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Evaluating Environmental and Public Health Risks of Medical Waste Incineration Using Air Dispersion Modeling in Indonesia

Ibnu Susanto Joyosemito[1*], Sophia Shanti Meilani[2], Muhammad Azmi[3]

[1] Magister of Science in Sustainability, Universitas Pertamina, Indonesia
[2] Department of Environmental Engineering, Universitas Bhayangkara Jakarta Raya, Indonesia
[3] Malaysian Institute of Industrial Technology, Universiti Kuala Lumpur, Malaysia
[*]Corresponding author: ibnu.susanto@universitaspertamina.ac.id

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ABSTRAK

Latar belakang: Pengembangan fasilitas pengolahan limbah medis tetap menjadi persoalan utama, terutama di wilayah yang memiliki infrastruktur yang belum memadai. Sebagai tanggapan atas masalah ini, pemerintah Indonesia telah merancang pembangunan insinerator limbah medis yang ditujukan untuk meningkatkan sistem penanganan limbah di dalam negeri. Meskipun proyek ini menjanjikan peningkatan dalam pengelolaan limbah, implikasi lingkungan dari insinerator perlu diperhatikan, khususnya yang berkaitan dengan penurunan kualitas udara ambien.

Metode: Penelitian ini menggunakan pendekatan pemodelan dispersi udara Gaussian untuk menganalisis pola penyebaran dan besarnya konsentrasi polutan udara yang dihasilkan dari spesifikasi insinerator limbah medis yang diusulkan. Investigasi difokuskan pada area pemukiman yang ada di dekatnya, berjarak 100 meter dari lokasi instalasi cerobong insinerator yang diusulkan, guna mempelajari dampak langsung terhadap populasi sekitar. Penelitian ini mensimulasikan dua skenario stabilitas atmosfer: 'sangat tidak stabil' (A) dan 'tidak stabil' (B) berdasarkan kondisi meteorologi tahunan di lokasi.

Hasil: Hasil penelitian menunjukkan bahwa lima parameter kualitas udara ambien utama—nitrogen dioksida (NO_2), sulfur dioksida (SO_2), karbon monoksida (CO), partikel tersuspensi total (TSP), dan timbal (Pb)—masih memenuhi Baku Mutu Udara Ambien Nasional (BMUAN) Indonesia dalam kedua skenario stabilitas atmosfer yang disimulasikan. Meskipun konsentrasi Pb dan NO_2 masih berada dalam batas yang diperkenankan BMUAN yaitu 2 $\mu g/m^3$ untuk Pb dan 200 $\mu g/m^3$ untuk NO_2, nilainya mendekati ambang batas regulasi. Dalam skenario terburuk, konsentrasi maksimum yang tercatat adalah 1,459 $\mu g/m^3$ untuk Pb (72,95% dari batas BMUAN) dan 128,840 $\mu g/m^3$ untuk NO_2 (64,42% dari batas BMUAN), temuan ini menegaskan pentingnya pemantauan kualitas udara secara berkala untuk memitigasi potensi risiko lingkungan.

Simpulan: Meskipun kelima parameter kualitas udara yang dianalisis masih berada dalam batas BMUAN, pemantauan berkala tetap diperlukan karena konsentrasi Pb dan NO_2 mendekati ambang batas regulasi. Studi ini menyoroti pentingnya strategi mitigasi, termasuk pemantauan kualitas udara jangka pendek dan panjang serta biomonitoring bagi populasi berisiko, untuk mengantisipasi dampak kesehatan akibat paparan kumulatif. Selain itu, hasil penelitian ini menunjukkan bahwa evaluasi dampak polutan berdasarkan variasi musiman dan kondisi cuaca ekstrem perlu dipertimbangkan dalam model dispersi udara guna meningkatkan akurasi prediksi. Penguatan regulasi emisi insinerator dalam Peraturan Pemerintah RI No. 22/2021, serta eksplorasi teknologi alternatif pengolahan limbah medis, seperti autoclaving dan pyrolysis, direkomendasikan untuk mendukung praktik pengelolaan lingkungan yang lebih berkelanjutan.

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Kata kunci: Limbah Medis; Insinerator; Kualitas Udara; Pemodelan Dispersi Udara; Persamaan Gaussian

ABSTRACT

Background: *The development of medical waste processing facilities remains a major issue, especially in areas with inadequate infrastructure. In response to this issue, the Indonesian government has initiated plans for a medical waste incinerator aimed at improving waste management practices in the country. While the project promises improvements in waste management, the environmental implications of the incinerator need to be addressed, particularly in relation to ambient air quality degradation.*

Method: *This study employs a Gaussian air dispersion modeling approach to analyze the dispersion patterns and magnitude of air pollutant concentrations emanating from the proposed medical waste incinerator specifications. Our investigation is focused on a nearby existing residential area located 100 meters from the proposed incinerator stack installation to study the immediate impact on nearby population. The study simulated two atmospheric stability scenarios: 'very unstable' (A) and 'unstable' (B) based on annual meteorological condition at site.*

Result: *The study revealed that concentrations of five key ambient air quality parameters—nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), total suspended particulate (TSP), and lead (Pb)— comply with Indonesia's National Ambient Air Quality Standards (INAQS) under both tested atmospheric stability scenarios. Although the concentrations of Pb and NO_2 remain within the permissible limits set by INAQS, which are 2 µg/m³ for Pb and 200 µg/m³ for NO_2, their values are approaching the regulatory thresholds. Under the worst-case scenario, the maximum concentrations recorded were 1.459 µg/m³ for Pb (72.95% of the INAQS limit) and 128.840 µg/m³ for NO_2 (64.42% of the INAQS limit),* these findings *highlight the need for continuous air quality monitoring to mitigate potential environmental risks.*

Conclusion: *Although the five analyzed ambient air quality parameters remain within the INAQS limits, regular monitoring is still required as Pb and NO_2 concentrations are approaching regulatory thresholds. This study highlights the importance of mitigation strategies, including short- and long-term air quality monitoring and biomonitoring for at-risk populations, to anticipate the health impacts of cumulative exposure. Furthermore, the findings indicate that the evaluation of pollutant impacts based on seasonal variations and extreme weather conditions should be incorporated into air dispersion models to enhance predictive accuracy. Strengthening emission regulations for incinerators under Government Regulation No. 22/2021, along with exploring alternative medical waste treatment technologies, such as autoclaving and pyrolysis, is recommended to support more sustainable environmental management practices.*

Keywords: Medical Waste; Incinerator; Air Quality; Air Dispersion Modeling; Gaussian Equation

INTRODUCTION

The growing demand for healthcare services in Indonesia, particularly during the COVID-19 pandemic, has driven the expansion of healthcare facilities. However, many of these facilities face persistent challenges in managing medical waste effectively[1]. The number of healthcare facilities in Indonesia has steadily increased over the past few years. In 2019, there were 2,877 hospitals and 10,134 community health centers (puskesmas), whereas by 2023, these figures had grown to 3,155 hospitals and 10,180 puskesmas[2,3]. This expansion has significantly contributed to the increase in medical waste generation, requiring a more effective waste management system. However, medical waste management in Indonesia continues to face major challenges, particularly in terms of technology and regulatory frameworks. Effective medical waste management continues to pose a serious challenge, especially in regions where waste infrastructure is inadequate. This issue is further intensified by limited awareness and insufficient training among healthcare personnel on standardized waste handling procedures[4]. As a result, improper disposal of medical waste, including direct release into the environmental and landfill deposition, has become a widespread concern. The COVID-19 pandemic has exacerbated this problem by significantly increasing the volume of infectious medical waste in healthcare facilities treating infected patients. A study by Andeobu et al. revealed that the COVID-19 pandemic led to a three- to fivefold increase in medical waste generation worldwide, including in Indonesia[5]. This waste consists of disposable masks, personal protective equipment (PPE), and infectious materials, placing additional strain on the already limited waste management system.

To tackle these urgent issues, the Indonesian government has initiated plans to develop medical waste treatment facilities, such as incinerators, as part of efforts to strengthen waste management systems. These facilities aim to fill existing gaps in medical waste handling, support environmental preservation, and reduce potential health hazards for the public. The use of incineration technology offers several advantages, including the reduction of waste volume, overall mass, and hazardous properties of solid waste streams[6,7]. These facilities aim to address current gaps in medical waste disposal, protect the environmental protection, and reduce public health risks. However, as with any technological intervention, the implementation of medical waste incineration technology also raises valid concerns about potential environmental impacts, particularly regarding air quality degradation[8–10]. Incineration processes release a range of air pollutants into the environment, including nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), particulate matter (PM), and other hazardous substances. These pollutants can degrade ambient air quality and subsequently pose potential health risks to communities living near the incinerator facilities[11,12]. Thus, assessing these impacts is crucial before implementing incinerator facilities at scale.

This study aims to quantitatively assess the environmental impact of medical waste incineration on ambient air quality using Gaussian air dispersion modeling. Specifically, focusing on predicting the dispersion patterns and concentrations of air pollutants emitted from the proposed incinerator, with a keen interest in the immediate impact on a nearby residential area located 100 meters from the incinerator, identified as the key receptor site for potential air quality degradation. This study employs a Gaussian air dispersion modeling approach to simulate the distribution of pollutants under different atmospheric stability scenarios. The analysis centers on key ambient air quality parameters, including NO_2, SO_2, CO, total suspended particulate (TSP), and lead (Pb), which are pivotal in evaluating compliance with Indonesia's National Ambient Air Quality Standard (INAAQS) as regulated under Government Regulation No. 22/2021[13]. Furthermore, the study supplement the assessment with mass balance data obtained during the incinerator's operational trial. These data were subsequently compared with existing air quality monitoring parameters measured at the designated impact point, located approximately 100 meters away form the proposed incinerator stack site prior to its operation (see Figure 1). This integration of modeled emissions and real-world air quality observations strengthens the validity of the air dispersion model and enhances the credibility of the environmental impact assessment. Through this comprehensive study, we aim to highlight potential environmental and health risks associated with medical waste incineration, which may inform future air quality management practices and support the development of more sustainable waste management strategies. Given that the Indonesia’s National Ambient Air Quality Standards (IDN-NAAQS) are outlined in Government Regulation No. 22/2021 on Environmental Protection and Management, this study provides a scientific basis for evaluating the compliance of incinerator emissions with national air quality limits. The findings will support the development of more stringent emission control measures and offer recommendations for improving medical waste management policies to minimize environmental and public health risks.

MATERIALS AND METHODS

This study utilized a combination of primary and secondary data sources. Primary data were collected through direct ambient air quality sampling in the study area and from unpublished technical documents, including engineering design files and laboratory analyses related to the incinerator's heat and mass balance. Sampling was conducted at the proposed incinerator site in Barru Regency, South Sulawesi with a reference point of 4°23'05.7" South Latitude (S) and 119°37'02.8" East Longitude (E) and within a 100-meter radius, covering the nearest residential area at 4°23'7.59"S, 119°37'5.63"E. Air quality sampling took place in May 2022 at multiple locations (4°23'3.81"S, 119°37'3.29"E; 4°23'7.59"S, 119°37'5.63"E; 4°23'5.63"S, 119°37'2.14"E; 4°23'7.59"S, 119°37'5.63"E; 4°23'6.38"S, 119°37'0.45"E) to ensure representativeness under varied meteorological conditions. Pollutant concentrations were measured following standard protocols outlined in Standar Nasional Indonesia (SNI) 19-7119.6-2005. All laboratory analyses, including heat and mass balance assessments, were conducted by a certified environmental laboratory, ensuring compliance with national regulatory standards. Secondary data was obtained through an extensive review of literature and online databases, including meteorological records from the Indonesia Meteorology, Climatology, and Geophysics Agency (IDN-MCGA) Class 1 Maros station[14], covering temperature, humidity, wind speed, wind direction, and precipitation. To ensure data credibility and compliance, primary data sources were derived from accredited third-party laboratories that adhere to national environmental standards. These procedures ensure that the data used in this study is representative of real-world conditions and suitable for dispersion modeling.

Figure 1. Satellite image for the planned location of the incinerator and the nearest residential area (100 meters away from the planned incinerator stack).

1. Air Dispersion Modeling

Simulation approaches are recognized as effective tools for decision-making in environmental studies, aligning with findings by Prasad et.al[15].

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Leveraging existing environmental datasets in specific case studies adds substantial value, but it is imperative to address uncertainties within these cases, as emphasized by Sütçü[16]. Moreover, employing multiple evaluation software tools, as advocated by Khoo el.al and Foszcz, enhances the comprehensiveness of decision assessments[17,18]. In presenting environmental impact studies, graphical representations, as demonstrated by Capgras et.al, Palmer, and Yalcinkaya, play a pivotal role in conveying complex environmental data effectively[19–21]. This study constructed an air dispersion model based on the Gaussian equation which is most commonly used to describe mathematically the three-dimensional patterns of continuous, buoyant air pollution plumes, which is in line with methods by Zhao et.al, Tian et.al, and Tang et.al[22–24].

The equation (Table 1) is implemented in Analytica Educational Professional (AEP 5.4.6)[25] which focused on algorithms for air dispersion model application. Furthermore, meteorological factors, spatial dispersion patterns, and magnitude of air pollutant concentration are modeled using Wind Rose Plots for Meteorological Data View (WRPLOT 8.0.2)[26] and Arc Geographic Information System (ArcGIS 10.8)[27]. These software tools are further integrated with Google Earth Pro software (GEP 2023)[28] for improved visualization of models outputs via geospatial imagery. The integration of these four software tools, this study comprehensively analyzed and processed the necessary data, facilitating a comprehensive assessment of air pollution dispersion patterns, thus supporting a more detailed environmental assessment.

Table 1. Mathematical equation for the air dispersion model

Variables	Equation
Dispersed air pollutant concentration ($\Delta C_{(x,y,z)}$) [µicrogram/meter^3 -µg/m^3]	= $\frac{Q}{2\pi\sigma_y\sigma_z U_z} \exp\left[-0.5\left(\frac{y}{\sigma_y}\right)^2\right] x \left\{\exp\left[-0.5\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-0.5\left(\frac{z+H}{\sigma_z}\right)^2\right]\right\}$ where: $\Delta C_{(x,y,z)}$ = Air pollutant concentration at some point in space with coordinates x, y, z. Q = Emission rate of the pollutant source [µg/s] Uz = Wind speed [m/s] σ_y = Standar deviation of the plume in the y direction [m] σz = Standar deviation of the plume in the z direction[m] π = phi (3.14) H = Effective stack height [m] x = Downwind distance from the emission source point [m] y = Crosswind distance from the emission plume centerline [m] z = Vertical distance from ground level [m]
Wind speed at stack height (U_z) [meter/second -m/s]	= $U_0 \left(\frac{Z_e}{Z_0}\right)^P$ where: U_0 = measured wind speed [m/s] Z_0 = sampling elevation from ground [m] Z_e = effective elevation [m] P = wind speed exponential according to atmospheric stability
Standard deviation of the concentration in the horizontal or the vertical (σ_y or $_z$) [m]	= $\exp(I + J(\ln x) + K(\ln x)^2)$ where: *ln x* = Natural log of downwind distance [kilometer –km] I, J, K = Empirical constants according to atmospheric stability
Effective stack height (H) [m]	= $h_s + \Delta h$ where: h_s = Physical stack height [m] Δh = Plume rise [m]
Plume rise (Δh) [m]	= $\frac{V_s \cdot d_s}{U_z}\left[1.5 + 2.68 \times 10^{-3} P_a \frac{T_s - T_a}{T_s} d_s\right]$ where: V_s = Stack gas emission velocity [m/s] d_s = Stack diameter [m] Uz = Wind speed at stack height [m/s] T_s = Stack gas emission temperature [Kelvin –K] T_a = Atmospheric temperature [K] P_a = Atmospheric pressure [millibar –mbar] 2,68x10^{-3} = Constant [m^{-1} mbar^{-1}]
Atmospheric pressure (Pa) [centimetres of mercury –cmHg]	= (Pu – h/100) where: Pu = Atmospheric pressure at sea level [=76 cmHg] h = Vertical height [m] $^{*)}$ 1 [cmHg] = 13.332239 [mbar]
Pollutant concentration in ambient air (C) [µg/m^3]	= $C_0 + \Delta C_{(x,y,z)}$ where: C_0 = Initial pollutant concentration in ambient air [µg/m^3] ΔC = Dispersed air pollutant concentration from the stack [µg/m^3]

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2. Data and Simulation

Meteorological data spanning over a decade (2012–2022) was obtained from the Indonesia Meteorology, Climatology, and Geophysics Agency (IDN-MCGA) Class 1 Maros station. This dataset includes temperature, humidity, wind speed, wind direction, and precipitation, which are essential parameters for air dispersion modeling. The meteorological data was processed using WRPLOT 8.0.2 to generate wind distribution patterns, dominant wind directions, and wind speed variations across different directions. The analysis of this dataset indicates an annual average wind speed of 1.99 m/s, with a standard deviation of 10.63 m/s. Based on this, the atmospheric stability within the study area can be categorized as either very unstable (A) or unstable (B) under varying sunshine conditions. These classifications encompass a spectrum of strong, moderate, and slight stability conditions following recommendations by Weiner & Matthews and Cooper & Alley[29,30]. Consequently, two primary scenarios are simulated to differentiate between the atmospheric stability classes: very unstable (Scenario A) and unstable (Scenario B).

Table 2 provides a comprehensive inventory of both primary and secondary data utilized for modeling purposes. It is crucial to acknowledge that certain data inputs adhere to specific probability distributions. Consequently, the projections in this study concerning spatial dispersion patterns and air pollutant concentration levels originating from the proposed incinerator not only yield deterministic values but also incorporate an element of uncertainty, resulting in probabilistic outcomes. To comprehensively address the multitude of uncertainty sources inherent in this air dispersion model, the study employs a simultaneous Monte Carlo sampling technique embedded within the AEP 5.4.6 software. The Monte Carlo method systematically samples from input probability distributions to generate probability estimates of pollutant concentrations. The model was configured to run 1,000 random simulations, producing maximum, mean (average), and minimum estimates. By integrating stochastic variability in model simulations, this approach ensures that model predictions account for a realistic range of possible outcomes, enhancing the robustness of the air quality impact assessment.

Table 2. Input data for the air dispersion model simulation

No.	Data	Value	Remarks
1	Physical stack dimention		Engineering drawing for proposed stack design
	Height (hs)	24.650 [m]	
	Diameter (ds)	1.508 [m]	
2	Stack gas emission velocity (v_s)	11.68 [m/s]	
3	Stack gas emission temperature (Ts)	473.15 [K]	
4	Mass transfer coefficient of Stack gas emission		Heat and mass balance data for proposed incinerator design (unpublished documents)
	Nitrogen oxide (NO_2)	0.7765	
	Sulphur oxide (SO_2)	0.043953	
	Carbon monoxide (CO)	0.014651	
	Total Suspended Particulate (TSP)	0.043953	
	Lead (Pb)	0.00879	
5	Atmospheric temperature (Ta)	Normal distribution (mean= 300.49 ; SD= 0.73) [K]	2012-2021 Data Processing[14]
6	Measured wind speed (U_0)	Normal distribution (mean= 1.99 ; SD= 0.63) [m/s]	
7	Atmospheric pressure (Pa)	1010 [mbar]	Estimated Pa at stack height (Eq.6)
8	Emission rate of the pollutant source(Q)	134841.67 [μg/s]	Heat and mass balance data for the proposed incinerator design
9	Wind speed sampling height from ground (Z_0)	10 [m]	Weiner & Matthews[29] Meteorological Equipment[31]
10	Effective emission height (Ze)	25 [m]	Engineering drawing for proposed stack design
11	Wind speed exponential of the atmospheric stability (P) for class A and B	0.07	Cooper & Alley[30]
12	Downwind distance from the emission source point (x)	20-1000 [m]	Distance for model simulation
13	Crosswind distance from the emission plume centerline (y)	20-240 [m]	
14	Vertical distance from ground level (z)	1-5 [m]	Height of impacted recipient for model simulation
15	Standard deviation of the concentration in the horizontal (σy)	Empirical constants according to atmospheric stability class A	McMullen and Johansson et.al[32,33]
	I	5.357	
	J	0.8828	
	K	-0.0076	
16	Standard deviation of the concentration in the horizontal or the vertical (σz)	Empirical constants according to atmospheric stability class A	
	I	6.035	
	J	2.1097	
	K	0,2770	

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No.	Data	Value	Remarks
17	Standard deviation of the concentration in the horizontal (σy)	Empirical constants according to atmospheric stability class B	
	I	5.058	
	J	0.9024	
	K	-0.0096	
18	Standard deviation of the concentration in the vertical (σz)	Empirical constants according to atmospheric stability class B	
	I	4.694	
	J	1.0629	
	K	0.0136	
19	Initial pollutant concentration in ambient air (C_0)		Analysis of ambient quality monitoring in the residential area (100 meters away from the incinerator stack with reference of 4°23'7.59" South Latitude and 119°37'5.63" East Longitude
	C_0 NO_2	7 [$\mu g/m^3$]	
	C_0 SO_2	25 [$\mu g/m^3$]	
	C_0 CO	229 [$\mu g/m^3$]	
	C_0 TSP	31 [$\mu g/m^3$]	
	C_0 Pb	0.08 [$\mu g/m^3$]	

RESULT AND DISCUSSION

To enhance the reliability of the air dispersion model in this study, two model validation techniques, dimensional consistency and reference mode reproduction testing suggested by Sterman[34] were applied to evaluate the model's structure and behavioral fidelity in simulating pollutant spatial dispersion patterns and air pollutant concentrations. The dimensional consistency check was carried out by reviewing the mathematical formulas and primary and secondary data to ensure that all variables were expressed in compatible units. Inconsistencies in unit dimensions can result in erroneous model outputs and undermine the credibility of the simulation. To perform this test, variables listed in Table 1 were cross-checked against the input data summarized in Table 2 to verify unit consistency. Reference mode reproduction testing was evaluated by comparing the model simulation results to established reference modes, which may include graphical trends, behavior patterns, or other descriptive data depicting pollutant dispersion patterns based on atmospheric stability classes. Figure 2 presents this comparison, with the reference mode shown on the left and the corresponding model output on the right. As previously discussed, the atmospheric stability at the study location is classified as very unstable (Scenario A) and unstable (Scenario B). The model output correspondingly indicates a greater vertical dispersion of pollutants. This dispersion behavior is consistent with the expected dynamics of atmospheric stability under unstable classification in the reference mode, as indicated by the graph showing higher air turbulence in the vertical direction compared to neutral and stable atmospheric conditions. Based on Figure 2, the model developed in this study successfully reproduces pollutant dispersion typical pollutant dispersion behavior observed in real systems under different atmospheric stability classifications. Thus, this confirms that the model has accurately replicated the reference mode, demonstrating reliable behavioral consistency with real-world conditions.

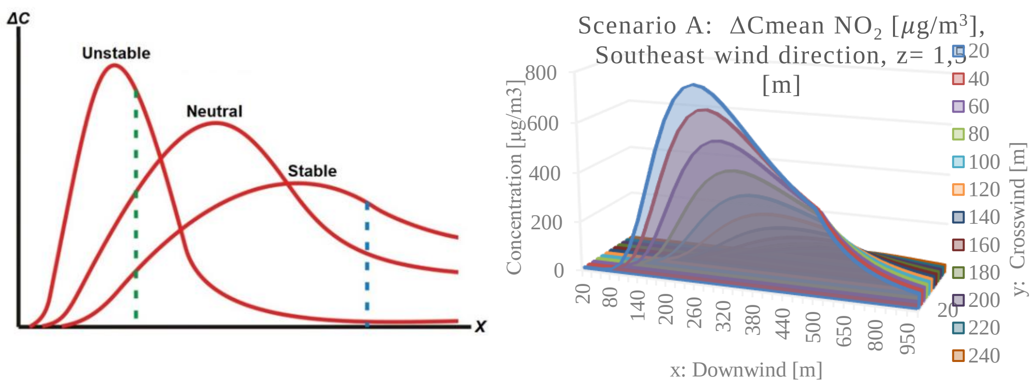

Figure 2. Comparison between the reference mode for the pollutant dispersion pattern based on atmospheric stability classification (left)[30,35] and the model output of this study showing the dispersion patterns of NO_2 emission concentration from the proposed incinerator stack toward the nearest residential area under scenario A (right)

Meteorological data covering the period from 2012 to 2021 with monthly, daily, and hourly observations were processed using WRPLOT 8.0.2, and visualized through the GEP. The use of high-resolution data allows for a more detailed assessment of wind patterns, capturing short-term variations that

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influence pollutant dispersion. Figure 3 and Figure 4 depict the wind rose at the proposed incinerator plant location, illustrating prevailing wind directions and frequencies. By considering six dominant wind directions, the simulation projects that pollutant emissions from the proposed incinerator stack will likely disperse: 53.6% toward the Northwest (315^0), 18% to the Southwest (45^0), 8.6% to the Northeast (45^0), 8.2% to the Southeast (135^0), 2.6% to the South (180^0), and 2.5% to the North (0^0). The two farthest dispersion distances are in the Northwest and the Southwest, with pollutant emissions potentially reaching 999.25 m at wind speeds ranging from 0.5 to 8.8 m/s and 336.81 m at wind speeds between 0.5 and 5.7 m/s, respectively. Importantly, pollutant emissions that move toward or potentially affect the nearest residential area transported under southeasterly wind conditions, reaching up to 153.77 m with a speeds ranging from 0.5 to 3.6 m/s.

Tables 3 and 4 present the estimated average and maximum dispersed concentrations (ΔC) of NO_2 emissions originating from the incinerator stack under Southeasterly wind conditions. These estimations are based on a receptor height of 1.5 meters, reflecting the simulation results under atmospheric stability scenario A. To calculate the pollutant concentration in the ambient air (C) of NO_2, ΔC values from Tables 3 and 4 are added to the background concentration C_0 (as provided in Table 2, No.19), in accordance with Eq. 7 in Table 1. Figure 4 visualizes these average and maximum C values for NO_2 at the nearest residential area under scenario A conditions. While full model results for all pollutants are not shown, Table 5 provides a consolidated summary of the modeled concentrations (C) for all five target parameters at the residential impact point under both scenarios A and B, along with their comparison to the applicable INAAQS limits.

The model results indicate that, for all five parameters, under both scenarios A and B, the simulated ambient concentrations (C) for both average and maximum values remain within the permissible limits defined by the applicable ambient air quality regulations. Notably, concentrations observed under scenario A are consistently higher than those under scenario B across all parameters. When focusing on the maximum concentrations under scenario A, the pollutants ranked closest to the INAAQS thresholds are, in order: Pb, NO_2, SO_2, TSP, and CO. Among these, Pb and NO_2 warrant particular attention, as their concentrations approach the regulatory limits more closely than the others (see Table 5).

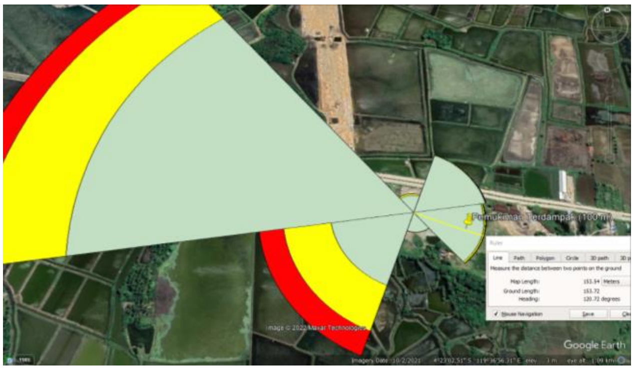

Figure 3. Geospatial visualization for the wind rose at the proposed incinerator plant location (reference point: 4°23'05.7" S and 119°37'02.8" E.

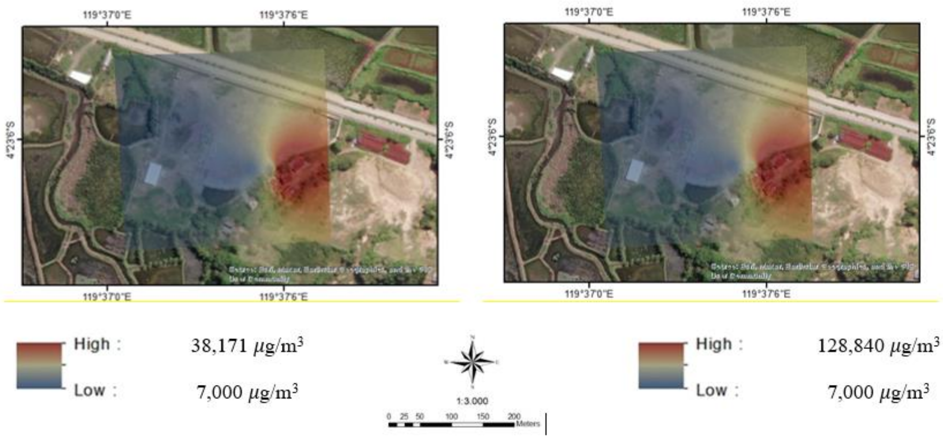

Figure 4. Geospatial visualization for the pollutant concentration in ambient air ($C = \Delta C_{x,y,z} + C_0$) of NO_2 under Southeasterly wind direction (135°), showing average values (left) and maximum values (right) at the nearest residential area, located 100 meters from the incinerator stack (reference point: 4°23'7.59" S, 119°37'5.63" E.

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Table 3. Estimated average dispersed concentration of NO_2 ($\mu g/m^3$) from the incinerator stack ($\Delta C_{x,y,z}$) to the Southeasterly wind conditions under scenario A

Crosswind (y) [m]	Scenario A: $\Delta C_{(x,y,z)}$ Average NO_2 [$\mu g/m^3$], southeast wind direction, z= 1,5 [m]												
20	$6x10^{-10}$	$2x10^{-5}$	0.007	0.381	5.39	504.6	763.2	566.9	369.3	272.7	180.7	123.8	87.45
40	$4x10^{-37}$	$1x10^{-12}$	$8x10^{-5}$	0.044	1.513	378.3	670.5	526.1	351.6	262.3	175.6	121	85.9
60	$2x10^{-82}$	$8x10^{-25}$	$4x10^{-8}$	0.001	0.182	234.1	540.5	464.5	323.9	246	167.4	116.6	83.4
80	$9x10^{-146}$	$7x10^{-42}$	$8x10^{-13}$	$8\ x10^{-6}$	0.009	119.5	399.6	390.2	288.8	224.9	156.6	110.8	80.01
100	$3x10^{-227}$	$9\ x10^{-64}$	$8\ x10^{-19}$	$1\ x10^{-8}$	$2x10^{-4}$	50.38	271.1	311.9	249.2	200.3	143.7	103.6	75.85
120	0	$1\ x10^{-90}$	$4x10^{-26}$	$4\ x10^{-12}$	$2x10^{-6}$	17.52	168.7	237.2	208.1	173.9	129.4	95.52	71.07
140	0	$3x10^{-122}$	$1x10^{-34}$	$4\ x10^{-16}$	$8\ x10^{-9}$	5.03	96.27	171.6	168.2	147.2	114.3	86.76	65.8
160	0	$9\ x10^{-159}$	$1x10^{-44}$	$7\ x10^{-21}$	$1\ x10^{-11}$	1.192	50.41	118.1	131.6	121.4	99.09	77.65	60.2
180	0	$4\ x10^{-200}$	$5x10^{-56}$	$4\ x10^{-26}$	$1\ x10^{-14}$	0.233	24.22	77.36	99.59	97.56	84.25	68.47	54.43
200	0	$2\ x10^{-246}$	$1x10^{-68}$	$4\ x10^{-32}$	$3\ x10^{-18}$	0.038	10.67	48.21	72.95	76.43	70.28	59.49	48.63
220	0	$1\ x10^{-297}$	$1\ x10^{-82}$	$1\ x10^{-38}$	$5x10^{-22}$	0.005	4.313	28.58	51.72	58.36	57.52	50.93	42.94
240	0	0	$7\ x10^{-98}$	$7\ x10^{-46}$	$3x10^{-26}$	$6x10^{-4}$	1.6	16.12	35.48	43.43	46.19	42.96	37.47
Downwind (x) [m]	20	40	60	80	100	200	300	400	500	600	700	800	900

Table 4. Estimated Maximum dispersed concentration of NO_2 ($\mu g/m^3$) resulted from the incinerator stack ($\Delta C_{x,y,z}$) to the Southeast wind conditions under scenario B

Crosswind (y) [m]	Scenario B: ΔC(x,y,z) Average NO2 [μg/m3], southeast wind direction, z= 1,5 [m]												
20	$8x10^{-9}$	$5x10^{-4}$	0.129	3.942	33.2	652.2	846.1	835.1	652.9	511.4	354.4	248.1	177.4
40	$6\ x10^{-36}$	$3x10^{-11}$	0.001	0.454	9.32	489	743.4	775	621.6	492.1	344.4	242.6	174.3
60	$3\ x10^{-81}$	$2x10^{-23}$	$6\ x10^{-7}$	0.012	1.122	302.5	599.2	684.3	572.7	461.5	328.3	233.8	169.2
80	$1x10^{-144}$	$2x10^{-40}$	$1x10^{-11}$	$8x10^{-5}$	0.058	154.5	443	574.9	510.7	421.8	307.1	222	162.3
100	$4x10^{-226}$	$2x10^{-62}$	$1x10^{-17}$	$1x10^{-7}$	0.001	65.11	300.5	459.5	440.7	375.8	281.8	207.7	153.9
120	0	$3x10^{-89}$	$7x10^{-25}$	$4x10^{-11}$	$1x10^{-5}$	22.65	187	349.4	368	326.2	253.8	191.5	144.2
140	0	$7x10^{-121}$	$2x10^{-33}$	$4x10^{-15}$	$5x10^{-8}$	6.501	106.7	252.8	297.4	276.1	224.2	173.9	133.5
160	0	$2x10^{-157}$	$2x10^{-43}$	$8x10^{-20}$	$9x10^{-11}$	1.54	55.89	174	232.6	227.7	194.3	155.7	122.1
180	0	$8x10^{-199}$	$9x10^{-55}$	$4x10^{-25}$	$6x10^{-14}$	0.301	26.85	114	176.1	183	165.2	137.3	110.4
200	0	$5x10^{-245}$	$2x10^{-67}$	$4x10^{-31}$	$2x10^{-17}$	0.049	11.83	71.02	129	143.4	137.8	119.3	98.66
220	0	$3x10^{-296}$	$2x10^{-81}$	$1x10^{-37}$	$3x10^{-21}$	0.006	4.782	42.11	91.44	109.5	112.8	102.1	87.11
240	0	0	$1x10^{-96}$	$7x10^{-45}$	$2x10^{-25}$	$7x10^{-4}$	1.773	23.75	62.73	81.47	90.57	86.13	76.01
Downwind (x) [m]	**20**	**40**	**60**	**80**	**100**	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**

Table 5. Dispersed ambient air pollutant concentration (C = ΔCx,y,z + C0) toward the nearest residential area under southeasterly wind conditions, with comparison to INAQS thresholds

Parameter	**$C_{x,y,z}$ under southeasterly wind direction (135^0) at the nearest residential area: downwind (x)= 100[m], crosswind (y)= 20[m], a receptor height (z)= 1.5 [m] [µg/m^3]**				**INAAQS [µg/m^3]** [11]
	Scenario A		**Scenario B**		
	Average	**Maximum**	**Average**	**Maximum**	
NO_2	38.171	128.84	7.61	12.841	200
SO_2	26.764	31.896	25.,34	25.331	150
CO	229.588	231.299	229.011	229.11	10,000
TSP	32.764	37.897	31.035	31.331	230
Pb	0.433	1.459	0.087	0.146	2

Furthermore, among these two parameters, Pb requires particular attention due to its concentration nearing the INAAQS threshold (recorded at 1.459 µg/m^3, compared to the standard limit of 2 µg/m^3). Once absorbed into the human body, Pb is distributed through the bloodstream and stored primarily in the bones, where it can exert harmful effects on the nervous system, kidneys, immune function, reproductive and developmental processes, as well as cardiovascular health. Environmentally, Pb is highly persistent , contributing to reduced growth and reproduction in flora and fauna, and causing neurotoxic effects in vertebrate species[36]. While the health and environmental effects of NO_2 are well-documented, this gas is known to irritate the airways, with short-term exposure exacerbating respiratory diseases particularly asthma, leading to symptoms like coughing, wheezing, and difficulty breathing. Environmentally, NO_2 reacts with water, oxygen, and other atmospheric chemicals, contributing to acid rain and photochemical smog, which degrades visibility and air quality[37]. Although the model projections

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suggest that the proposed incinerator activities currently pose no significant impact on the nearest residential area, the potential long-term risks associated with Pb and NO_2 emissions necessitate continuous vigilance and the implementation of proactive mitigation strategies to safeguard both environmental and public health.

To mitigate the potential risks associated with Pb and NO_2 emissions, several proactive strategies should be implemented. Regular ambient air quality monitoring is essential to track pollutant concentrations over time, considering meteorological influences, including seasonal variations (rainy and dry seasons) and climate change effects, which can significantly alter dispersion patterns. In addition to environmental monitoring, biomonitoring programs should be established for at-risk populations. Periodic blood lead level testing is particularly important for children due to their heightened susceptibility to lead toxicity. Similarly, regular respiratory health assessments for local residents, especially those with pre-existing conditions can provide valuable insights into long-term exposure effects. Raising community awareness about air pollution risks is another critical step. Public health campaigns should be conducted to educate residents on exposure risks and encourage protective measures, such as limiting outdoor activities during high-pollution events. From a policy and technological perspective, implementing stricter emission thresholds and promoting low-emission waste treatment technologies are essential to minimizing long-term health risks. Further epidemiological studies should be conducted to assess the cumulative impact of emissions on public health, providing a scientific basis for future regulatory improvements and environmental management strategies.

The findings of this study suggest that while the estimated pollutant concentrations from the proposed incinerator remain within regulatory limits, the proximity of Pb and NO_2 levels to INAQS thresholds indicates a potential risk that warrants regular and targeted monitoring. The reliance on incineration for medical waste disposal should be carefully reconsidered, particularly in densely populated areas, where pollutant dispersion could pose long-term health hazards. Alternative medical waste treatment technologies, such as autoclaving, pyrolysis, or plasma gasification, should be explored as potentially safer and more sustainable waste management options. These findings further reinforce the need for stringent environmental regulations and continuous advancements in emission control technologies to minimize adverse public health effects.

CONCLUSION

This study's air dispersion model demonstrates that, even when accounting for uncertainty, the concentrations of five air pollutants in the nearest residential area under both very unstable and unstable atmospheric stability conditions, remain within the INAAQS limits as regulated under Government Regulation No. 22/2021. Nevertheless, it is important to underscore that while the incinerator activities currently pose no substantial adverse impact, continuous monitoring and management of ambient air quality in nearby residential zones remain essential. This is particularly critical for pollutants such as Pb and NO_2, whose concentrations are approaching their regulatory thresholds and may pose long-term health and environmental risks if not properly controlled.

Despite utilizing high-resolution meteorological datasets (monthly, daily, and hourly observations), this study does not fully capture short-term extreme weather events that could temporarily alter pollutant dispersion patterns. Future research should integrate real-time weather simulation models to refine predictive accuracy, particularly under extreme meteorological conditions. Additionally, given that Indonesia experiences two distinct seasons (dry and rainy seasons), further studies should assess seasonal variations in pollutant dispersion patterns and concentration fluctuations to enhance environmental impact evaluations. If future estimations indicate pollutant concentrations exceeding safe limits, environmental risk assessments must be conducted to evaluate potential health hazards in nearby communities. Both short-term and long-term air quality monitoring, along with biomonitoring of at-risk populations, is crucial to understanding the cumulative health effects of incinerator emissions. These findings highlight the importance of proactive emission management, stricter regulatory frameworks, and the exploration of alternative medical waste treatment technologies to ensure sustainable environmental practices in Indonesia.

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