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Modeling and Analysis of Total Suspended Particulate (TSP) on the Cement Industry Distribution Route in Grobogan Regency, Central Java

Pemodelan dan Analisis Sebaran Total Partikulat Tersuspensi (TSP) pada Jalur Distribusi Industri Semen di Kabupaten Grobogan, Jawa Tengah

IKHA NOVITA MA'WA SUKRIYA[1*], HARTUTI PURNAWENI[2], AND FUAD MUHAMMAD[3]
[1]Master Program in Environmental Science, Diponegoro University, Semarang 50241, Indonesia
[2]Faculty of Social and Political Science, Diponegoro University, Semarang 50139, Indonesia
[3]Faculty of Science and Mathematics, Diponegoro University, Semarang 50275, Indonesia
*ikhanovitaschool1@gmail.com

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ABSTRAK

Peningkatan aktivitas transportasi dan operasional industri berkontribusi signifikan terhadap pencemaran udara, termasuk emisi polutan gas dan materi partikulat. Paparan total partikulat tersuspensi atau total suspended particulate (TSP) dapat meningkatkan risiko gangguan pernapasan bagi makhluk hidup. Aktivitas utama maupun penunjang dalam industri semen menghasilkan emisi polutan dalam jumlah besar ke udara dan lingkungan sekitar. Penelitian ini bertujuan untuk memodelkan dan menganalisis distribusi konsentrasi TSP di udara ambien pada musim kering dan musim basah yang bersumber dari kegiatan transportasi bahan baku dan hasil produksi semen. Pemodelan dispersi dilakukan menggunakan model American Meteorological Environmental Protection Agency Regulatory Model (AERMOD). Laju emisi TSP dihitung dan digunakan sebagai input untuk mengestimasi beban emisi dan nilai konsentrasi TSP. Analisis arah angin (wind rose) dilakukan untuk menentukan pola arah sebaran konsentrasi TSP yang dihasilkan oleh AERMOD. Hasil pemodelan menunjukkan bahwa konsentrasi TSP cenderung tinggi di sisi kanan dan kiri jalur utama, mengikuti arah angin dominan. Peningkatan konsentrasi tahunan TSP berkisar antara 3 hingga 325 µg/m³ dalam radius 7,2 meter dari as jalan raya, namun tidak ditemukan permukiman penduduk dalam radius tersebut. Pada musim basah, peningkatan konsentrasi tertinggi tercatat antara 200 hingga 281 µg/m³ dalam radius 38 meter dari as jalan, dengan jumlah rumah terdampak sebanyak 76 unit. Sementara itu, pada musim kering, konsentrasi tertinggi antara 2 hingga 176 µg/m³ dalam radius 80,3 meter, dengan 125 rumah yang berpotensi menerima paparan partikulat. Tingkat paparan materi partikulat di kawasan permukiman ini tergolong mengkhawatirkan, sehingga diperlukan studi lanjutan terkait dampak kesehatan dan persepsi masyarakat terhadap kualitas udara di wilayah terdampak.

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ABSTRACT

Increased transportation activities and industrial operations contribute significantly to air pollution, including emissions of gaseous pollutants and particulate matter. Exposure to total suspended particulate (TSP) can increase the risk of respiratory problems in living beings. Both primary and ancillary activities in the cement industry produce large amounts of pollutant emissions into the air and the surrounding environment. This study aims to model and analyze the distribution of TSP concentrations in ambient air in the dry and wet seasons sourced from the transportation of raw materials and cement products. Dispersion modeling was conducted using the American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD). The TSP emission rate was calculated and used as input to estimate the emission load and TSP concentration values. A wind rose was analyzed to determine the directional pattern of TSP concentration distribution generated by AERMOD. The modeling results show that TSP concentrations tend to be high on the right and left sides of the main road, following the dominant wind direction. The annual increase in TSP concentrations ranged from 3 to 325 µg/m³ within a radius of 7.2 meters from the road axle, but no residential areas were found within this radius. In the wet season, the highest concentration increase was recorded between 200 and 281 µg/m³ within a radius of 38 meters from the road axle, with a total of 76 houses affected. Meanwhile, in the dry season, the highest concentrations ranged from 2 to 176 µg/m³ within a radius of 80.3 meters, with 125 houses potentially receiving particulate matter exposure. The exposure to particulate matter in this residential area is alarming, so further studies are needed regarding health impacts and community perceptions of air quality in the affected area.

1. INTRODUCTION

1.1 Background

With its expanding transportation and industrial activities, modern society has harmed air quality, increasing gaseous and particulate pollution. Particulate matter is classified by particle size; one category is dust or Total Suspended Particulate (TSP), which consists of particles with diameters smaller than 100 μm (Arbi et al., 2023). TSP includes soot particles, metal particles, pollen, and other fine particles (Murnasih, 2020). In 2010, particulate air pollution was responsible for 223,000 deaths from lung cancer. Notably, 9% of all such deaths that year (139,000) occurred in China (Loomis, 2014). When TSP concentrations exceed quality standards, they can negatively impact the environment and living organisms in the surrounding area (Oktaviani, 2018). Exposure to elevated TSP levels increases the risk of respiratory diseases such as acute respiratory infections, asthma, emphysema, heart disease, and chronic obstructive pulmonary disease (COPD) (Hesti, 2020).

The cement industry is a major source of air pollution, emitting significant quantities of gases (CO_2, NO_x, SO_2), particulate matter of various sizes, and heavy metals (Elehinafe et al., 2022). Particulate emissions are the primary pollutants produced by cement plants during manufacturing, especially during the transportation, loading, and unloading of clinker stored outside silos (Mohamad et al., 2022). Research indicates that in urban areas of Russia, more than 80% of particulate matter at sampling sites contains cement particles, posing health risks by damaging the respiratory tract of exposed populations (Kholodov et al., 2020; John, 2020; Gawad et al., 2022). A study in Brazil found that PM2.5 emissions from cement plants contribute to mortality, cardiovascular disease, and respiratory illness (Zorzenão et al., 2024). In Indonesia, research at a cement factory in Maros Regency reported TSP concentrations ranging from 18.48 to 133.24 μg/m^3, with potential health risks from inhalation near the facility (Rauf et al., 2021).

Cement Grobogan is one of Indonesia's cement factories, located in Grobogan Regency, Central Java, with a production capacity of 8,000 tons per day, or 2.5 million tons annually. According to Wijayanti (2022), particulate pollution from the factory significantly affects nearby residents, particularly those involved in raw material transportation and cement distribution, especially during the dry season.

Given the severe health impacts associated with particulate emissions from the Grobogan Cement factory and the limited research on emissions from its transportation activities, it is essential to analyze the relationship between emission sources and the distribution of particulate emissions, particularly from transportation. Air dispersion modeling is a method used to predict the spatial and temporal distribution of pollutants through algorithmic approaches that account for atmospheric dispersion as well as chemical and physical processes (Zou et al., 2010). The American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD) is one example of such a model. It is based on a Gaussian plume approach and takes into account how topography and weather affect the dispersion of pollutants. AERMAP is used to analyze topography, while AERMET is used to handle meteorological data (Cimorelli et al., 2004; Wangsa et al., 2022). Several studies have successfully used AERMOD to estimate particulate concentrations and distribution, demonstrating good agreement with field measurements (Fadavi et al., 2016; Wangsa et al., 2022).

This research plays an important role in complementing existing studies on the impact of particulate emissions from transportation activities associated with the cement industry, particularly in the Grobogan area. The results are expected to provide a more comprehensive understanding of the spatial and temporal distribution of TSP concentrations along cement distribution routes. Furthermore, the findings potentially stimulate research in environmental epidemiology and raise public and governmental awareness of the importance of maintaining air quality in areas affected by intensive industrial operations.

1.2 Research Objectives

This study aims to model and analyze the distribution of TSP concentrations in ambient air during the dry and wet seasons, originating from the transportation of raw materials and cement production. The TSP distribution pattern is modeled using the AERMOD dispersion model to assess changes in TSP concentrations after the factory begins operations along Jalan Semen Grobogan in Grobogan Regency.

2. METHODOLOGY

2.1 Study Location

The research was conducted along the transportation or distribution route of the cement industry in Grobogan, located at coordinates 07°4′49.75″S and 110°32′26.81″E. The study area covers the 4.6 km long Semen Grobogan Road, which passes through Mangunsari Village, Sukorejo Village, and Tanggirejo Village in Tegowanu District, Grobogan Regency. The topography of the study site is characterized by flat (0–3%) and undulating (3–8%) terrain, as shown on the factory site plan and its surroundings in Figure 1.

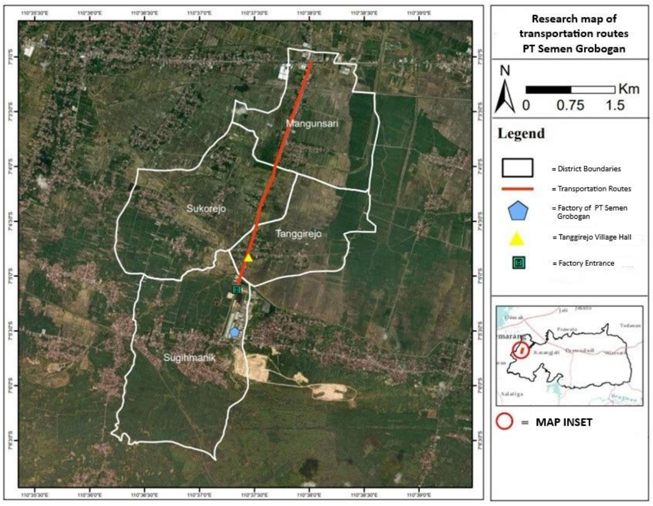


Figure 1. Location of the study area along the cement industry transportation route

The Grobogan cement factory was chosen as the study location because previous environmental impact studies of cement factories have focused only on chimney emissions. In contrast, the potential impacts of raw material transportation and cement production activities on ambient air quality in the surrounding environment have not been studied comprehensively.

2.2 Data

The data used in this study included baseline TSP concentration data, vehicle traffic data, and meteorological data. The baseline TSP concentration data referred to measurements taken before the cement plant's complete operational phase in 2018. These measurements were conducted along the factory's transportation route, specifically in front of the Tanggirejo Village Hall, Tegowanu District, Grobogan Regency. The measured baseline TSP concentration was 81.7 μg/m³ (Document Addendum to Environmental Impact Assessment and Environmental Management Plan (AMDAL) and Environmental Management Plan (RKL-RPL) of PT Semen Grobogan, 2020).
Vehicle traffic data, representing the number of vehicles transporting raw materials and finished products for Semen Grobogan, were used to calculate TSP emissions. Meteorological data from 2022–2023 for the study area—including temperature, humidity, pressure, wind direction and speed, precipitation, and solar radiation—were obtained from the NASA website (https://larc.nasa.gov/data-access-viewer/). Data on cloud cover and lowest cloud height (ceiling height) were obtained from ERA5 reanalysis meteorological data (https://cds.climate.copernicus.eu/).

2.3 Analysis

Analysis of the data processing results includes calculations of TSP emissions and dispersion modeling using AERMOD, as well as wind rose analysis using WRPLOT. Emission calculations were conducted to estimate the particulate emission load generated by the friction between vehicle tires and paved roads, using the following equation (USEPA, 1998):

$$E = K^b \left(\frac{sL}{2}\right)\left(\frac{sL}{2}\right)^{0.65} \times \left(\frac{W^{1.5}}{3}\right) \quad (1)$$

where:
E = Emission factor for vehicle traffic on dry paved roads (g per vehicle-kilometer)
Kb = Empirical Particle Size Factors
sL = Clay or Mud Loading on Road Surface (g/m²)
W = Average vehicle weight (tons)

The wind direction and speed data obtained were analyzed using WRPLOT to generate wind profiles for the wet, dry and the annual seasons. AERMOD was employed to model the distribution of TSP particulates along the cement industry transportation route in Grobogan Regency. AERMET was used to process meteorological data, including hourly surface and upper air profiles. AERMAP was utilized to process the study's area geological and topographic data. The modeling workflow using AERMOD is illustrated in Figure 2.

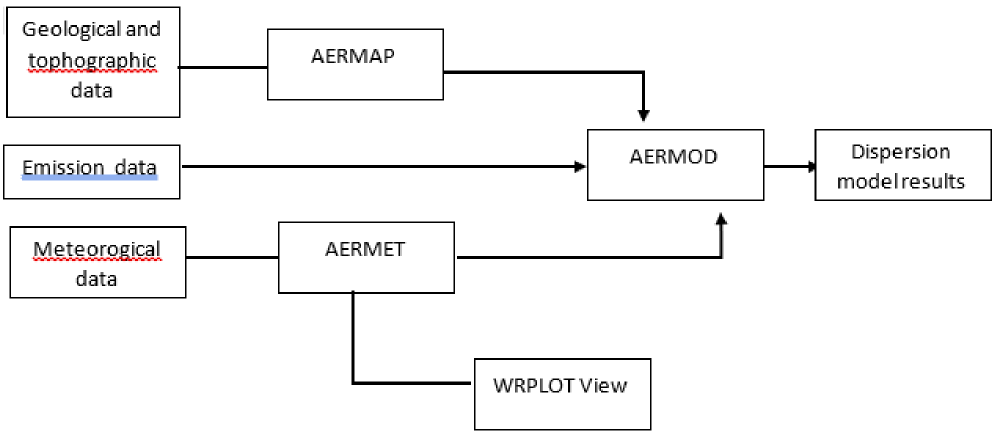


Figure 2. Process Flow of AERMOD Modeling

3. RESULTS AND DISCUSSION

3.1 Particulate Emissions

The calculated emission source in this study comprises TSP emissions resulting from the number of vehicles entering and leaving the cement factory during the study period. The calculation begins with determining the emission factor for heavy vehicles using Equation (1), with an emission factor value of 50.927 g/VKT. The next step involves calculating the emission load by multiplying the emission factor by the number of vehicles per hour passing through the study area. This emission load is then converted into an emission rate in g/s·m². The TSP emission rate is obtained by dividing the emission load by the area of the traffic lane—4 km in length and 6 m in width—while converting the time unit into seconds. This emission rate value serves as input for the AERMOD dispersion modeling.

The calculation was performed to determine differences in emission loads during the dry season, wet season, and annual period. As shown in Figure 3, during the dry season—with a peak vehicle count of 786 vehicles/day—the calculated TSP emission rate is 1.93×10^{-5} g/s·m². Meanwhile, during the wet season, with a reduced vehicle count of 748 vehicles/day, the TSP emission rate is 1.83×10^{-5} g/s·m².

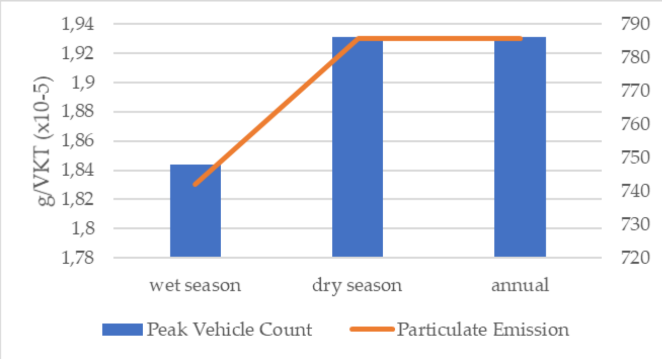


Figure 3. Relationship between the number of vehicles and particulate emissions at the study location in 2022-2023

Figure 3 indicates that vehicle numbers are lower in the wet season than in the dry season, thus influencing the resulting TSP emission concentrations. TSP emissions are linearly related to the number of vehicles, with increased traffic leading to higher emissions. Moreover, during the wet season, atmospheric leaching from rainfall deposits airborne particulate matter onto surfaces, resulting in generally lower ambient concentrations compared to the dry season (Cholianawati et al., 2024). Therefore, in the wet season, both reduced vehicle numbers and rainfall contribute to lower TSP concentrations at the study site. Conversely, during the dry season, increased vehicle numbers combined with the absence of rainfall lead to higher TSP emissions.

Particulate matter emissions from vehicles are influenced by factors such as fuel type and road surface characteristics. Diesel-fueled vehicle engines, commonly used in heavy transport at cement factories, emit substantial amounts of NO_x and particulates into the ambient air (Han et al., 2020). The use of diesel fuel thus contributes to elevated TSP concentrations at the study site. Additionally, road surface type affects TSP emissions. Research by Penkala et al. (2023) found that the mass fraction of particulates smaller than 100 μm from road dust ranges from 12.8% to 3.4% for asphalt surfaces and from 12.0% to 6.5% for concrete surfaces. The TSP emission load calculation in this study specifically accounts for emissions arising from the friction between vehicle tires and asphalt roads.

3.2 Wind Rose Analysis

Wind patterns in Grobogan Regency are influenced by monsoonal systems, with seasonal differences between the wet and dry periods affecting wind direction. Wind patterns were analyzed and visualized as wind roses using WRPLOT software. Figure 4 presents wind patterns for the wet season, dry season, and annual period for 2022–2023. Wind speed is classified into several color categories: light green (0.5–2.1 m/s), yellow (2.1–3.6 m/s), red (3.6–5.7 m/s), dark blue (5.7–8.8 m/s), dark green (8.8–11 m/s), and light blue (≥ 11 m/s).

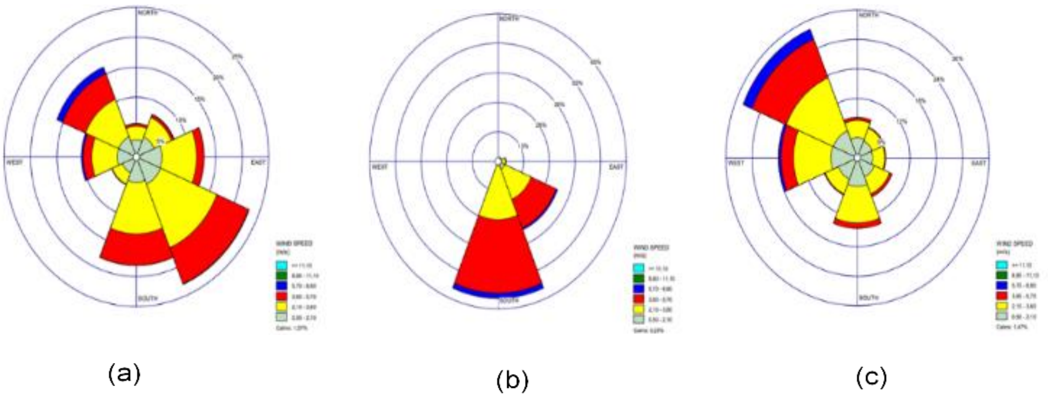


Figure 4. Wind rose analysis of wind direction and speed patterns: (a) annual, (b) dry season, and (c) wet season at the study site, 2022–2023

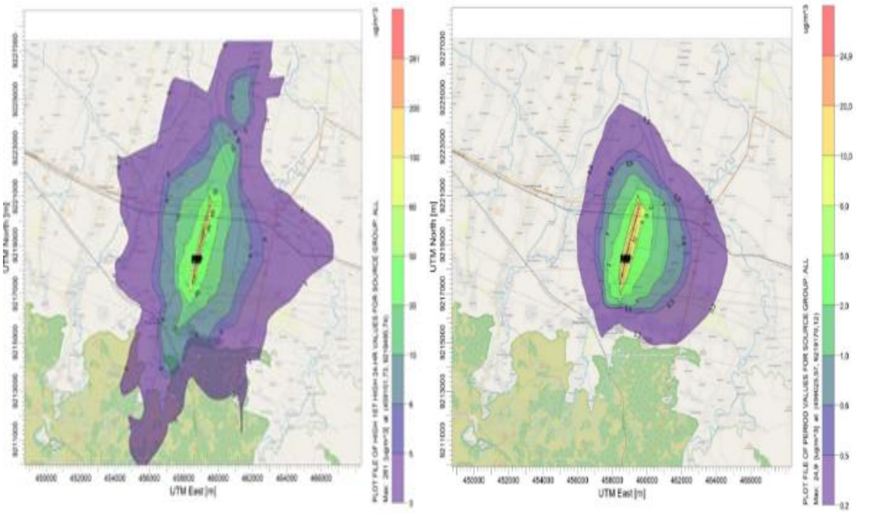
This study analyzed annual, wet-season, and dry-season wind patterns. The annual pattern is based on meteorological data from 2022 to 2023. The wet season includes January–April 2022, November–December 2022, January–April 2023, and November–December 2023. The dry season spans May to October 2022 and May to October 2023. Figure 4a shows the annual wind pattern, with dominant winds from the southeast to northwest (23.28%), south to north (18.32%), and east to west (16.41%). Calm conditions account for 1.07% of the year, and the average annual wind speed is 2.49 m/s. The most frequent wind speed range is 2.1–3.6 m/s, comprising 11.49% of observations.

During the dry season (Figure 4b), the dominant wind direction is south to north (60.19%), followed by southeast to northwest (32.56%). Calm conditions occur in 0.25% of cases, with an average wind speed of 3.34 m/s. The most frequent wind speed range is 3.6–5.7 m/s, making up 32.27% of cases.In contrast, during the wet season (Figure 4c), dominant wind directions are northwest to southeast (28.56%), west to east (18.23%), and south to north (14.53%). Calm conditions account for 1.47%, with an average wind speed of 2.31 m/s. The highest frequency is observed in the 2.1–3.6 m/s range, at 11.59%.

Air pollution dispersion is strongly influenced by meteorological factors such as turbulence, wind patterns, temperature, the Planetary Boundary Layer (PBL), and atmospheric waves. The combination of these factors determines the pattern and intensity of pollutant dispersion in the atmosphere (Hitchcock et al., 2014). The wind rose analysis results are compared with the isopleths generated by AERMOD modeling to assess the distribution of particulate emissions at the study site, as discussed in the AERMOD analysis subsection.

3.3 AERMOD Analysis

Predicting the distribution of TSP pollutants using AERMOD begins with processing meteorological data using AERMET and topographic data using AERMAP. The TSP emission rate input into AERMOD was 1.93×10^{-5} g/s·m² for the dry season and 1.83×10^{-5} g/s·m² for the wet season. The initial environmental baseline data, measured in 2018 in front of the Tanggirejo Village Hall (Document Addendum to Environmental Impact Assessment and Environmental Management Plan (ANDAL) and Environmental Management Plan (RKL-RPL) of PT Semen Grobogan, 2020), reported a TSP concentration of 81.7 μg/m³. This baseline concentration was used as the background value, to which the modeled concentration increase from AERMOD was added to estimate current ambient TSP levels. The AERMOD receptor height was set at 1.5 meters, representing the average height of Indonesians as specified by SNI 19-7119.6-2005 on Ambient Air Quality.



(a) (b)

Figure 5. AERMOD modeling results of TSP distribution during the wet season (a) 24 hours and (b) period at the study location in 2023.

The wet-season modeling results are presented in Figure 5, consistent with the wind rose patterns in Figure 4, indicating dominant wind directions from the northwest and west toward the southeast and east during this period. AERMOD results were analyzed in two categories: 24-hour TSP pollutant distribution and period-average distribution. The 24-hour results represent the highest predicted daily TSP concentration during the 2022–2023 study period, while the period results represent the most frequent or typical concentration distribution for the same timeframe.

During the wet season, the 24-hour AERMOD simulation showed that TSP concentrations trended eastward and southeastward. Due to cement factory transportation activities, modeled concentration increases ranged from 3 to 281 μg/m³. When combined with the baseline, total concentrations ranged from 84.7 μg/m³ to 362.7 μg/m³. The highest modeled concentration increases (200–281 μg/m³) were observed within a 38 m radius of the main road, affecting three residential clusters. In total, 76 homes were identified within these high-concentration zones.

These peak concentrations were also influenced by road conditions, including intersections where vehicle braking increases tire–road friction and particulate emissions. Overall, TSP dispersion during the wet season consistently showed southeastward trends, aligning with the wind rose analysis from WRPLOT.

For the annual period, AERMOD simulations showed TSP concentration increases ranging from 0.2 to 24.9 μg/m³ along both sides of the road. The highest modeled addition (20–24.9 μg/m³) occurred approximately 50.5 m from the highway centerline. The number of residences affected at this highest concentration range was 113 houses (Figure 5).

The AERMOD modeling results for the dry season, presented in Figure 6, are consistent with the wind rose analysis, showing dominant wind directions from the south and southeast toward the north and northwest. During the dry season, the 24-hour AERMOD simulation indicates that TSP concentration increases tend to be directed northward and northwestward. The modeled range of added concentrations is 2–176 μg/m³ along the transportation corridor in the study area. When these increases are added to the baseline concentration, the resulting range is 83.7–257.7 μg/m³. The highest modeled concentration increases (100–176 μg/m³) were observed within 80.3 m of the highway centerline, affecting 125 residential houses. Meanwhile, the overall distribution of TSP during the dry season also exhibits a southeastward component. It is important to note that these modeled concentrations account only for emissions from vehicles entering and leaving the cement factory, and do not include other vehicular sources.

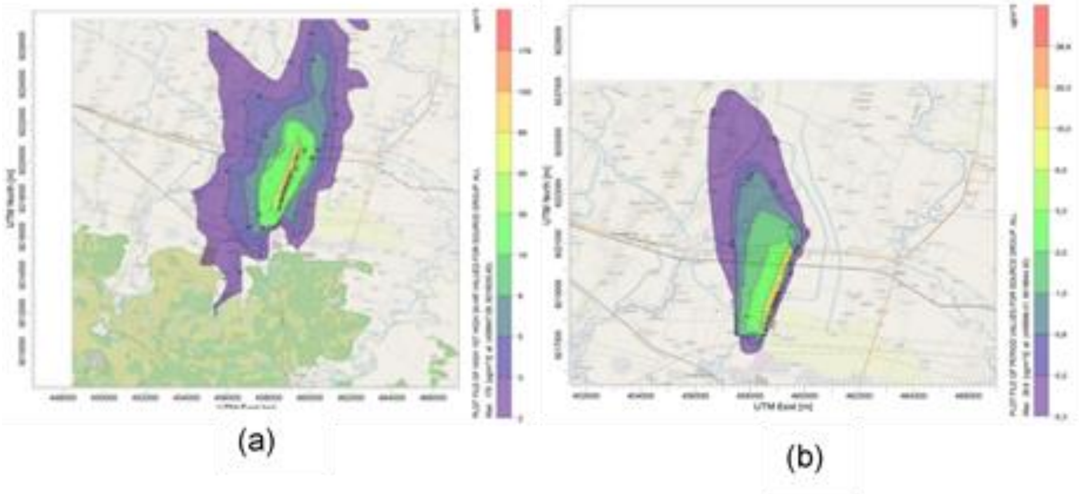


Figure 6. AERMOD modeling results of TSP distribution during the dry season (a) 24 hours and (b) period at the study location in 2023.

The distribution of TSP pollutants modeled with AERMOD over both 24-hour and annual periods aligns with the wind rose patterns produced using WRPLOT. For the annual period, modeled increases in TSP concentrations ranged from 0.3 to 26.6 μg/m³ along both sides of the road. Including the baseline, total concentrations ranged from 82.0 μg/m³ to 108.3 μg/m³. The highest modeled increases (20–26.6 μg/m³) occurred within 47.3 m of the highway axis. The affected areas were primarily rice fields and dry agricultural land at these highest concentrations, with no residential buildings impacted (Figure 6).

The dominant wind direction in the annual AERMOD results, illustrated in Figure 7, shows TSP dispersion trending toward the north and northwest, consistent with the wind rose analysis. For the 24-hour annual pattern, TSP concentration increases predominantly extend northward, with modeled additions ranging from 3 to 325 μg/m³. The highest increases (300–325 μg/m³) were found within 7.2 m of the highway axis, in areas near road intersections where no residential buildings are present due to proximity to the highway.

For the annual period average, TSP dispersion trends northwestward. The modeled range of concentration increases in this pattern is 0.2–23.7 μg/m³ along both sides of the road. The highest modeled additions (20–23.7 μg/m³) were observed within a 42 m radius of the highway centerline, in areas without residential development (Figure 7).

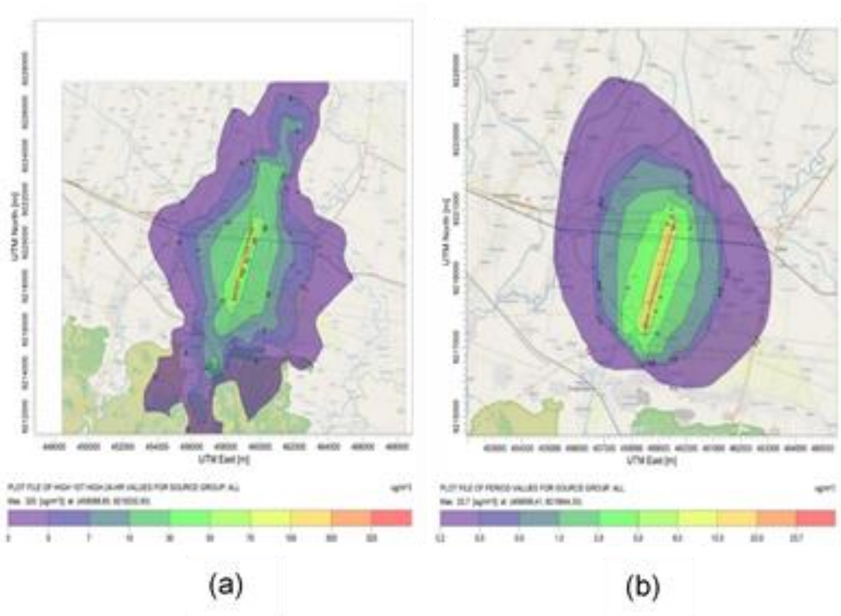


Figure 7. AERMOD modeling results of annual TSP distribution (a) 24 hours and (b) period at the study location in 2023.

Compared to the ambient air quality standards, the AERMOD modeling indicates that increases in TSP concentrations during the wet season, dry season, and annually can result in total concentrations exceeding the established limits. According to Appendix VII of Government Regulation of the Republic of Indonesia Number 22 of 2021 on Ambient Air Quality Standards, the 24-hour TSP standard is 230 μg/m³. This situation requires attention, as elevated TSP concentrations in ambient air pose health risks to residents living near cement factory operations. These risks arise not only from chimney emissions but also from emissions generated by transportation activities within the cement industry.

4. CONCLUSION

Based on the results of AERMOD modeling of TSP concentration distributions resulting from raw material transportation and cement production activities at the Grobogan Cement Factory, there is a clear tendency for elevated TSP levels to occur along both sides of the road axis, with distribution patterns shaped by prevailing wind directions. In the annual scenario, modeled increases in TSP concentrations range from 3 to 325 µg/m³ within a 7.2 m radius of the highway axis, although no residential areas are located within this radius. During the wet season, the highest modeled concentration increases from 200 to 281 µg/m³ within 38 m of the highway axis, potentially exposing 76 residential houses to elevated particulate levels. In the dry season, the highest modeled increases range from 2 to 176 µg/m³ within an 80.3 m radius, with 125 houses potentially affected by particulate matter exposure.

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