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Gaussian Plume Modelling of Volcanic Ash Distribution from Mount Ibu Eruptions

Nurul Istiqomah[1], Fanny Maulidya[2], Izza Dinillah[3], Dian Candra Rini Novitasari[4*]
[1234*] Departement of Mathematics, Faculty Science and Technology, UIN Sunan Ampel, Surabaya, Indonesia.

Corresponding email: *diancrini@uinsa.ac.id*

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Abstract

Indonesia is part of the Pacific Ring of Fire and hosts 129 active volcanoes, including Mount Ibu in Halmahera Regency, North Maluku. Mount Ibu, standing 1,340 meters above sea level, has shown increased volcanic activity since 2008, with 2,136 eruptions recorded up to 2025. This study aims to apply the Gaussian Cloud Model to simulate the distribution of volcanic ash, especially PM10, and map the potential impacts of the eruption of Mount Ibu as part of an early warning system. Data were obtained from PVMBG. The modelling results show that volcanic ash dispersed toward the northwest, reaching a maximum concentration of 2.35×10^{-188} µg/m³. A MATLAB-based Graphical User Interface (GUI) was developed to visualize the ash distribution. The highest concentration occurred around the Talen region, near the eruption source, and gradually decreased in other areas such as Tolofu and Gam Ici due to particle dispersion and dilution. These findings indicate that the proposed model can support early warning systems and contribute to disaster mitigation efforts related to volcanic activity

Keywords: Eruption, Gaussian Plume, Mount Ibu, PM10, Volcanic Ash

1. Introduction

Indonesia is part of the Pacific Ring of Fire because it lies at the convergence of three major tectonic plates: the Indo-Australian Plate, the Eurasian Plate, and the Pacific Plate. The interactions among these highly active plates make Indonesia prone to various geological disasters, including volcanic eruptions (Benyamin & Setyorini, 2024; Irfan et al., 2022). Indonesia has 129 active volcanoes and experiences eruptions almost every year (Virkhansa et al., 2019).

Volcanic eruptions not only produce direct hazards such as lava flows and pyroclastic materials that threaten human safety, but also indirect hazards through the dispersion of volcanic ash (Leli Honesti et al., 2025). The ash emitted during eruptions contains SO_2, sulfur, PM10, and other fine particulate matter that pose significant health risks (Stewart et al., 2022). Carried by the wind, these particles can travel far from the eruption site, reducing air quality and causing respiratory problems. Furthermore, volcanic ash can disrupt social activities, damage agricultural land, and lead to crop failures that negatively affect the local economy (Leli Honesti et al., 2025). One of the volcanoes that remains active and has the potential to erupt is Mount Ibu.

Mount Ibu is located in Halmahera Regency, North Maluku, with an elevation of 1,340 meters above sea level (Kayla Septia Salma et al., 2025). The volcano is one of five active volcanic systems in North

Maluku and has exhibited increased activity since 2008 (Firmansyah, 2024). Based on records from the Ministry of Energy and Mineral Resources (MEMR) up to 2025, Mount Ibu has experienced 2,136 eruptions, underscoring its high level of activity and the associated risks to surrounding communities (Magma, 2025). On June 2, 2024, at 12:45 p.m. WIT, an eruption generated an ash column reaching approximately 7,000 meters. Following this event, several nearby villages were evacuated to designated safe zones, and activities within a 4–7 km radius of the active crater were restricted to reduce exposure to volcanic ash hazards (Hafizh, 2024). These conditions highlight the need for developing a mathematical model to support a more comprehensive understanding of volcanic ash dispersion.

The development of mathematical models to determine the distribution of volcanic ash is essential for supporting early-warning systems and enabling faster access to hazard information. One of the most widely used approaches for predicting the continuous spread of atmospheric pollutants is the Gaussian dispersion model, which can represent emissions released from the surface or from elevated sources. A common form of this approach is the Gaussian plume model, which incorporates the effects of turbulent diffusion and wind advection to estimate pollutant concentrations in the air (Assegaf, 2018), (Abidin & Artauli Hasibuan, 2019). This model has been extensively applied to the dispersion of pollutants from industrial chimneys, as demonstrated by (Adinda Laili Febriyanti et al., 2022), who used it to simulate pollutant distribution and determine safe distances for residential areas. Furthermore, (Lubab et al., 2016) adapted the Gaussian model to estimate the spread of volcanic ash during eruptions by treating the volcanic vent analogously to a chimney as the emission source. The resulting dispersion patterns were then used to support preventive measures for exposed communities. Building on these studies, the present research aims to apply the Gaussian plume model to simulate volcanic ash dispersion from the Mount Ibu eruption as a basis for improving early-warning capabilities.

2. Study Literature

2.1. Gaussian Plume Model

The transport of volcanic ash in the atmosphere is primarily influenced by gravitational forces acting on the particles. This phenomenon, known as gravitational settling, determines the rate at which particles descend toward the Earth's surface. The settling velocity depends on the physical properties of the particles including their size and density as well as gravitational acceleration (Saxby et al., 2020). To calculate this velocity, Stokes Law approach is used to calculate the particle settling velocity, as shown in the simplified equation (Lubab et al., 2016).

$$v_t = \frac{g {d_p}^2 \rho_p}{18\mu_g} \tag{1}$$

which is,
v_t = Particle falling velocity (m/s)
g = Gravitational acceleration (m/s^2)
d_p = Particle diameter (μm)
ρ_p = Particle density (gr/cm)
μ_g = Dynamic viscosity (μm)

The ash emitted during a volcanic eruption disperses outward from the source. The distribution of volcanic ash can be estimated using a Gaussian plume model, which allows the calculation of key parameters such as eruption column height, horizontal transport distance, and lateral deviation based on wind direction. The eruption height can be determined using the following equation (Lubab et al., 2016).

$$\mathrm{H} = \mathrm{H_s} + \Delta\mathrm{h} \tag{2}$$

which is,
H = Height of highest eruption (m asl)
$\mathrm{H_s}$ = Height of volcano (m asl)
Δh = Height of volcanic ash (m)
Next, the horizontal transport distance and lateral deviation of the ash cloud can be calculated based on wind direction using the following equation (Assegaf, 2018).

$$x = [X_r - X_s]\cos(WD) + [Y_r - Y_s]\sin(WD) \tag{3}$$

$$y = [X_r - X_s]\sin(WD) - [Y_r - Y_s]\cos(WD) \quad (4)$$

which is,
x = Downwind distance of ash distribution (m)
y = Crosswind distance of ash distribution (m)
X_s, Y_s = Source position of volcanic ash (°)
X_r, Y_r = Receptor position of observation point (°)
WD = Wind direction (°).

The Gaussian plume model is derived from the advection–diffusion equation as follows (Adinda Laili Febriyanti et al., 2022).

$$J = J_D + J_A \quad (5)$$

which is,
$J =$ Total flux
$J_D =$ Diffusion flux (kg/m^2s)
$J_A =$ Advection flux (kg/m^2s)

Based on the advection diffusion flux equation, the Gaussian plume model for volcanic ash dispersion can be derived as follows.

$$C(x,y,z) = \frac{\mathrm{Q}}{2\pi \mathrm{u}\sigma_y\sigma_z}\left\{exp\left(\frac{-(z-H)^2}{2\sigma_z^2}\right) + exp\left(\frac{-(z+H)^2}{2\sigma_z^2}\right)\right\}\left\{exp\left(\frac{-(y)^2}{2\sigma_y^2}\right)\right\} \quad (6)$$

which is,
Q = Ash emission rate
H = Ash height
u = Wind speed
z = Observation distance perpendicular to the x-axis
σ_y, σ_z = Dispersion coefficient

2.2. Dispersion Coefficient

The dispersion coefficients are then used to quantify the extent to which the ash spreads horizontally and vertically from the emission source. The magnitude of these coefficients depends on the degree of atmospheric stability. The determination of the dispersion coefficients follows Equation (7) and (8) (Micallef & Micallef, 2024).

$$\sigma_y = cx^m \quad (7)$$
$$\sigma_z = dx^n \quad (8)$$

which is,
$\sigma_y =$ Horizontal distribution of volcanic ash (transverse to the wind direction).
$\sigma_z =$ Vertical distribution of volcanic ash (up and down)
The constants c, d, m, n are determined based on atmospheric stability classes (Pasquill–Gifford classes), as shown in Table 1 (Micallef & Micallef, 2024).

Tabel 1. Dispersion Coefficient Stability Class

Stability Class	**Dispersion Coefficient (σ_y)**		**Dispersion Coefficient (σ_z)**	
	c	m	d	n
A – B	1,46	0,71	0,01	1,54
C	1,52	0,69	0,04	1,17
D	1,36	0,67	0,09	0,95
E – F	0,79	0,70	0,40	0,67

2.3. Simulation
The simulation is utilized to depict the dispersion pattern of volcanic ash emitted from Mount Ibu. It is developed using the Gaussian plume model described in Equation (5) and incorporates several key input parameters, including mountain elevation, emission rate, wind speed, and dispersion coefficients. The resulting ash distribution is presented through graphical plots, contour maps, and concentration distribution maps. A MATLAB Graphical User Interface (GUI) is employed to facilitate an efficient and intuitive visualization process.

3. Methods
3.1. Data
This study utilizes data from the eruption of Mount Ibu in Halmahera on June 2, 2024, obtained from the Center for Volcanology and Geological Hazard Mitigation (PVMBG). The data include the mountain's coordinates, elevation, and the height of the eruption column (Roeroe, 2024). In addition to eruption-specific parameters, this research also incorporates several atmospheric variables sourced from earth.nullschool.net, such as wind direction, wind speed during the eruption, and the type of particles released, with a specific focus on PM10 (Cameron, n.d.). Furthermore, this study uses coordinate points representing observational locations for volcanic ash dispersion, specifically Pasalulu Village. The complete dataset used in this analysis is presented in Table 2.

Table 2. Research Variable

No.	Variable	Value
1.	Height of Mount Ibu	1340 m asl.
2.	Height of eruption column	$\pm$ 7000 m
3.	Wind direction	115°
4.	Wind speed	9,2 m/s
5.	PM 10 particles	4 μg/m^3
6.	Coordinates of Mount Ibu (X_s, Y_s)	127,63° E 1,49° N
7.	Coordinates of Pasalulu Village (X_r, Y_r)	127,67° E 1,52° N

The data presented in Table 2. were processed using the Gaussian plume model to estimate the maximum concentration of airborne pollutants, specifically PM10. The stages of the Gaussian plume modelling procedure applied in this study are illustrated in Figure 1.

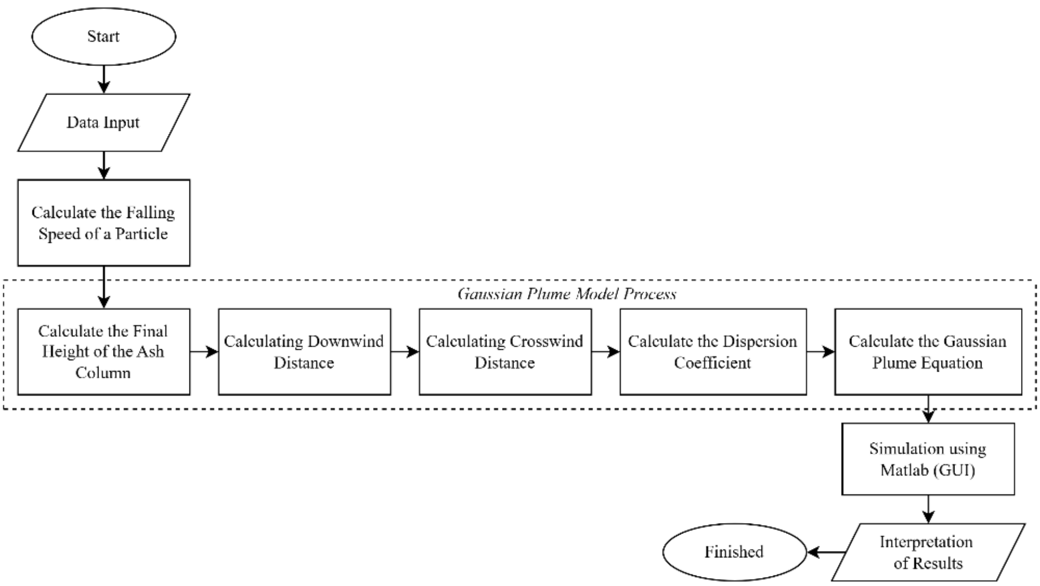

Figure 1. Flowchart Gaussian Plume Model

The research process began with the collection of eruption, meteorological, and geographic data related to Mount Ibu, as presented in Figure 1. The particle settling velocity (fall velocity) was calculated to

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determine the deposition behavior of PM10 particles in the atmosphere. The final height of the volcanic ash column was then estimated based on the eruption parameters. Subsequently, the source and receptor coordinates were used to calculate the downwind and crosswind distances relative to the wind direction. These distances were employed to determine the atmospheric dispersion coefficients (σ_y) and (σ_z), which were then substituted into the Gaussian plume equation to estimate the concentration and spatial distribution of volcanic ash. The simulation was performed using a MATLAB graphical user interface (GUI) to visualize the ash dispersion pattern, and the resulting outputs were interpreted to evaluate the distribution characteristics of volcanic ash from Mount Ibu.

4. Result and Discussion

On 2 June 2024, Mount Ibu erupted, generating an eruption column approximately ±7000 m above the summit. To estimate the ash dispersion from this event, the analysis begins by determining the particle settling velocity v_t using Equation (1).

$$v_t = \frac{g{d_p}^2\rho_p}{18\mu_g}$$
$$v_t = \frac{9{,}81\times(1\times10^{-5})^2\times2500}{18\times(1{,}8\times10^{-5})}$$
$$v_t = 0{,}00756944\ \mathrm{m/s}$$

The settling velocity of PM10 particles is calculated to be 0.00756944 m/s. This relatively small value indicates that PM10 particles descend very slowly in the atmosphere, allowing them to remain suspended for extended periods and to be transported over long distances before settling. The next step is to determine the final height of the ash column using Equation (2), with PM10 chosen as the representative particle type. This computation produces the following result.

$$\mathrm{H} = \mathrm{H_s} + \Delta\mathrm{h}$$
$$\mathrm{H} = 1340 + 7000$$
$$\mathrm{H} = 8340\ \text{m asl.}$$

The calculated H value is then applied within the Gaussian plume model. Before applying the model, the coordinates x, y, and z must be determined using Equation (3) and (4). The observation point (X_r, Y_r) corresponds to Pasalulu Village, one of the closest settlements to Mount Ibu, while X_s, Y_s represents the coordinates of Mount Ibu itself.

Since the source and receptor locations are initially expressed in geographic coordinates (latitude and longitude), the coordinate differences cannot be directly used in the Gaussian plume model. Therefore, the geographic coordinates were converted into Cartesian distances in meters using an approximation based on the Earth's curvature. At the latitude of Mount Ibu (1.49° N), one degree of latitude corresponds to approximately 111.32 km, while one degree of longitude corresponds to approximately 111.28 km. The resulting distances were then used to calculate the downwind distance (x) and crosswind distance (y) in meters, which are required inputs for the Gaussian plume model.
For the x value:

$$x = [X_r - X_s]\cos(WD) + [Y_r - Y_s]\sin(WD)$$
$$x = [(X_r - X_s)(111281{,}6)]\cos(115°) + [(Y_r - Y_s)(111320)]\sin(115°)$$
$$x = [(127{,}67 - 127{,}63)(111281{,}6)]\cos(115°) + [(1{,}52 - 1{,}49)(111320)]\sin(115°)$$
$$x = 1145{,}1\ m$$

For the y value:

$$y = [X_r - X_s]\sin(WD) - [Y_r - Y_s]\cos(WD)$$
$$x = [(X_r - X_s)(111281{,}6)]\sin(115°) + [(Y_r - Y_s)(111320)]\cos(115°)$$

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$$y = [(127{,}67 - 127{,}63)(111281{,}6)]\sin(115°) - [(1{,}52 - 1{,}49)(111320)]\cos(115°)$$
$$y = 5445{,}6\ m$$

The z value is taken at ground level, so $z = 0$. The calculated values of x, y, and z are then used to obtain the dispersion coefficients. Based on Table 2. the dispersion coefficients were evaluated for stability classes A–B, yielding the following results.

$$\sigma_y = cx^m \qquad \sigma_z = dx^n$$
$$\sigma_y = 1{,}46(1145{,}1)^{0{,}71} \qquad \sigma_z = 0{,}01(1145{,}1)^{1{,}54}$$
$$\sigma_y = 216{,}8\ m \qquad \sigma_z = 513{,}6\ m$$

These values are subsequently inserted into the Gaussian plume model presented in Equation (6) producing the following output.

$$C = \frac{Q}{2\pi u \sigma_y \sigma_z}\left\{exp\left(\frac{-(z-H)^2}{2\sigma_z^2}\right) + exp\left(\frac{-(z+H)^2}{2\sigma_z^2}\right)\right\}\left\{exp\left(\frac{-(y)^2}{2\sigma_y^2}\right)\right\}$$
$$C = \frac{9100}{2\pi(9{,}2)(216{,}8)(513{,}6)}\left\{exp\left(-\frac{(0-8340)^2}{2(513{,}6)^2}\right) exp\left(-\frac{(0+8340)^2}{2(513{,}6)^2}\right)\right\}\left\{exp\left(-\frac{(5445{,}6)^2}{2(216{,}8)^2}\right)\right\}$$
$$C = 2.35 \times 10^{-188}\ \mu g/m^3$$

The model results are then simulated using a MATLAB-based GUI. In this study, the simulation of the Mount Ibu eruption corresponds to the event that occurred on 2 June 2024 at 12:45 p.m. WIT. The visualization of volcanic ash dispersion covers an area bounded by coordinates 0.3°–2.7° North Latitude and 126.5°–128.8° East Longitude. The map scale indicates that one unit in the legend corresponds to 5 km on the ground, enabling the dispersion pattern to be observed over several kilometers from the eruption source, consistent with the prevailing wind direction. This spatial coverage shows that the map focuses on the area surrounding Mount Ibu on Halmahera Island, spanning approximately 270 km from north to south and 250 km from west to east.

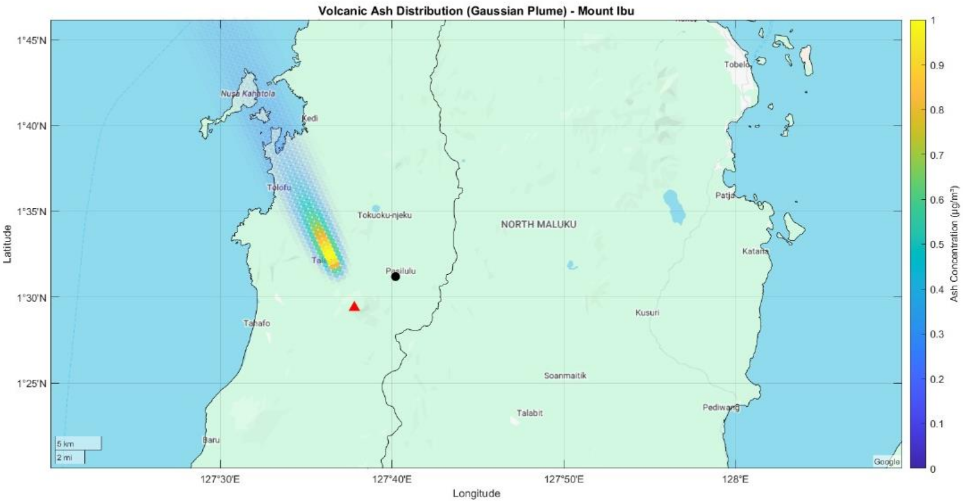

Figure 2. Simulation Results of Volcanic Ash Distribution (PM 10)

Based on the Gaussian plume modelling results simulated using the MATLAB GUI, the distribution of volcanic ash (PM10) from Mount Ibu shows a dominant northwestward spread from the eruption source. The red triangle marks the location of Mount Ibu, while the black point represents the observation site in Pasalulu Village.

With a wind direction of 115° at an altitude of 8340 m above sea level, the ash plume extends northwestward from the volcano. The color distribution on the map represents the spatial variation in simulated ash concentration. Higher concentrations, shown in yellow to red, are observed near the eruption source, particularly around the Talen area. In contrast, areas shaded in green to blue, such as Tolofu and Gam Ici, indicate lower ash concentrations due to atmospheric dispersion.

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At the observation point in Pasalulu Village, the predicted PM10 concentration was 2.35×10^{-188} μg/m³. This extremely low concentration indicates that only a negligible amount of volcanic ash reached the observation site under the assumed meteorological conditions. The low concentration is attributed to the location of Pasalulu Village, which lies considerably away from the plume centerline relative to the prevailing wind direction, resulting in substantial dilution and dispersion of ash particles before reaching the observation point.

This is consistent with the news report (Akbar, 2024), which states that volcanic ash was carried by the wind toward the evacuation site in Gam Ici Village and also reached the Volcano Observation Post (VOP) as it drifted westward. Next, a simulation will be conducted using the same data but at different times to determine the distribution of ash. The simulation will be conducted at 05:36 WIT, 07:46 WIT, 21:50 WIT, and 04:14 WIT, yielding the following results.

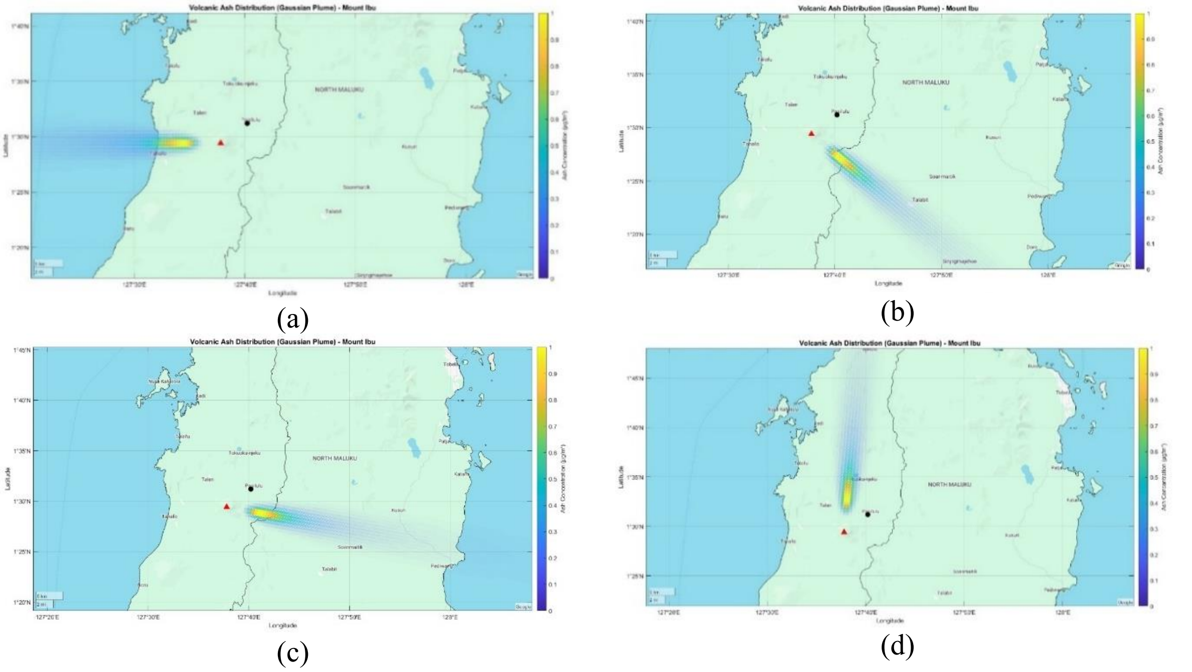

Figure 3. Volcanic Ash Distribution Simulation Results
(a) at 05.36 WIT, (b) at 07.46 WIT, (c) at 21.50 WIT, dan (d) at 04.14 WIT.

The four maps show that variations in wind direction strongly influence the spread of volcanic ash from Mount Ibu, producing different plume patterns under each condition. In map (a), the ash is carried westward, in map (b) it moves southeastward, in map (c) it spreads eastward, and in map (d) it extends northward. This pattern shows that every shift in wind direction produces a different ash transport pathway. Nevertheless, all maps consistently exhibit the typical characteristics of a Gaussian plume: high ash concentrations near the eruption source that progressively decrease with increasing distance

5. Conclusion

This study successfully applied the Gaussian plume model to simulate the dispersion of PM10 volcanic ash from the Mount Ibu eruption on June 2, 2024. The simulation results indicate that the ash plume was dispersed predominantly toward the west-northwest under a wind direction of 115°, while the predicted PM10 concentration at Pasalulu Village was 2.35×10^{-188} μg/m³, indicating a negligible ash impact at the observation location under the simulated conditions. The Gaussian plume model offers the advantage of simplicity and computational efficiency, enabling rapid estimation and visualization of volcanic ash dispersion using limited input data. However, the model is based on steady-state assumptions and does not account for complex terrain effects, temporal variations in meteorological conditions, or particle interactions that may influence ash transport. Therefore, future studies should incorporate real-time meteorological data, more advanced atmospheric dispersion models, and additional observation locations to improve prediction accuracy and support volcanic ash hazard assessment in the vicinity of Mount Ibu.

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