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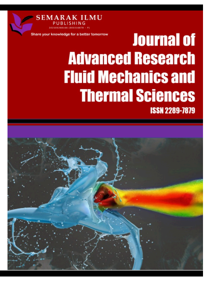

Clearing the Air: Assessing Air Quality Impact from A Proposed Medical Waste Incinerator Using Gaussian Dispersion Modeling

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ABSTRACT

The increase of medical waste is a critical concern in regions grappling with limited infrastructure. Indonesia responds to this challenge by proposing a medical waste incinerator to enhance their waste management practices. However, it is the important to evaluate potential environmental repercussions, in particular air quality degradation. This study employs a Gaussian air dispersion modeling approach to analyse the dispersion patterns and magnitude of air pollutant concentrations emanating from the proposed medical waste incinerator. Our investigation is focused on a nearby existing residential area located 100 meters from the proposed incinerator stack installation to study the immediate impact. The study simulated two atmospheric stability scenarios: 'very unstable' (A) and 'unstable' (B) based on annual meteorological condition at site, highlighting the adherence of five key ambient air quality parameters—Nitrogen Dioxide (NO2), Sulfur Dioxide (SO2), Carbon Monoxide (CO), Total Suspended Particulate (TSP), and Lead (Pb)— against Indonesia's National Ambient Air Quality Standard (INAQS) within both atmospheric stability scenarios. Notably, the concentrations of Pb and NO2, while below INAQS limits, is approaching the threshold levels with peaks of 1.459 μg/m³ and 128.840 μg/m³. Although results comply with local regulation, significance of continuous vigilance in air quality management emerges.

1. Introduction

The increasing demand for healthcare services in Indonesia has led to a proliferation of healthcare facilities [1], many of which struggle with effective medical waste disposal practices. The proper management of medical waste remains a critical challenge in regions characterized by limited waste infrastructure. This challenge is compounded by inadequate waste management infrastructure and a lack of awareness and training in medical waste handling [2], [3]. As a result, improper disposal of medical waste, including direct environmental release and landfill deposition, has become a prevailing issue in the country. The severity of this problem is further exacerbated by the ongoing

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COVID-19 pandemic, which has escalated the generation of medical waste, particularly in healthcare facilities dealing with infected patients.

The increasing demand for healthcare services in Indonesia has led to a proliferation of healthcare facilities, many of which struggle with effective medical waste disposal practices [4]. The proper management of medical waste remains a critical challenge in regions characterized by limited waste infrastructure. This challenge is compounded by a lack of awareness and training in medical waste handling [5]. As a result, improper disposal of medical waste, including direct environmental release and landfill deposition, has become a prevailing issue in the country. The severity of this problem is further exacerbated by the ongoing COVID-19 pandemic, which has escalated the generation of medical waste, particularly in healthcare facilities dealing with infected patients [6], [7].

In response to these pressing challenges, the Indonesian government has proposed the establishment of medical waste treatment facilities, including incinerators, as a means to improve waste management practices. These facilities are intended to address the existing gaps in medical waste disposal, enhance environmental protection, and mitigate public health risks. The proposed incineration method offers several benefits, including the reduction of waste volume, mass, and hazardous content [8], [9].

However, as with any technological intervention, the implementation of medical waste incinerators raises valid concerns about potential environmental impacts, particularly in terms of air quality degradation [10], [11], [12]. Incineration processes emit various pollutants into the atmosphere, including nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), particulate matter (PM), and other harmful substances. These emissions have the potential to affect ambient air quality and subsequently impact the health and well-being of nearby communities [13], [14].

This research aims to address the critical need for assessing the potential environmental consequences of medical waste incineration on air quality. Specifically, we focus on 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. Our study employs a Gaussian air dispersion modeling approach to predict the distribution of pollutants in 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).

Furthermore, the study supplements the assessment with mass balance data obtained during the incinerator's operational trial. These data are then compared with existing air quality monitoring parameters at the 'point of impact' before the incinerator's operation, which situated 100 meters away from the incinerator stack site (see Figure 1). By conducting this comprehensive study, we aim to shed light on the potential risks and environmental impact associated with medical waste incineration, ultimately contributing valuable insights to the field of air quality management.

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

2. Methodology

2.1 Air Dispersion Modeling

Simulation approaches are recognized as effective tools for informed decision-making in environmental studies, aligning with findings by Prasad et al. [15]. 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 et al. [17] and Foszcz, Niedoba, and Siewior [18], enhances the comprehensiveness of decision assessments. In presenting environmental impact studies, graphical representations, as demonstrated by Capgras, Barhebwa Mushamuka, and Feuilleaubois [19], Palmer [20], and Yalcinkaya [21], play a pivotal role in conveying complex environmental data effectively.

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. [22] Tian, Liang, and Li [23], and Tang, McNabola and Misstear [24]. The equation (Table 1) is implemented in Analytica Educational Professional (AEP 5.4.6) which focused on algorithms for air dispersion model application. Furthermore, meteorological factors, spatial dispersion pattern, and magnitude of air pollutant concentration are modeled using Wind Rose Plots for Meteorological Data View (WRPLOT 8.0.2) and Arc Geographic Information System (ArcGIS 10.8), which are then integrated with Google Earth Pro software (Version 2023) for improved visualization. By integrating these four software tools, this study comprehensively analyzed and processed the necessary data, facilitating a comprehensive assessment of air pollution dispersion patterns.

Table 1
Mathematical Equation for the air dispersion model

No	Variable	Equation/Mathematical Model (Equation)
1	Dispersed air pollutant concentration ($\Delta C_{(x,y,z)}$) [µicrogram/meter^3 - µg/m^3-]	$= \frac{Q}{2\pi\sigma_y\sigma_z U_z}\exp\left[-0.5\left(\frac{y}{\sigma_y}\right)^2\right] x \{\exp\left[-0.5\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-0.5\left(\frac{z+H}{\sigma_z}\right)^2\right]\}$ 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]
2	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
3	Standard deviation of the concentration in the horizontal or the vertical (σ_y or σ_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
4	Effective stack height (H) [m]	= $h_s + \Delta h$ where: h_s = Physical stack height [m] Δh = Plume rise [m]
5	Plume rise (Δh)	= $\frac{V_s \cdot d_s}{U_z}\,[1{,}5 + 2{,}68 \times 10^{-3}\, P_a \frac{T_s - T_a}{Ts}\, d_s\,]$ 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-] $2{,}68 \times 10^{-3}$ = Constant [m^{-1} $mbar^{-1}$]

6	Atmospheric pressure (Pa) [millimetres of mercury –cmHg-]	= (Pu – h/100) where: Pu = Atmospheric pressure at sea level [=76 cmHg] h = Vertical height [m]
7	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]

Source: [25] [26] [27]

2.2 Data and Simulation

This study draws upon a combination of primary and secondary data sources. Primary data is gathered through direct sampling within the study area, as well as unpublished documents containing engineering design and laboratory analysis data related to heat and mass balance, done in laboratory & on-site experiments. Secondary data, on the other hand, is meticulously curated through an extensive review of existing literature and various online databases, such as the Indonesia Meteorology, Climatology, and Geophysics Agency (IDN-MCGA). 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 introduce an element of uncertainty, resulting in probabilistic outcomes.

The analysis of meteorological data spanning over a decade, obtained from the IDN-MCGA Class 1 Maros station, indicates an annual average wind speed of 1.99 m/s, with a standard deviation of 10.63 m/s. Based on this annual average wind speed, the atmospheric stability within the study area can be categorized as either very unstable (A) or unstable (B) under varying sunshine conditions, encompassing a spectrum of strong, moderate, and slight stability conditions [25], [27]. Consequently, two primary scenarios are simulated, differentiating between the atmospheric stability classes: very unstable (Scenario A) and unstable (Scenario B).

To comprehensively address the multitude of uncertainty sources inherent in this air dispersion model, the study employs a simultaneous Monte Carlo sampling technique. Therefore, the model's output presented in this study reflects probabilistic values, including maximum, mean (average), and minimum estimates, which are derived from 1000 random samples.

Table 2
Input Data for the air dispersion model simulation

No.	Data	Value	Remarks
1	Physical stack dimension		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]	Heat and mass balance data for proposed incinerator design (laboratory experiment)
3	Stack gas emission temperature (Ts)	473.15 [K]	
4	Mass transfer coefficient of Stack gas emission		
	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 [28]
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]	Laboratory analysis result from proposed design. (laboratory experiment)
9	Wind speed sampling height from ground (Z_0)	10 [m]	[25] [29]
10	Effective emission height (Ze)	25 [m]	Engineering drawing for proposed stack design (laboratory experiment)
11	Wind speed exponential of the atmospheric stability (P) for class A and B	0.07	[1]

No.	Data	Value	Remarks
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	[1]
	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	
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 [$\mu g/m^3$]	

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3. Result & Discussion

Two model validation procedures, dimensional consistency, and reference mode reproduction testing [31], have been undertaken to instill confidence in the acceptability and utility of the air dispersion model in this study for projecting spatial dispersion patterns and air pollutant concentrations. The dimensional consistency test involves an examination of mathematical equations, primary and secondary data to ensure that the units of each variable are consistently measured. Errors in dimensional consistency can lead to a flawed model output. To assess the dimensional consistency of the model, a comparison was made between the variables in Table 1 and the data in Table 2.

Reference mode reproduction testing was conducted by comparing the model's output data with a reference mode, which can be in the form of graphs, patterns of behaviors, or other descriptive data depicting pollutant dispersion patterns based on atmospheric stability classes. Figure 2 presents a comparison of the model output (on the right side) and the reference mode (on the left side), confirming that the model has successfully reproduced the reference mode as the desired pattern for the model's data behavior.

Utilizing meteorological data spanning a decade, from 2012 to 2021, processed and simulated using WRPLOT 8.0.2, and projected onto the GEP, Figure 3 and Figure 4 illustrate the wind rose at the proposed incinerator plant location. By considering six dominant wind directions, the projection indicates that pollutant emissions from the proposed incinerator stack are expected to disperse as follows: 53.6% to the Northwest (3150), 18% to the Southwest (450), 8.6% to the Northeast (450), 8.2% to the Southeast (1350), 2.6% to the South (1800), and 2.5% to the North (00). The two farthest distances for pollutant dispersion are in the Northwest and the Southwest, reaching 999.25 m with a wind speed range of 0.5 – 8.8 m/s and 336.81 m with a wind speed range of 0.5 – 5.7 m/s, respectively. Notably, the dispersion of incinerator pollutant emissions that move towards or could affect the nearest residential area occurs in the southeast wind direction, extending up to 153.77 m with a speed range of 0.5 – 3.6 m/s.

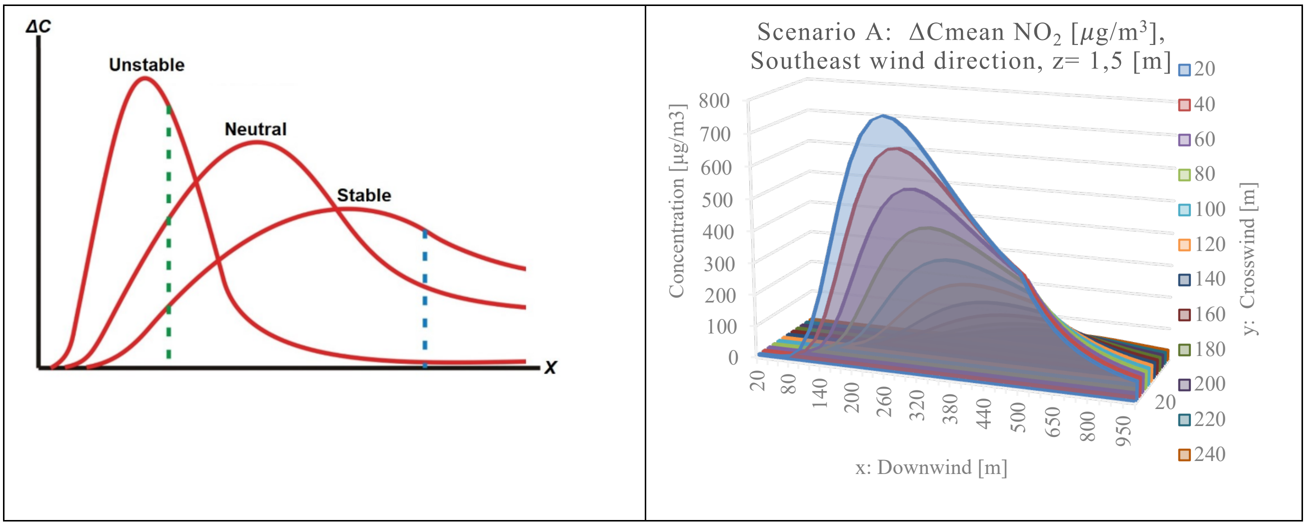

Fig. 2. Reference mode for the pollutant dispersion pattern based on the atmospheric stability class (left figure) [26] [27] and model output of this study for the dispersion patterns of NO_2 emission concentration from the proposed incinerator stack to the nearest residential area under scenario A (right figure)

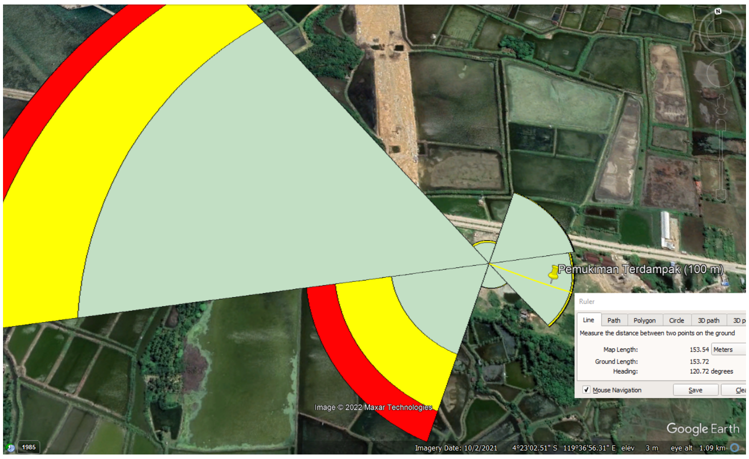

Fig. 3. Geospatial imagery for the wind rose at the proposed incinerator plant location with a reference point of 4° 23' 05.7" South Latitude and 119° 37' 02.8" East Longitude

Tables 3 and 4 provide estimations for both average and maximum dispersed concentrations (ΔC) of NO_2 emissions originating from the incinerator stack when the wind direction is from the Southeast. These estimations are made at a receiving height of 1.5 meters, taking into account the proposed incinerator activities under scenario A. To calculate the pollutant concentration in the ambient air (C) of NO_2, ΔC (as listed in Tables 3 and 4) is added to C0 (found in Table 2, No.19), as shown in Eq. 7 in Table 1. Figure 4 illustrates the average and maximum values of C for NO_2 emissions from the proposed incinerator plant to the nearest residential area, specifically under scenario A. While not all model results for each parameter are displayed, Table 5 presents a summary of the model's outcomes for the concentration (C) of the five parameters resulting from the proposed incinerator activities at the point nearest to the residential area, considering both scenarios A and B. This table also provides a comparison with the IDN-NAAQS.

The model's findings reveal that, for all five parameters, under scenarios A and B, and for both average and maximum values, the concentrations (C) remain in compliance with the applicable ambient air quality regulations, as stipulated in IDN-GR 22/2021.

Table 3
Average dispersed concentration of NO_2 (μg/m^3) resulted from the incinerator stack ($\Delta C_{x,y,z}$) to the Southeast wind direction under scenario A

Crosswind (y) [m]	Scenario A: $\Delta C_{(x,y,z)}$ Average NO_2 [μg/m^3], southeast wind direction, z= 1,5 [m]											
20	6E-10	2E-05	0.007	0.381	5.39	504.6	763.2	566.9	369.3	272.7	180.7	123.8	87.45
40	4E-37	1E-12	8E-05	0.044	1.513	378.3	670.5	526.1	351.6	262.3	175.6	121	85.9
60	2E-82	8E-25	4E-08	0.001	0.182	234.1	540.5	464.5	323.9	246	167.4	116.6	83.4
80	9E-146	7E-42	8E-13	8E-06	0.009	119.5	399.6	390.2	288.8	224.9	156.6	110.8	80.01
100	3E-227	9E-64	8E-19	1E-08	2E-04	50.38	271.1	311.9	249.2	200.3	143.7	103.6	75.85
120	0	1E-90	4E-26	4E-12	2E-06	17.52	168.7	237.2	208.1	173.9	129.4	95.52	71.07
140	0	3E-122	1E-34	4E-16	8E-09	5.03	96.27	171.6	168.2	147.2	114.3	86.76	65.8
160	0	9E-159	1E-44	7E-21	1E-11	1.192	50.41	118.1	131.6	121.4	99.09	77.65	60.2
180	0	4E-200	5E-56	4E-26	1E-14	0.233	24.22	77.36	99.59	97.56	84.25	68.47	54.43
200	0	2E-246	1E-68	4E-32	3E-18	0.038	10.67	48.21	72.95	76.43	70.28	59.49	48.63
220	0	1E-297	1E-82	1E-38	5E-22	0.005	4.313	28.58	51.72	58.36	57.52	50.93	42.94

240	0	0	7E-98	7E-46	3E-26	6E-04	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

Tabel 4
Maximum dispersed concentration of NO_2 (μg/m^3) resulted from the incinerator stack ($\Delta C_{x,y,z}$) to the Southeast wind direction under scenario B

Crosswind (y) [m]	Scenario B: $\Delta C_{(x,y,z)}$ Average NO_2 [μg/m^3], southeast wind direction, z= 1,5 [m]												
20	8E-09	5E-04	0.129	3.942	33.2	652.2	846.1	835.1	652.9	511.4	354.4	248.1	177.4
40	6E-36	3E-11	0.001	0.454	9.32	489	743.4	775	621.6	492.1	344.4	242.6	174.3
60	3E-81	2E-23	6E-07	0.012	1.122	302.5	599.2	684.3	572.7	461.5	328.3	233.8	169.2
80	1E-144	2E-40	1E-11	8E-05	0.058	154.5	443	574.9	510.7	421.8	307.1	222	162.3
100	4E-226	2E-62	1E-17	1E-07	0.001	65.11	300.5	459.5	440.7	375.8	281.8	207.7	153.9
120	0	3E-89	7E-25	4E-11	1E-05	22.65	187	349.4	368	326.2	253.8	191.5	144.2
140	0	7E-121	2E-33	4E-15	5E-08	6.501	106.7	252.8	297.4	276.1	224.2	173.9	133.5
160	0	2E-157	2E-43	8E-20	9E-11	1.54	55.89	174	232.6	227.7	194.3	155.7	122.1
180	0	8E-199	9E-55	4E-25	6E-14	0.301	26.85	114	176.1	183	165.2	137.3	110.4
200	0	5E-245	2E-67	4E-31	2E-17	0.049	11.83	71.02	129	143.4	137.8	119.3	98.66
220	0	3E-296	2E-81	1E-37	3E-21	0.006	4.782	42.11	91.44	109.5	112.8	102.1	87.11
240	0	0	1E-96	7E-45	2E-25	7E-04	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

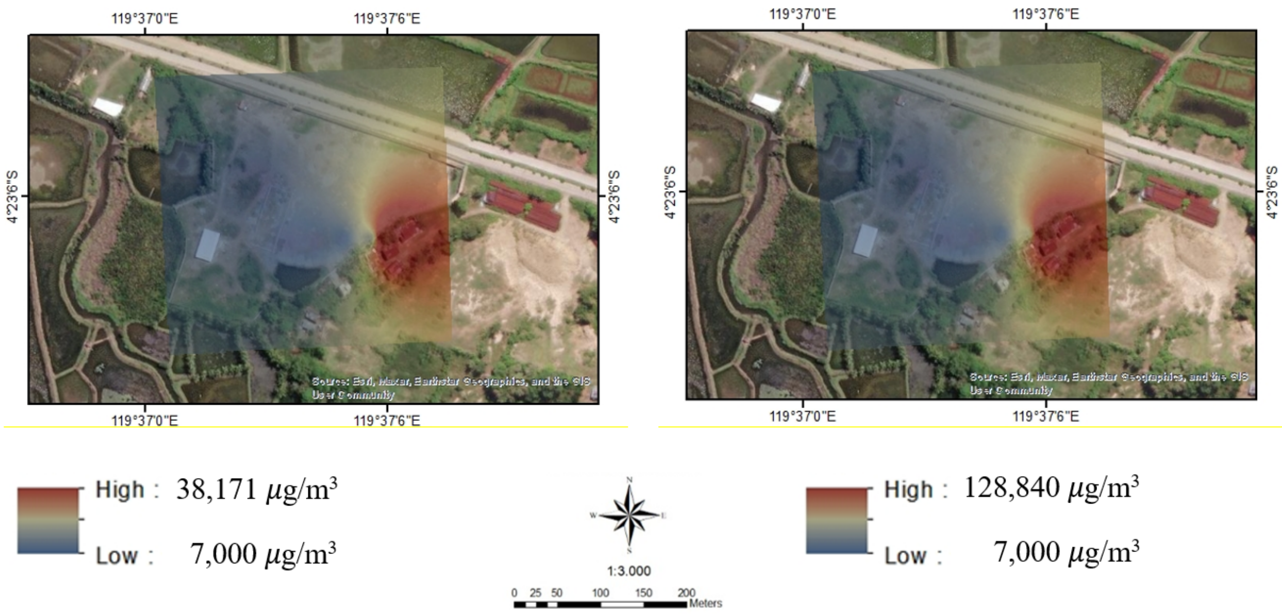

Fig. 4. Geospatial imagery for the pollutant concentration in ambient air (C = ΔCx,y,z + C0) of NO_2 to the Southeast wind direction with average (left figure) and maximum values (right figure) in the nearest residential area with a reference point of 4° 23' 7.59" South Latitude and 119° 37' 5.63" East Longitude (100 meters away from the incinerator stack)

Table 5
Dispersed air pollutant concentration (C = ΔCx,y,z + C0) to southeast wind direction towards the nearest residential area

Parameter	$C_{x,y,z}$ in southeast wind direction (135^0) to the nearest residential area: downwind (x)= 100[m], crosswind (y)= 20[m], recipient height (z)= 1.5 [m]				IDN-NAAQS [µg/m³]
	Scenario A		Scenario B		
	Average [µg/m³]	Maximum [µg/m³]	Average [µg/m³]	Maximum [µg/m³]	
NO_2	38.171	128.84	7.61	12.841	200
SO_2	26.764	31.896	25.,034	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

Under scenario A, the concentrations (both average and maximum values) of the five parameters are notably higher than those under scenario B. Among these parameters, when considering the maximum values under scenario A, the five ambient air quality parameters that are closest to the IDN-NAAQS values, in rank order, are Pb, NO_2, SO_2, TSP, and CO. Of particular concern are Pb and NO_2 concentrations, which rank as the first and second parameters closest to the IDN-NAAQS values. These two parameters require careful monitoring because they have nearly reached their threshold values compared to the other three parameters (refer to Table 5).

Furthermore, between these two parameters, Pb warrants heightened attention for monitoring due to the concentration's proximity to the NAAQS (1.459 µg/m3 for Pb compared to 2 µg/m^3 for NO_2). After entering the human body, Pb distributes in the blood and accumulates in the bones, leading to adverse effects on the nervous system, kidney function, immune system, reproductive and developmental systems, and cardiovascular system. It's important to note that Pb is persistent in the environment, resulting in reduced growth and reproduction in plants and animals, along with neurological effects in vertebrates (USEPA, 2023).

While the health and environmental effects of NO_2 have been previously explained, it's worth emphasizing that even though the model's projections indicate that the proposed incinerator activities currently do not have a significant impact on the nearest residential area, regular ambient air quality monitoring is imperative. This monitoring should also take into consideration the influence of meteorological conditions, including seasonal variations (rainy and dry seasons) and the effects of climate change in the area. Continuous vigilance and proactive measures are necessary to ensure the well-being of both the environment and human health in the vicinity of the incinerator.

4. Conclusion

Indonesia faces a significant shortage of medical waste treatment facilities. The construction of such facilities is undeniably beneficial for the proper management of medical waste. However, it also has adverse consequences, particularly on ambient air quality and the environment. This study has effectively applied an air dispersion model to predict the dispersion patterns and concentration levels of air pollutants arising from medical waste treatment facilities that utilize incineration. The focus of this investigation centered on a residential area situated 100 meters away from the incinerator stack.

The model has demonstrated that, even when considering uncertainty values, the concentrations of the five pollutants in the nearest residential area, classified under the atmospheric stability classes of very unstable and unstable, still conform to Indonesia's national air quality standards as outlined in Government Regulation Number 22 Year 2021. However, it is crucial to emphasize that while the incinerator activities presently do not have a substantial adverse impact, continuous management and monitoring of ambient air quality in the nearest residential area are imperative. This emphasis is especially vital for pollutants like Pb and NO_2, as their concentrations are nearly reaching their threshold values.

Considering that Indonesia experiences two distinct seasons, further research is warranted to extend the atmospheric stability class assessments into dry and rainy season scenarios. This extension will enable a more comprehensive understanding of the spatial dispersion patterns and the magnitude of air pollutant concentrations during different climatic conditions.

If the estimation results reveal air pollutant concentrations exceeding their threshold values, it is essential to proceed with environmental risk assessment, focusing on determining the severity of adverse effects on residents living in the nearest residential area adjacent to the medical waste treatment facility.

Considering these findings, proactive measures, vigilant monitoring, and continuous assessment are vital to safeguard both environmental quality and the well-being of communities residing near medical waste treatment facilities in Indonesia.

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