



## Analysis of the Effect of Stack Height and Exit Gas Velocity on Boiler Emission Dispersion at a Palm Oil Mill Using the AERMOD Model

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### Abstract

Air pollution generated from fuel combustion in palm oil mill boilers poses potential risks to both environmental quality and public health. One of the main factors influencing pollutant dispersion is the stack height and flue gas exit velocity. This study was conducted at PT X, Indragiri Hilir, to analyze the effect of stack height variations (45–70 m) and exit gas velocities (15–25 m/s) on the maximum concentrations of SO<sub>2</sub>, NO<sub>2</sub>, and particulate matter (PM). Meteorological data were obtained from ECMWF and NASA for a ten-year period (2015–2024), while topographical data were processed using a Digital Elevation Model (DEM). Meteorological inputs were prepared with AERMET, and topography was processed using AERMAP as inputs for AERMOD dispersion modeling. The results indicated that increasing stack height significantly reduced maximum pollutant concentrations in ambient air. Similarly, higher exit gas velocity (25 m/s) enhanced plume rise and mixing, producing lower pollutant concentrations compared to lower velocities (15 m/s). Under the actual operating condition of six active boiler stacks, the maximum hourly and daily concentrations of SO<sub>2</sub>, NO<sub>2</sub>, and PM were found to be well below the Indonesian ambient air quality standards set by the Ministry of Environment and Forestry (KLHK). In conclusion, technical variations in stack design play an essential role in reducing pollutant concentrations, and AERMOD modeling can serve as a reference for formulating emission control strategies in palm oil mill industries.

## Introduction

Air pollution is one of the most serious problems in the world today because it not only impacts climate change but also endangers public health by increasing the risk of cardiovascular disease, respiratory disorders, lung cancer, and worsening asthma in vulnerable individuals (Wang et al., 2023). Based on the latest data from the World Health Organization (WHO), air pollution contributes to approximately 4.2 million premature deaths globally each year (Hidajat et al., 2023; WHO, 2021). The impact of air pollution, which can reduce life expectancy and disrupt people's physical and mental health, also has the potential to affect the effectiveness of decision-making and the smooth operation of companies. The issue of air pollution has raised concerns in various circles, both in academia and the wider community (Tan et al., 2021; Wang et al., 2022). Various types of air pollutants, such as carbon monoxide (CO), sulfur dioxide (SO<sub>2</sub>), ozone (O<sub>3</sub>), nitrogen dioxide (NO<sub>2</sub>), and particulate matter (PM), are produced from a number of sources, including fossil fuel combustion, industrial activities, motor vehicles, and forest fires, both natural and human-caused (Wang et al., 2023).

Serious development is needed to implement pollution prevention and management strategies to effectively reduce, prevent, or eliminate the negative impacts of air pollution. Therefore, air

quality monitoring, analysis of emission levels of various pollutants, and modeling the distribution of pollutants in the atmosphere are crucial to achieving these goals (Saleh et al., 2021; Sokhi et al., 2022; Izah et al., 2024; Tahir Bahadur et al., 2024). As problems in science and technology become increasingly complex, computational modeling approaches are increasingly being used to analyze and project air pollutant distribution patterns. This modeling provides significant support for city planners in formulating air quality improvement strategies, thereby protecting public health, mitigating negative environmental impacts, and minimizing economic losses. Several studies on air pollutant dispersion have been published utilizing various air quality modeling approaches, examining the characteristics of emissions from various pollutant sources (Kalhor & Bajoghli, 2017; Mak et al., 2020; Liang et al., 2023; Talukdar et al., 2023). Several studies have summarized measurements of the concentrations of various air pollutants and modeled their dispersion from various emission sources (Indah Wibisono et al., 2024). Several studies have been analyzed in depth to demonstrate the importance of this topic (Amer & Abbas, 2015; Jayadipraja et al., 2020).

SO<sub>2</sub> and NO<sub>2</sub> emissions from the Tembilahan coal-fired power plant (PLTU) were predicted using AERMOD modeling over a one-year period. Simulation results showed that the annual SO<sub>2</sub> concentration of 75.18 µg/m<sup>3</sup> exceeded the established threshold. Meanwhile, the annual NO<sub>2</sub> concentration of 43.53 µg/m<sup>3</sup> remains below the applicable threshold (Sasmita et al., 2021; Tang et al., 2025).

Several studies have shown that industrial activities, including palm oil processing, are a major contributor to increasing air pollutant emissions. This occurs because the combustion of fuels, such as biomass and diesel, produces gas and particulate emissions that impact air quality. Air pollution has been recognized as one of the greatest environmental risks affecting public health, particularly in developing countries that still rely on fossil fuels for their industrial activities (O'malley et al., 2021; Obianyo et al., 2025; Rathod et al., 2024).

In the palm oil processing industry, various types of fuel, such as biomass, are often used to operate critical units, including boilers (Urian & Calderon, 2023). Combustion of these fuels produces gas and particulate emissions that can degrade air quality in the surrounding environment (Razek et al., 2025; Odubo & Kosoe, 2024). This condition is common in many industrial areas, particularly in areas that have not yet fully transitioned to clean energy and still rely on conventional fuels to support factory operations (Paminto et al., 2022; Salsabila et al., 2023).

The combustion of fuels such as shells and fibers in boilers and in the palm oil processing industry requires high energy consumption, which is commensurate with increased air pollutant emissions, particularly particulate matter, which in some conditions exceeds quality standards (Faisal, 2024).

Combustion of fuels in units such as boilers in the palm oil industry can produce significant amounts of pollutants, especially if the emission control system is not functioning properly (Chairat et al., 2024). This can negatively impact air quality, the surrounding environment, and the health of residents living near the mill. Therefore, it is important to measure the levels of pollutants released into the air, especially pollutants such as Particulate Matter (PM), nitrogen dioxide (NO<sub>2</sub>), and sulfur dioxide (SO<sub>2</sub>), because these substances often arise from the combustion process (Fazakas et al., 2024; Onivefu & Imarhiagbe, 2024). Although boiler chimneys are the main source of emissions, studies that directly measure emission concentrations and simulate their distribution in the surrounding environment, especially in the palm oil industry, are still rare (Cavalcanti et al., 2024). Therefore, the implementation of this research focused on three main aspects: direct measurement of pollutant concentrations from

boiler factory chimneys and to describe emission conditions in various factory areas, modeling emission distribution using AERMOD software by considering technical data such as chimney height, flue gas flow velocity, and meteorological data such as wind direction and speed, and comparison of modeling results with ambient air quality standards based on Government Regulation Number 22 of 2021 and Regulation of the Minister of Environment and Forestry No. 11 of 2021 as a basis for developing an emission control strategy that is expected to help the palm oil industry meet applicable emission standards and support the sustainability of its operations (Ministry of Energy and Mineral Resources, 2020; Ministry of Environment and Forestry, 2018b; Jamaludin et al., 2024).

## Methods

### Location and Time of Research

This study employs a quantitative dispersion-modeling research design utilizing the AERMOD modeling system to predict and analyze the dispersion of boiler emissions. The research was conducted at PT X, a palm oil mill located in Indragiri Hilir, Indonesia. This company covers an area of 83,873.3023 hectares dedicated to plantation activities and fresh fruit bunch (FFB) processing. In its operations, the mill utilizes six boiler units as primary emission sources, with the six active chimneys acting as the focal point of this study. The geographical layout and positions of these active chimneys within the factory area are illustrated in Figure 1.



Figure 1. Research Location

### Data and Data Sources

#### Meteorological Data

Meteorological data were obtained from the European Centre for Medium Range Weather Forecasts (ECMWF) and NASA. The collected parameters included wind direction and speed, air temperature, humidity, atmospheric pressure, rainfall, and solar radiation. Data were gathered over a ten year continuous period (January 1, 2015, to December 31, 2024) to ensure the capture of representative, long term annual climate conditions.

### ***Topographic Data and Receptor Grid Configuration***

The topographic data of the study area were extracted using a Digital Elevation Model (DEM) acquired from the U.S. Geological Survey (USGS). A Cartesian receptor grid was configured covering a macro area of  $35 \times 35$  km<sup>2</sup> with a grid spacing of 3,500 meters between nodes. This extensive grid size and spacing were justified to effectively capture the far field dispersion footprint and exponential decay of the pollutants over the ten year meteorological cycle while maintaining computational efficiency. Furthermore, discrete sensitive receptors were explicitly mapped at the coordinates of nearby residential areas, specifically Ularbemban and Teluksialang villages (as seen in Figure 1), to accurately monitor community exposure levels.

### ***Simulated Chimney Characteristics Data and Emission Data***

The emission data for sulfur dioxide (SO<sub>2</sub>), nitrogen dioxide (NO<sub>2</sub>), and particulate matter (PM) under actual operating conditions were obtained directly from field measurements conducted by certified third party laboratories, supplemented by official company operational records of PT X. Under actual conditions, the boiler stacks operate at a height of 24 meters (with some variations at 20 and 21 meters), a diameter of 1.2 to 2.0 meters, and varying gas exit velocities.

To analyze the optimal engineering configuration for emission reduction, simulation scenarios were developed by modifying these baseline conditions. The selection of stack height variations (45–70 m, in 5-meter intervals) was mathematically justified to evaluate the minimum elevation required to overcome building downwash and local aerodynamic wakes. Concurrently, gas exit velocity variations (15–25 m/s) were selected based on standard induced draft fan capacities in palm oil mills to assess the enhancement of vertical plume momentum and turbulent mixing.

### ***Stages of Air Quality Modeling and Quality Assurance***

The dispersion modeling was systematically executed using the AERMOD modeling system. The processing of raw data involved the following technical preparations:

#### ***AERMET***

The ECMWF and NASA meteorological data were processed through the AERMET preprocessor to extract surface characteristics and calculate critical planetary boundary layer parameters, such as friction velocity, Monin-Obukhov length, and convective velocity scale.

#### ***AERMAP***

The DEM topographic data were processed using the AERMAP terrain preprocessor to calculate the specific elevation and controlling hill height scale for each receptor node and emission source, ensuring terrain-induced flow alterations were accurately simulated.

#### ***AERMOD***

The calculated emission rates, processed meteorological profiles, and topographical elevations were synthesized into AERMOD to simulate the atmospheric dispersion.

For model validation and quality assurance, all meteorological and terrain input data underwent range checking to eliminate anomalies prior to execution. The reliability of the model was further validated by comparing the baseline scenario's predicted maximum ground level concentrations against the Indonesian National Ambient Air Quality Standards (established by the Ministry of Environment and Forestry) to ensure the physical realism and regulatory compliance of the outputs.

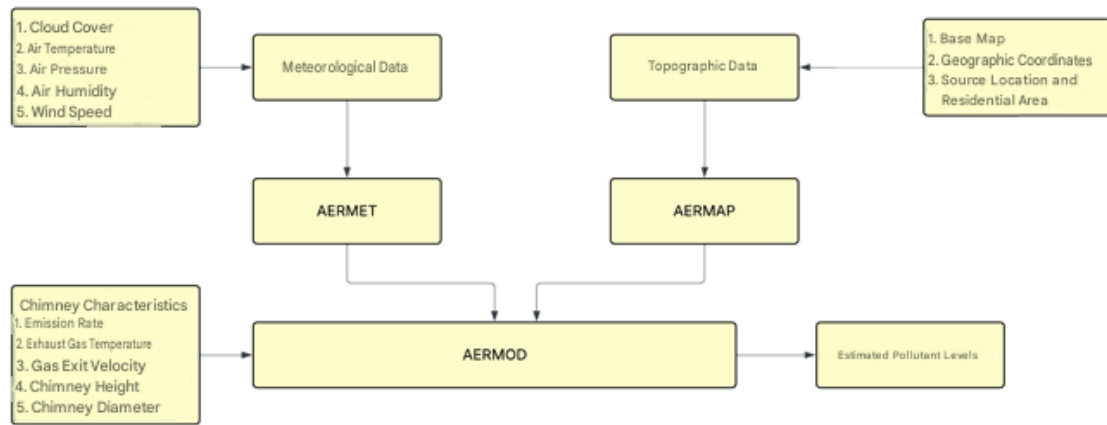


Figure 2. AERMOD Flowchart

### Emission Rate

The pollutant emission rate required as an input for the simulation was calculated based on the measured pollutant concentration and the volumetric flow rate of the exhaust gas (Mishra et al., 2020). To ensure dimensional consistency, the emission rate equation is defined as follow:

$$E = C_{av} \times Q \times 0.0036 \times t_{op} \quad (1)$$

Where:

$E$  = Pollutant emission rate (kg/day)

$C_{av}$  = Daily average pollutant concentration (mg/Nm<sup>3</sup>)

$Q$  = Volumetric flow rate of emissions from the chimney (m<sup>3</sup>/s)

0.0036 = Constant conversion factor (converting mg/s to kg/hour)

$t_{op}$  = Operational time of the boiler in one day (hours/day)

Note: For the direct input into the AERMOD system, the continuous emission rate was converted to grams per second (g/s) using the standard conversion  $E_{g/s} = C_{av} \times Q \times 10^{-3}$

## Results and Discussion

### Meteorological Profile and Wind Vector Analysis

To ensure the accuracy of the dispersion model, a robust meteorological profile was established using a ten year dataset (2015–2024). The wind rose diagram (Figure 3) illustrates the dominant wind movement patterns, which play a crucial role in dictating the trajectory of airborne pollutants. The data reveals that the primary wind vectors travel from the east and northeast (NE) toward the west and southwest (SW), predominantly within the 60°–270° directional range. The average wind speed during this ten year observation was 2.90 knots, with the majority of wind speeds falling between 0.97 and 7.00 knots. Calm conditions were exceedingly rare, occurring only 2.54% of the time. This meteorological behavior implies that emissions generated by the facility will consistently be advected toward the western and southwestern quadrants of the domain.

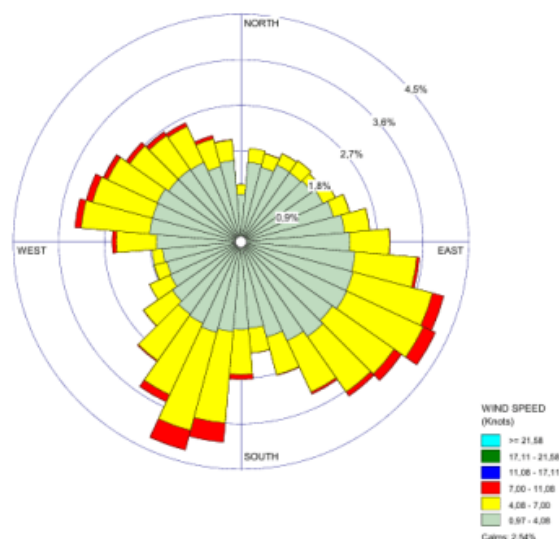


Figure 3. Windrose diagram of Meteorological Data Wind Direction and Speed

### Baseline Dispersion Analysis: Actual Operating Conditions

To evaluate the real world environmental impact of the palm oil mill, the baseline scenario modeled the actual operating conditions of the facility, which utilizes six active boiler stacks. The empirical engineering parameters for these six active emission sources are detailed in Table 1.

Table 1. Actual Chimney Characteristics of the Six Active Boilers at PT X

| Emission Source | X Coordinate (UTM) | Y Coordinate (UTM) | Stack Height (m) | Diameter (m) | Gas Exit Velocity (m/s) | Temp (K) | SO <sub>2</sub> (g/s) | NO <sub>2</sub> (g/s) | PM (g/s) |
|-----------------|--------------------|--------------------|------------------|--------------|-------------------------|----------|-----------------------|-----------------------|----------|
| Boiler 1        | 295520.13          | 24490.78           | 24               | 1.8          | 18.13                   | 573.00   | 0.9138                | 0.750                 | 21.386   |
| Boiler 2        | 281238.79          | 11407.93           | 24               | 1.8          | 6.63                    | 573.00   | 0.6388                | 0.527                 | 14.969   |
| Boiler 3        | 296413.46          | 11675.68           | 24               | 1.8          | 1.55                    | 373.15   | 0.2750                | 0.222                 | 6.4166   |
| Boiler 4        | 274980.87          | 27196.08           | 24               | 1.2          | 14.08                   | 573.00   | 0.7305                | 0.611                 | 17.108   |
| Boiler 5        | 294603.12          | 14525.71           | 21               | 2.0          | 12.60                   | 373.15   | 0.5472                | 0.444                 | 12.833   |
| Boiler 6        | 278471.97          | 21760.62           | 20               | 1.5          | 14.42                   | 573.00   | 0.5472                | 0.444                 | 12.833   |

The AERMOD spatial isopleths (Figures 4, 5, and 6) visually project the dispersion footprint of these cumulative emissions. Numerical interpretation of the model outputs reveals that the maximum 1 hour ground level concentration for SO<sub>2</sub> reached 7.484 µg/m<sup>3</sup> at the specific receptor coordinate of UTM X: 296381.16, Y: 11742.78. Similarly, the maximum 1 hour concentrations for NO<sub>2</sub> and PM peaked at 5.977 µg/m<sup>3</sup> and 5.907 µg/m<sup>3</sup>, respectively, at the exact same geographical coordinate. Spatially, this peak concentration hotspot is highly localized in close proximity to the industrial facility. The isopleth gradients demonstrate an exponential decay in pollutant concentrations before reaching the designated sensitive

receptors, confirming that the residential zones of Ularbemban and Teluksialang are not subjected to hazardous exposure levels.

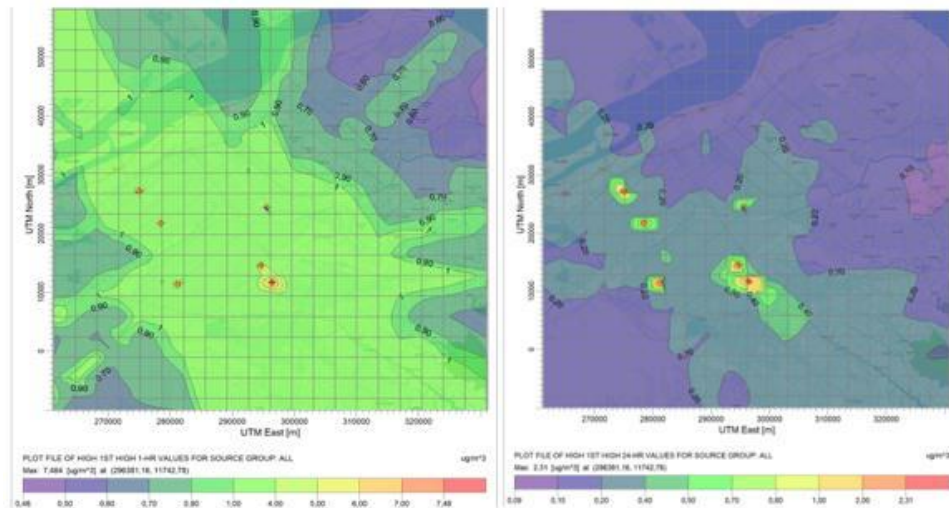


Figure 4 Dispersion of SO<sub>2</sub> Emissions from Boiler Chimneys at PT X in 2015-2024: (a) Maximum Hourly Concentration (MH), (b) Daily Maximum Concentration (MD).

Source: AERMOD, 2025

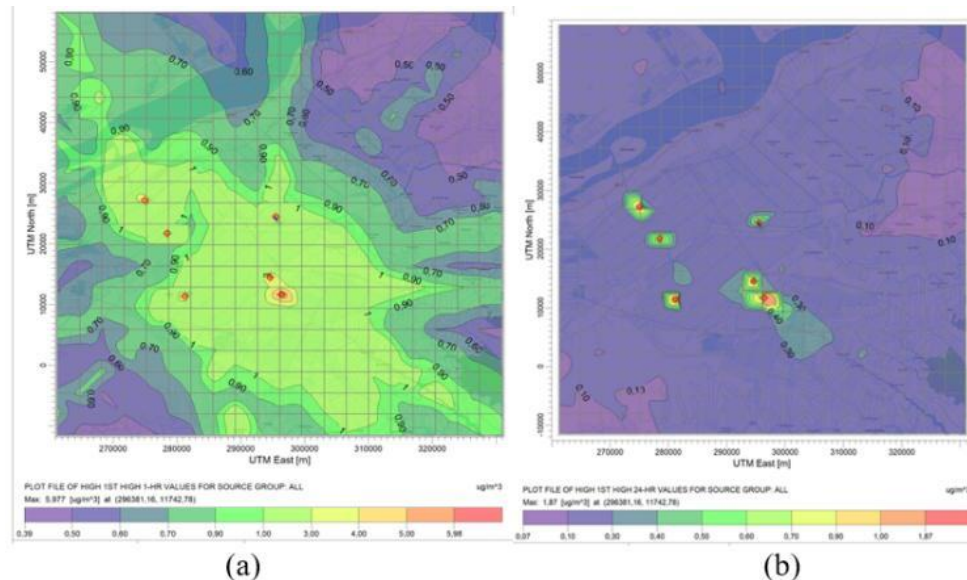


Figure 5 Dispersion of NO<sub>2</sub> Emissions from Boiler Chimneys at PT X in 2015-2024: (a) Maximum Hourly Concentration (MH), (b) Daily Maximum Concentration (MD).

Source: AERMOD, 2025

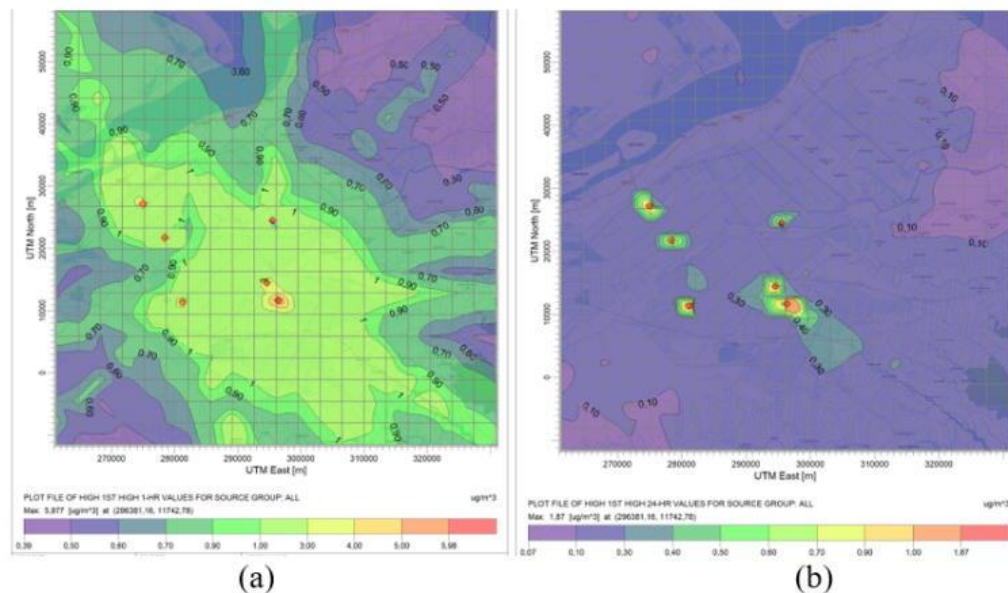


Figure 6 Dispersion of PM Emissions from Boiler Chimneys at PT X 2015-2024: (a) Maximum Hourly Concentration (MH), (b) Daily Maximum Concentration (MD)

Source: AERMOD, 2025

To validate the environmental compliance of the facility, the modeled maximum concentrations were benchmarked against the national ambient air quality standards mandated by the Ministry of Environment and Forestry (KLHK), as presented in Table 2.

Table 2. Comparison of Modeled Maximum Concentrations (Actual Conditions) vs. KLHK Standards

| Pollutant       | Modeled Max 1-Hour ( $\mu\text{g}/\text{m}^3$ ) | KLHK Standard 1-Hour ( $\mu\text{g}/\text{m}^3$ ) | Modeled Max 24-Hour ( $\mu\text{g}/\text{m}^3$ ) | KLHK Standard 24-Hour ( $\mu\text{g}/\text{m}^3$ ) |
|-----------------|-------------------------------------------------|---------------------------------------------------|--------------------------------------------------|----------------------------------------------------|
| SO <sub>2</sub> | 7,484                                           | 150                                               | 2.31                                             | 75                                                 |
| NO <sub>2</sub> | 5,977                                           | 200                                               | 1.87                                             | 65                                                 |
| PM              | 5,907                                           | -                                                 | 1.82                                             | 75                                                 |

The comparative analysis clearly indicates a massive safety margin. The maximum hourly concentration of SO<sub>2</sub> (7.484  $\mu\text{g}/\text{m}^3$ ) represents less than 5% of the 150  $\mu\text{g}/\text{m}^3$  regulatory limit. Similarly, NO<sub>2</sub> and PM concentrations remain exponentially below the maximum thresholds. This proves that the actual operating parameters of the current six boiler stacks are highly effective and environmentally secure.

### Hypothetical Simulation Scenarios: Optimization of Stack Parameters

To explore the aerodynamic optimization of the emissions and address theoretical dispersion dynamics, the study executed a series of hypothetical simulation scenarios. These scenarios mathematically isolated a single representative stack to evaluate how variations in stack height (45 to 70 m, at 5 m intervals) and gas exit velocity (15, 20, and 25 m/s) influence the maximum ground level pollutant concentrations. The consolidated numerical results of these simulations are presented in Table 3.

Table 3. Simulated Maximum Pollutant Concentrations under Varying Stack Heights and Exit Velocities

| Stack Height (m) | Gas Exit Velocity (m/s) | Max SO <sub>2</sub> (µg/m <sup>3</sup> ) | Max NO <sub>2</sub> (µg/m <sup>3</sup> ) | Max PM (µg/m <sup>3</sup> ) |
|------------------|-------------------------|------------------------------------------|------------------------------------------|-----------------------------|
| 45               | 15                      | 18                                       | 24                                       | 9                           |
| 45               | 20                      | 18                                       | 24                                       | 9                           |
| 45               | 25                      | 18                                       | 24                                       | 9                           |
| 50               | 15                      | 18                                       | 24                                       | 9                           |
| 50               | 20                      | 18                                       | 24                                       | 9                           |
| 50               | 25                      | 18                                       | 24                                       | 9                           |
| 70               | 15                      | 18                                       | 24                                       | 9                           |
| 70               | 20                      | 18                                       | 24                                       | 9                           |
| 70               | 25                      | 18                                       | 24                                       | 9                           |

(Note: Data extracted from hypothetical AERMOD scenario outputs)

As evidenced by the numerical data and supported by the line graphs in Figure 7, there is a consistent inverse correlation between stack height, exit velocity, and ground level concentrations. Increasing the physical height of the chimney elevates the point of emission, allowing the buoyant plume to disperse over a significantly larger atmospheric volume before settling.

Furthermore, variations in gas exit velocity dictate the initial vertical momentum of the plume. The simulations unequivocally demonstrate that a higher exit velocity (25 m/s) accelerates turbulent mixing and induces a higher effective plume rise compared to moderate (20 m/s) and low (15 m/s) velocities. Consequently, the combination of a 70 meter stack height operating at a 25 m/s exit velocity yielded the absolute lowest ground level concentrations across all evaluated pollutants. These hypothetical findings emphasize that mechanical adjustments to exhaust fans and stack elevations are highly viable engineering strategies for industries aiming to further mitigate their environmental footprint.

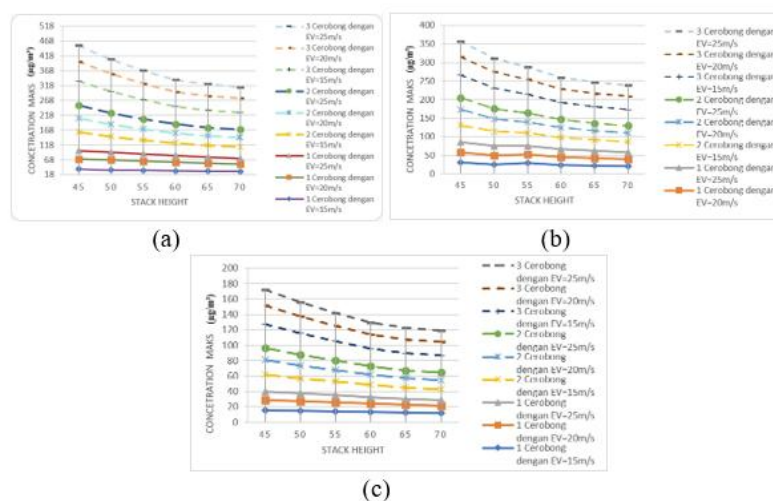


Figure 7. Simulation Results of the Effect of Variations in Chimney Height and Gas Exhaust Velocity on Maximum Concentration: (a) NO<sub>2</sub>, (b) SO<sub>2</sub>, (c) PM

## Conclusion

The height of the chimney and the speed of the gas output are two main factors that influence the distribution of pollutants in the air. Increasing the chimney height and gas output velocity has been proven to be able to increase the effective chimney height, so that the buoyancy force is more dominant in pushing the plume into the atmosphere. This condition causes the process of mixing pollutants with ambient air to take place better and has an impact on reducing the maximum concentration of pollutants.

Based on modeling results, in full operation of six boiler chimneys in palm oil mills, SO<sub>2</sub>, NO<sub>2</sub> and PM emission concentrations are still far below the ambient air quality standards set by the Ministry of Environment and Forestry (KLHK). Thus, it can be concluded that operating the boiler with the current chimney parameters is quite effective in reducing emission concentrations, so that it does not cause air pollution that exceeds environmental limits.

## Declaration of Generative AI Use

The authors employed OpenAI ChatGPT, with an implementation of GPT-5.6 Sol (OpenAI), as an academic language assistant and grammar editor during revision and preparation of this manuscript for clarity and coherence, as well as for the purposes of selecting passages for restructuring and grammatical correction and selecting sections for refinement, according to the suggestions of the reviewers. The tool was also used to enhance textual description of the AERMOD modelling procedure and presentation and interpretation of the reported simulation results. Emissions measurements, meteorological data, topographic data, operational parameters, receptor coordinates, and numerical modeling outputs were not generated nor obtained, operated, modified, fabricated or independently analyzed by Generative AI, AERMET, AERMAP, or AERMOD nor used to arrive at the scientific conclusions of the study. All content created with AI was critically reviewed, verified, and revised by the authors over the original data, modeling outputs, regulatory standards and cited sources. The final manuscript is the responsibility of the authors for accuracy, scientific interpretation, originality, and integrity.

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