per day (mg/kg/day). Exposure analysis aims to identify and quantify the exposed population and determine the duration of exposure to the agent (23). This includes methods for estimating the potential, frequency, variation, and pathway of pollutant exposure in humans (20).

Figure 3 indicates that no significant non-carcinogenic health risks were identified based on both real-time and lifetime exposure durations for SO_2 parameters. These findings are consistent with the study by Thriel (24), which confirmed that acute exposure to SO_2 does not have significant effects on pulmonary function or sensory irritation in healthy individuals. However, individual variability and the presence of vulnerable populations, such as individuals with asthma or airway hypersensitivity to SO_2, should be taken into account in the formulation of emission limit policies.

The RQ values for CO, as presented in Figure 3, are consistent with those found by Aryagita (25). In her study, the RQ values for all parking attendant respondents exceeded 1, indicating that all parking attendants at Kapasan Market, Surabaya, were at risk of CO gas exposure, which might lead to adverse health effects. Carbon monoxide binds to hemoglobin (Hb), reducing its oxygen-carrying capacity and leading to CO poisoning (26). This gas is odorless, colorless, and highly toxic, leading to tissue damage and severe hypoxia (27). The severe clinical symptoms of CO poisoning, along with its high morbidity and mortality rates, make it a significant global health concern (28). CO poisoning is more prevalent among individuals with chronic heart disease, anemia, or respiratory conditions (29). Myocardial damage is common in CO poisoning, with 40% of tested individuals exhibiting elevated cardiac biomarkers. This condition can lead to ischemia, arrhythmias, heart failure, cognitive decline, seizures, and coma (30).

Carbon monoxide is one of the leading causes of fatal poisoning worldwide (31). The toxicity of carbon monoxide is primarily mediated through the hypoxia pathway, in which CO molecules displace oxygen (O_2) and bind to hemoglobin, forming carboxyhemoglobin (HbCO) (32). The increased presence of HbCO in the blood and the resulting leftward shift in the oxygen dissociation curve reduce both oxygen transport and its delivery to tissues. Other heme-containing molecules, such as myoglobin, are also affected (33). Organs with the highest metabolic demands, such as the heart and brain, are the most sensitive to tissue hypoxia caused by CO (34). It is estimated that 1,000 to 2,000 accidental deaths occur each year due to carbon monoxide poisoning (35). Recent publications have revealed that CO poisoning affects not only the lungs but also other organ systems, including the heart, kidneys, liver, and, most importantly, the brain. Brain involvement can lead to delayed neuropsychiatric syndrome symptoms in up to 40% of patients with high blood HbCO levels (36).

Conclusion

Port activities at cement plants contribute significantly to ambient air pollution, particularly through emissions of sulfur dioxide (SO_2) and carbon monoxide (CO). Dispersion modeling using AERMOD indicated that emission source characteristics, meteorological conditions, and topographic factors affect pollutant concentrations. The highest concentrations of SO_2 and CO, recorded in the second semester, reached 196 and 24,407 μg/m³, respectively, with predominant dispersion toward the northeast. The results of environmental health risk assessment (EHRA) revealed that long-term exposure to CO poses a significant non-carcinogenic health risk, as indicated by a risk quotient (RQ) value greater than 1 after 15 to 30 years of exposure. In contrast, SO_2 exposure remains within safe limits ($RQ < 1$) for healthy individuals. Nevertheless, the presence of vulnerable populations, such as individuals with respiratory or cardiovascular conditions, warrants special attention in the formulation of more protective emission limit policies. This study is limited by the exclusion of particulate parameters such as PM_{10}. The focus was directed toward chemical pollutants, namely CO and SO_2, which are directly emitted from fossil fuel combustion, exhibit different dispersion characteristics from particulates, and are closely related to long-term non-carcinogenic health risks. However, as PM_{10} and $PM_{2.5}$ also have significant impacts on respiratory and cardiovascular health, future research is recommended to include these parameters to provide a more comprehensive environmental health risk assessment of air pollution from port and cement industry activities.

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Visualization: A Muh Cipta Prawira Putra Muhammad Fahmi Aziz.
Writing – original draft: A Muh Cipta Prawira Putra
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Competing Interests

The authors declare no competing interests related to the content of this manuscript.

Ethical Approval

We hereby declare that the scientific article submitted for publication does not contain any ethical violations, including but not limited to plagiarism, data manipulation, or conflicts of interest. We also affirm that the entire research process conducted in the preparation of this article has adhered to ethical principles, particularly those concerning the impact on human health and environmental sustainability.

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