Jurnal Penelitian Sains Teknologi

Temporal and Spatial Dynamics of Volcanic Aerosols: Absorbing Aerosol Index (AAI) Analysis During the Eruption of Mount Lewotobi Laki-laki

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doi: 10.23917/saintek.v2i1.15729
Received: December 6th, 2025 | Revised: February 3rd, 2026 | Accepted: February 11th, 2026
Available Online: February 12th, 2026 | Published Regularly: March, 2026

Abstract

In November 2024, the eruption of Mount Lewotobi Laki-laki on Flores Island, Indonesia, resulted in the release of substantial volcanic aerosols, including sulfur dioxide (SO_2) and volcanic debris. These aerosols impacted the environment, health, and aviation activities. The objective of this investigation is to examine the temporal and spatial dynamics of volcanic aerosols by employing the Absorbing Aerosol Index (AAI) in conjunction with TROPOMI satellite data (Sentinel-5P). The methodologies employed are as follows: spatial-temporal analysis with Google Earth Engine (GEE), aerosol dispersion simulation with the HYSPLIT model, and data processing with the Sentinel Application Platform (SNAP). The results indicated a substantial increase in volcanic activity from November 8th to 11th, 2024, as evidenced by an ash column that reached a height of as much as 10,945 m. The distribution of aerosols was influenced by atmospheric dynamics, with high concentrations observed in the vicinity of Mount Lewotobi Laki-laki and extending to the east-southeast. Although the level of volcanic activity declined in late November, aerosol concentrations were still detected in the atmosphere. This investigation offers critical insights into the distribution of volcanic aerosols during the eruption and its effects on disaster risk mitigation and air quality. It is anticipated that these discoveries will facilitate the implementation of more sustainable and effective risk management strategies for volcanic eruptions.

Keywords: absorbing aerosol index, mount lewotobi laki-laki, remote sensing, tropomi, volcanic eruption.

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Introduction

Mount Lewotobi Laki-Laki, one of the active volcanoes on Flores Island, East Nusa Tenggara, has added to the historical record by experiencing a long eruption beginning on December 22, 2023, and ending with the worst eruption on November 3, 2024 [1], recording a history of significant eruptions that have had a wide impact on the environment and surrounding communities. Mount Lewotobi Laki-Laki, like other volcanoes, emits numerous aerosols into the atmosphere. These include volcanic ash, sulfur dioxide (SO_2), and other particles. This material has an impact not just on local air quality but also on aircraft, weather patterns (local weather conditions), and the global climate.

The presence of volcanic aerosols during eruptions can be detected using the Absorbing Aerosol Index (AAI), a metric determined using satellite-based remote sensing technologies [2], [3], [4]. The Absorbing Aerosol Index (AAI) is a key measure in atmospheric monitoring that detects the presence and dispersion of absorbing aerosols such as volcanic ash, mineral dust, and black carbon [5], [6]. AAI is estimated using Sentinel-5P satellite-based remote sensing technology to account for spectral variances in UV wavelengths [7], [8]. This method provides worldwide aerosol monitoring with great time resolution, making it perfect for identifying episodic occurrences like volcanic eruptions [9], [10]. The capacity of AAI to detect absorbing particles is crucial because these aerosols can have substantial effects on the atmosphere, such as altering the solar radiation absorbed by the Earth, influencing cloud formation, and contributing to climate change [11]. AAI can track volcanic aerosols in real time during eruptions [12], [13]. This data is not only essential for studying atmospheric dynamics during and after an eruption, but it also plays an important role in catastrophe effect mitigation, such as advising airlines to avoid areas with high levels of volcanic ash, which can damage aircraft engines.

Satellite spectrometer equipment like TROPOMI are intended to monitor particles and gases in the atmosphere by employing reflected sunlight reaching the upper atmosphere (TOA) at various wavelengths such as ultraviolet (UV), visible, and infrared [14]. TROPOMI's high temporal and spatial resolution allows for global monitoring of volcanic ash dispersal, giving real-time data crucial for understanding environmental impacts and managing disaster risks [15], [16]. TROPOMI's AAI detects volcanic ash and provides information on its spatial and temporal distribution in the atmosphere [17], [18], [19]. In the context of volcanic activity, this information is extremely important for predicting ash dispersal patterns and identifying possibly damaged locations [20]. Furthermore, AAI is a useful method for investigating the influence of volcanic ash on air quality at both local and regional scales, as well as its impact on the climate system via its interaction with solar radiation [21].

Research on AAI during the eruption of Mount Lewotobi Laki-Laki is critical for determining the temporal and spatial dispersion patterns of volcanic aerosols in the atmosphere. This study also tries to determine the longevity of volcanic aerosols in the atmosphere and their potential environmental implications. This study analyzed satellite measurement data related to Mount Lewotobi Laki-Laki's eruption in November 2024. It is hoped that the findings of this study will serve as a scientific foundation for future attempts to mitigate volcanic disasters more effectively and sustainably.

Method

a. Study Area

This study was conducted at Mount Lewotobi Laki-laki on Flores Island, Indonesia, at roughly 122.8667° E and -8.5427° S. This peak is part of a volcanic arc formed by the subduction zone between the Indo-Australian and Eurasian plates; hence, there is a lot of volcanic activity. Mount Lewotobi Laki-laki is an active stratovolcano characterized by explosive eruptions of the Strombolian and Vulcanian types, which emit huge amounts of aerosols into the atmosphere. Mount Lewotobi Laki-laki is one of Mount Lewotobi's "twins," together with Mount Lewotobi Perempuan. Despite their apparent differences, these two mountains share volcanic activity. Mount Lewotobi Laki-laki stands 1,584 m above sea level, while Mount Lewotobi Perempuan rises 1,703 m. The research region includes locations influenced by volcanic aerosol dispersal, which is derived using historical data on volcanic activity during Mount Lewotobi Laki-laki's eruption period, which runs from November 1 to November 30, 2024.

b. Sentinel Application Platform (SNAP).

SNAP is used to process the first Absorbing Aerosol Index (AAI) data from the TROPOMI device. Its primary duties include atmospheric correction, which eliminates atmospheric interference such as water vapor and other particles, ensuring reliable data. SNAP is also used for data validation, which ensures the dataset's validity prior to further analysis. SNAP's easy interface enables high-resolution data processing to easily discover volcanic aerosol dispersion patterns.

c. Google Earth Engine (GEE).

GEE is used to conduct spatial and temporal analyses of volcanic aerosol dispersal. GEE enables the mapping of aerosol distribution patterns in the Mount Lewotobi Laki-laki area using TROPOMI AAI data. In addition, GEE allows for time-series analysis to track variations in aerosol concentrations over time. GEE's cloud-based technology enables rapid processing of massive data, resulting in precise aerosol distribution and trend maps.

d. HYSPLIT model.

The HYSPLIT model simulates aerosol dispersion using meteorological variables such as wind direction, speed, and air pressure. This simulation provides a predictive view of aerosol transport and distribution across a larger area. HYSPLIT results supplement satellite data by offering deeper insights into air dynamics during eruptions, allowing for more accurate characterization of volcanic aerosol spatial and temporal distributions.

Result and Discussion

a. Volcanic Activity at Mount Lewotobi Laki-laki

Mount Lewotobi Laki-laki experienced a considerable rise in volcanic activity in November 2024, culminating in a massive eruption on November 3 at 23:58 WITA, which generated an ash column up to 6-7 km. Mount Lewotobi has a history of long eruptions and extended periods of inactivity. Previously, volcanic activity on Mount Lewotobi increased in 2002. The long interval between eruptions indicates a bigger concentration of energy, where the pressure and volume of magma locked in the mountain's bowels might cause stronger eruptions [22], [23]. Mount Lewotobi is located on oceanic crust, which typically produces effusive eruptions with calm lava flows. However, changes in magma composition from liquid basaltic to thick andesitic with high silica (SiO_2) content result in explosive eruption characteristics [24], as demonstrated in November 2024.

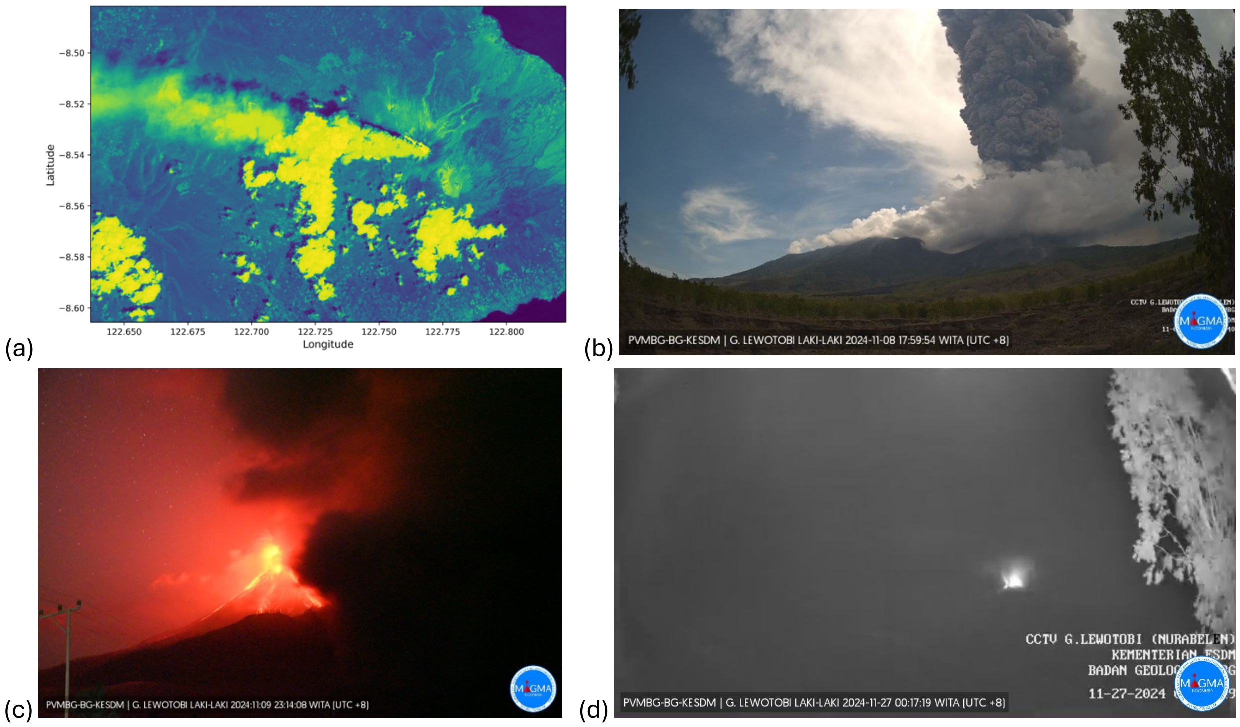

Figure 1. Eruption of Mount Lewotobi Laki-laki with a) satellite imagery using Sentinel-2, b) eruption of November 8, 2024, c) eruption of November 9, 2024, and d) eruption of November 26, 2024.

Figure 1 depicts the eruptive activity of Lewotobi Laki-laki in November 2024 from several perspectives. Figure (a) depicts satellite imagery from Sentinel-2 that depicts the spatial distribution of eruptive material such as aerosols or volcanic ash. The distribution of brilliant colors in the images suggests a high concentration of volcanic material in a specific area, consistent with a distribution pattern caused by wind direction. Meanwhile, figure (b) depicts the eruption on November 8, 2024, which features a dense ash column ascending high into the skies, signifying a large explosive eruption. Figures (c) and (d) show more eruptive activity on November 9, 2024, and November 26, 2024, including the ejection of incandescent material at night and observations utilizing CCTV with an infrared spectrum.

The photos show eruptive activity ranging from strombolian to vulcanian, which is characteristic in stratovolcanoes like Lewotobi-Laki. According to Moussallam [25], volcanic eruptions with large ash columns can have major environmental and public health consequences due to the extensive distribution of volcanic ash [17]. This eruption offers an overview of the release of enormous amounts of energy that can affect the atmosphere and surrounding environment, which is consistent with prior research on the impact of volcanic emissions on air quality and the global climate system [18]. Changes in the eruption pattern represent the transition phase of Mount Lewotobi Laki-Laki's eruptive activity. This was demonstrated on November 26, 2024, when there was a thick atmosphere due to volcanic ash, resulting in impaired visibility and air quality.

b. Aerosol Height Fluctuations.

Figure 2 represents aerosol height changes in November 2024, during the eruption of Mount Lewotobi Laki-laki. According to the aerosol height parameters from the TROPOMI instrument (Sentinel-5P), three major peaks of aerosol height were detected: November 10 (4,620 m), November 18 (10,945 m), and November 20 (8,690 m). The highest peak on November 18 shows a powerful explosive eruption, resulting in a volcanic ash column of about 11,000 m, which has the potential to impede air travel and harm public health. These variations are influenced by magma dynamics, atmospheric conditions, and weather patterns. The initial peak on November 10 implies a substantial eruption as a preparatory phase, although considerable changes on November 20 show that volcanic activity is still robust, albeit at a lower intensity. During other times, such as November 1-9 and November 21-29, aerosol heights are relatively low or close to nil, indicating little volcanic activity. Significant aerosol variations have a broad impact, both locally and regionally. The decline in eruption intensity in this final stage suggests that, while volcanic activity has lessened, the influence of volcanic ash remains in the atmosphere for a long period. This is consistent with the findings of Beckett [20].

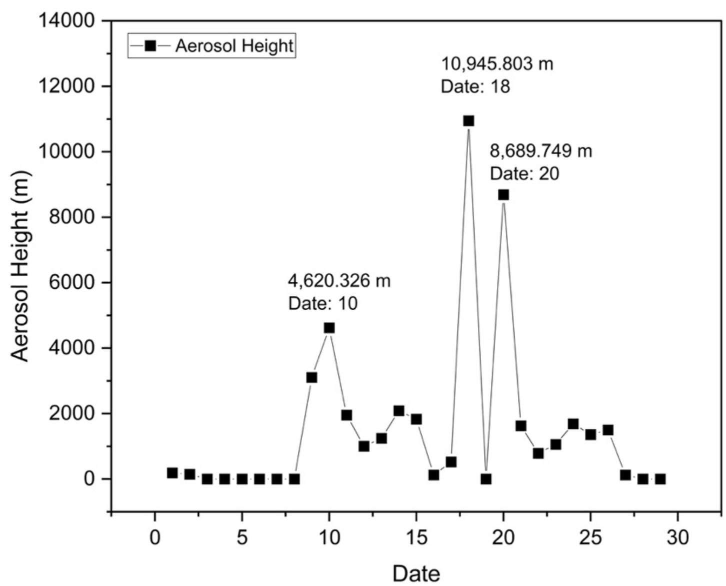

Figure 2. Aerosol Height Fluctuations during November 2024

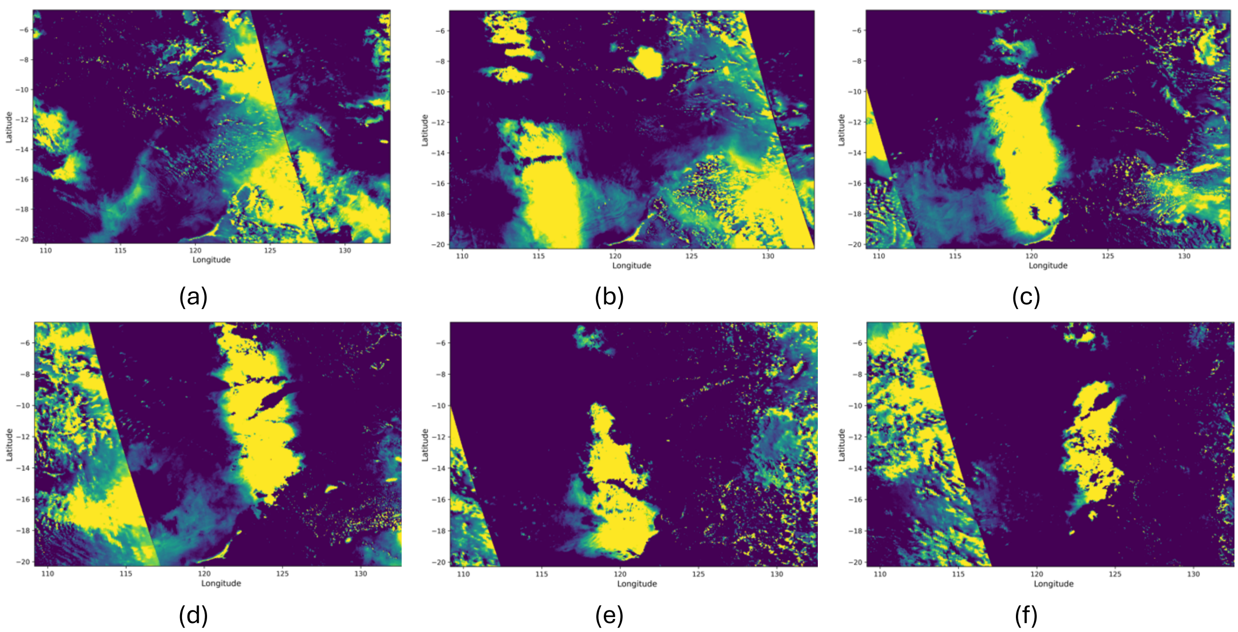

Figure 3. Aerosol Concentration, (a) 08 November 2024, (b) 09 November 2024, (c) 10 November 2024, (d) 11 November 2024, (e) 26 November 2024, (f) 27 November 2024

Figure 3 shows that the distribution of aerosols varies geographically and temporally. The vivid yellow tint on the map indicates a higher concentration of aerosols, most likely caused by volcanic material produced during the eruption. This distribution stretches across multiple locations, following wind patterns and atmospheric processes. Figure (a) depicts the first aerosol dispersal as of November 8, 2024, which is still limited. However, in figures (b) through (d), particularly on November 9-11, 2024, the aerosol concentration rises dramatically, indicating a vigorous eruption phase. Aerosols are distributed in various places surrounding Mount Lewotobi Laki-laki, depending on the wind direction. Furthermore, figures (e) and (f) depict the distribution of aerosols toward the conclusion of the month, on November 26 and 27, 2024. Although volcanic activity appears to have lessened, aerosol quantities are still found, indicating that residual volcanic material remains in the atmosphere. This distribution decreases in comparison to the preceding peak phase, but it is still substantial for the surrounding environment.

According to Schmidt and Carn [26], volcanic aerosol emissions typically peak within 1-3 days of a major eruption, depending on the intensity of the eruption and atmospheric conditions, whereas explosive eruptions of moderate to high intensity can result in a temporary increase in aerosol concentrations in the atmosphere, with the temporal pattern varying according to the duration and frequency of the eruption. However, after the eruption of Mount Lewotobi Laki-Laki in November, the amount increased. According to De Laat [27], the distribution of volcanic aerosols is determined by the height of the eruption column and the properties of volcanic gas emissions, such as sulfur dioxide (SO_2), which forms sulfate aerosols in the atmosphere. Furthermore, explosive volcanic activity has the potential to inject aerosols into the stratosphere, broadening their distribution and prolonging their presence in the atmosphere [28], [29].

According to Eliasson [30], the vast spread of aerosols during Mount Lewotobi Laki-Laki's eruption can be attributed to the impact of wind direction and speed. Wind can diminish aerosol levels in a given place by transporting these particles to a more distant location or transferring aerosol concentrations to different areas based on wind patterns in the atmosphere. Winds moving in the middle and upper air levels are most likely responsible for aerosol dispersal on Mount Lewotobi. Furthermore, Hamzeh [31] explains that atmospheric dynamics play an important role in the presence of aerosols in the atmosphere, with volcanic aerosol concentrations lasting several weeks to months, depending on particle size and atmospheric layer where the particles are dispersed. The pattern of decreasing aerosol dispersion in late November (November 26-27) can be attributed to atmospheric dynamics and gravity-induced particle deposition. Larger volcanic aerosol particles degrade faster due to gravity settling [29], [30], but small particles dispersed in upper atmospheric layers can survive for longer periods of time.

On November 28, 2024, the Lewotobi Laki-laki Volcano Observation Post reported that the eruption was still occurring, with a continuous tremor category. The Sikka Meteorological Station's wind condition data revealed that volcanic ash continued to be carried by winds that were dominating in the Southwest-Northwest direction, resulting in the haze phenomena. This phenomenon is supported by the presence of an inversion layer at an altitude of around 5,500 m (500 mb), which prevents dust and gas particles from rising higher into the atmosphere and spreading vertically, causing dust and gas particles to spread horizontally in accordance with wind movement. High aerosol concentrations, as indicated by the AAI pattern, can disrupt the balance of solar radiation in the atmosphere [32]. According to Trees [33], volcanic aerosol particles can reflect sunlight (cooling effect) and absorb infrared radiation, resulting in a reduction in local surface temperatures. In addition, aerosol deposition disrupts aviation activities from East Nusa Tenggara (NTT), particularly on Flores Island, to Bali due to impaired visibility.

Conclusion

Mount Lewotobi Laki-laki witnessed a considerable rise in volcanic activity in November 2024. The composition of the magma changed, becoming more viscous and rich in silica, resulting in a pattern of volcanic eruptions that had a tremendous impact on the ecology and atmosphere. This activity also caused oscillations in aerosol heights, with the highest peak reaching 10,945 m on November 18, which has the potential to disrupt flights and damage public health. During this period, aerosols were widely distributed due to atmospheric phenomena such as inversion layers, wind patterns, and volcanic gas releases, particularly sulfur dioxide (SO_2). The drop in aerosol concentrations in late November suggests that large particles were deposited by gravity, whereas small particles stayed in the atmosphere for a longer duration. This phenomenon shows that volcanic activity affects the atmosphere both locally and regionally. The aerosol distribution pattern suggests potential effects on air quality, visibility, and climate, supporting prior research on the effect of volcanic aerosols on solar radiation and surface temperature. More research is needed to look at the effect of eruptions on regional weather patterns, the chemical composition of volcanic aerosols on human health and the environment, and the use of machine learning to predict volcanic material dispersion patterns.

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