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Vegetation resilience and environmental impact following industrial mud eruption: Spatial distribution analysis

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ABSTRACT

Background: Hot mudflows from Lapindo Sidoarjo are often released consistently from cracks in the soil layer and begin to submerge the surrounding land cover, such as houses, school buildings, factories, agricultural land, and vegetation. Lapindo hot mud is hot volcanic mud that comes out due to cracks in the soil layer in Siring Village, Porong District, Sidoarjo Regency and has been researched to contain heavy metal compounds and high temperatures. This causes changes in vegetation biodiversity in the Lapindo mud region. This research aims to analyze the influence of the distance to the center of the Lapindo Sidoarjo mudflow on the physical characteristics of the environment and the spatial distribution of surrounding vegetation. **Methods:** The method used is the transect method for taking vegetation samples and snowball sampling for taking informants to support vegetation conditions in the research area. The observation and interview data obtained were then processed and analyzed quantitatively descriptively using multiple linear regression. **Findings:** The analysis carried out shows that the distance from the center of the burst does not have a significant influence on the distribution of air temperature and surface temperature. However, the distance from the center of the spray influences the acidity (pH) of the soil with an influence percentage of 41.2%. In statistical analysis, it was also proven that the physical characteristics of the Lapindo mud region did not affect the diversity of life form types. Apart from that, the analysis carried out in this research also produced six types of vegetation life forms consisting of herbs, bushes, trees, vines, epiphytes, and aquatic, which were distributed randomly throughout the research area in the form of the Lapindo muddy area. **Conclusion:** The existence of vegetation life forms is not determined by the physical characteristics of the Lapindo mud region but is influenced by the relative location characteristics, such as aquatic vegetation that grows due to the presence of water bodies and herbaceous vegetation that can grow on any open land. **Novelty/Originality of this article:** It can be concluded that the emergence of the Lapindo hot mud phenomenon in Sidoarjo only affects soil acidity. Moreover, this phenomenon does not have a significant influence on the spatial distribution of surrounding vegetation.

KEYWORDS: family; life form; location characteristics; spatial distribution; vegetation.

1. Introduction

Siring Village, Porong District, Sidoarjo Regency, East Java Province is a village dominated by the use of primary land for settlements and agricultural land in 2005 (Agustini, 2006). This village is an oil and gas drilling location controlled by PT Lapindo Brantas Inc. On May 26, 2006, a hot mud eruption disaster occurred in this village. PT Lapindo Brantas Inc. manages the Banjar Panji-1 (BPJ-1) oil and gas exploration well which has been operating since 1999 in Siring Village, Porong District, Sidoarjo Regency, East Java Province (Ajija et al., 2011) It is suspected that cracks in the soil layer caused the emergence of hot mud which is currently known as the Lapindo Sidoarjo mud (Anaputra et al., 2015).

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According to several geologists, this disaster is estimated to have a flow rate of 100,000 to 180,000 m3 per day (Antoniadis et al., 2017). Compared to other disasters, such as floods that occur daily or weekly, landslides that last for minutes, and earthquakes that last for seconds, the Lapindo mudflow is a long-term disaster with an estimated duration of up to 30 years (Arifin & Listriani, 2016).

Hot mudflows are often consistently released from cracks in the soil layer and begin to submerge the surrounding land cover, such as houses, school buildings, factories, agricultural land, and vegetation (Azkiyah & Tohari, 2019). This results in changes in land cover, land use, and the biodiversity of the surrounding vegetation. According to Bete et al. (2022), in addition to having an impact on agriculture, the Lapindo mud causes plant death due to high salt levels and excessive nutrient poisoning. Supported by Box (1981) that the Lapindo mudflow has an impact on the agricultural sector, especially rice, sugar cane, and secondary crops. This causes a shift and differentiation of the biodiversity of vegetation that grows above and around the Lapindo mudflow (Cahyaningprastiwi et al., 2021). There are several types of vegetation species that can adapt to using Lapindo mud as a planting medium, such as Allium ascalonicum L (Castree et al., 2009) and Thypa latifolia (Chmielewski et al., 2004) which are also commonly used for phytoremediation or environmental pollution cleaning methods using living plants (Conservation International, 1999). On the other hand, there are types of plant species that will actually experience growth inhibition and death due to the toxic heavy metal content mixed into the soil as a growing medium (Chrastný et al., 2012).

The hot mud overflow in Sidoarjo which was mixed with the soil had a significant impact on the physical, chemical, and biological conditions of the soil directly or indirectly (Danoedoro, 2012). Directly, the mud overflow caused the soil layer to be buried and covered with mud which destroyed rice fields, as well as irrigation facilities and infrastructure. In addition, the Lapindo Mud overflow also destroyed various types of vegetation (Ekawati et al., 2020). In addition to eliminating vegetation at the eruption site, the Lapindo mudflow phenomenon resulted in much of the surrounding agricultural land being neglected because the owners became victims and were unable to manage their land again indirectly (Ekperusi et al., 2019). Lapindo mud causes the surrounding environment to be contaminated with heavy metal elements, such as Mn, Zn, Co, Ni, Cu, Hg, Cr, Cd, and Pb (Erwiyansyah et al., 2021). According to Fitter & Hay (2002), the presence of contaminants can be in the form of toxic heavy metals to organic pollutants. This depends on the interaction of the intrinsic properties of the contaminant with the properties of the soil. An environment contaminated with metal content in the form of cations and anions that enter the soil affects the absorption, mobility, and solubility of metals in the soil (Galloway & Burbey, 2011). In addition, when contaminants, such as Arsenic and Mercury, enter the water system, the transformation process will occur simultaneously due to the aquatic environment (Gaston & Spicer, 2004).

Soil as a supporting medium for plant growth, a provider of oxygen, and a place of nutrition for plant roots can greatly affect vegetation biodiversity (Gelyaman, 2018) so that the entry of heavy metal elements contained in the soil can significantly affect vegetation (Ghozali, 2016). Soil productivity can decrease due to the entry of heavy metals which can then affect the activity of microorganisms and certain nutrients (Handayani, 2022). This condition affects the adaptability of vegetation life which includes process capability, suitability for certain species, and the productivity of the resulting vegetation (Handayani et al., 2013). The elements contained in the Lapindo mud are very toxic to plants. The release of hot mud from the Lapindo Mud source point causes land subsidence, resulting in plants losing their growing medium (Hanung et al., 2016). Land subsidence is a slow or sudden change in the subsidence of the earth's surface caused by the movement of sediment and earth material (Hardianto et al., 2021). The impact of land subsidence in the Lapindo Mud is a reduction in the composition of biodiversity, especially vegetation, which weakens the life support system, especially rice and horticultural plants that initially grew well (Hardjosuwarno, 1990).

According to Liebig's Minimum Law Theory in 1840 in Irwan (1992), the basic needs required for the growth and development of organisms must be available. These basic needs depend on the conditions and interactions of the environment that occur around it (Hidayat, 2007). The emergence of Lapindo hot mud resulted in environmental changes called succession (Himayah et al., 2020). Succession is the process of environmental change due to significant severe disturbances so that natural communities are lost or completely damaged (Indriyanto, 2008). Research conducted by Istiawan & Kastono (2019) stated that the succession that occurred in the Lapindo mud environment was still in its early stages and required a very long time to reach its climax. The mixed condition of Lapindo mud causes spatio-temporal environmental changes, especially air temperature (Jackson & Jackson, 1996), surface temperature (Jalil et al., 2010), and soil acidity (Juliandi et al., 2014), which function as a growing medium for vegetation. According to Karyati et al. (2018), the distribution of surface temperature also increased in line with the increase in the volume of Lapindo mud from 2006-2015. Several related literature studies have raised basic assumptions in this study, namely that there are variations in vegetation biodiversity based on the distance to the center of Lapindo mud (Krisnayanti & Agustawijaya, 2014).

This environmental variation also has an impact on the differentiation of vegetation biodiversity and land cover around it (Lakitan, 1997). Observation of vegetation biodiversity distribution was conducted with the aim of monitoring changes in vegetation biodiversity around the Lapindo mud region in a time-series manner starting from before the Sidoarjo hot mud phenomenon occurred until the current condition in 2024. Although located in the same region, vegetation biodiversity on each side of the Lapindo mud region can be heterogeneous. This is caused by various factors that change the physical characteristics of the environment that is formed, such as air temperature, surface temperature, and soil acidity, resulting in changes in the biodiversity of vegetation that grows in and around it.

2. Methods

2.1 Research flow

This study aims to examine the spatial distribution of vegetation biodiversity as an impact of the emergence of the volcanic mud phenomenon over a very long period of time. The Lapindo Sidoarjo mud phenomenon is a disaster caused by drilling errors (Laratu et al., 2014) by PT Lapindo Brantas Inc. which resulted in the eruption of volcanic mud over a very long period of time. This causes succession or environmental changes that are the basis for the needs of vegetation biodiversity growth and development (Latue et al., 2023). Ultimately, this phenomenon can shift the continuity of living things' activities, especially vegetation biodiversity and land cover, as well as human activities.

In this study, the Lapindo mud phenomenon is the basis for changes in the physical characteristics of the environment which result in changes in the density and distribution of vegetation around it. The Normalized Different Vegetation Index (NDVI) is used to identify changes in vegetation density in a time-series manner over 20 years, from 2004 to 2024. Through the visualization of changes in vegetation density, it can be seen how the Lapindo mud affects the vegetation in the surrounding environment. The next impact to be identified is the physical characteristics of the Lapindo mud region. Vegetation grows in an environment and media that can support the survival of each type of vegetation. Seeing the changes in vegetation density that occur through NDVI visualization, environmental characteristics are estimated to have changed. This is supported by several studies, namely Lenaini (2021), Londo & Kushia (2006), and Lubis (2007), which show that there are contaminants in the form of heavy metals entering the environment.

The physical characteristics used in this study are based on variables supporting vegetation growth in the form of air temperature, surface temperature, and soil acidity. From these variables, it will be studied how much variation in vegetation biodiversity is in the Lapindo mud environment which is toxic and extreme. Then, the distribution of vegetation that occurs in the Lapindo mud region will be studied and identified. Vegetation samples were taken and documented to identify the types of life forms they have. The closer to the source of pollution, the higher the concentration of accumulated heavy metals (Mcilroy, 1976) so that the distance to the center of the eruption is the unit of analysis used in this study and is supported by the absolute location and relative location around it.

2.2 Research workflow

The research workflow begins with preparation that includes literature study and area study on environmental conditions and biodiversity of Lapindo mudflow vegetation. At this stage, assumptions are determined to underlie the formulation of the problem which is the main focus to be studied in this study. In addition, literature study is also conducted to determine the condition of vegetation biodiversity before and after the Lapindo mudflow phenomenon. After the preparation stage, this study continues with the pre-field stage which begins with determining the number of stations and vegetation biodiversity observation plots, and determining the format of interviews with local figures, as well as collecting secondary data.

Furthermore, this research is continued with the field survey stage. At this stage, primary data collection is carried out which is used as the main focus of the research. The primary data collected can be seen in namely the type of life form of vegetation biodiversity that grows, the physical condition of the research area, the absolute location, and the relative location of the vegetation objects studied. In addition, at the field survey stage, validation of secondary data that has been processed at the pre-field stage is also carried out. Data validation is carried out by observing the research area and taking samples of the physical characteristics of the environment, as well as taking vegetation samples through photograph-based. In addition, researchers also conducted interviews with local figures to support the conditions of the physical characteristics and vegetation that grow in the research area.

2.3 Unit of analysis

Initially, Lapindo Mud only appeared in Siring Village, Porong District, Sidoarjo Regency, East Java, as an oil and gas drilling location by PT Lapindo Brantas Inc. However, the source point of the hot mud eruption continued to overflow which then spread to the surrounding areas. Until now, several villages in Porong, Jabon, and Tanggulangin Districts have felt the impact of Lapindo mud. In this study, the area will be studied regionally around the Lapindo mudflow.

The unit of analysis used in this study was an observation point that was determined randomly following the transect line. The transect line was made randomly based on the representative land cover in the study area. In addition, the distance of vegetation objects located at the observation point was also measured from the center of the Lapindo mudflow. The closer to the source of pollution, the higher the concentration of accumulated heavy metals (Naidu & Bolan, 2008) so that it can affect the physical condition of the environment as the basis for vegetation growth media. Therefore, distance is used in this study to examine the effect of Lapindo mud on the distribution of vegetation around it.

2.4 Research variables

This study will discuss the spatial distribution of vegetation as an impact of the emergence of the Lapindo hot mud phenomenon. The independent variables used in this study are the distance to the center of the Lapindo hot mud eruption (X1), air temperature (X2), surface temperature (X3), and soil acidity (X4) as physical characteristics of the environment in the research area. The dependent variable that is the result of the emergence of the Lapindo mud phenomenon is the diversity of vegetation life forms (Y). The parameters used were obtained through various literature studies listed in Table 1.

Table 1. Research variables

Research Variables	Mark
Distance to the center of the Lapindo mudflow	According to field survey conditions
Air temperature	< 20^0C, 20^0C - 25^0C, 25^0C - 30^0C, 30^0C - 35^0C, & > 35^0C
Surface temperature (Himayah et al., 2020)	< 23^0C, 23^0C - 26^0C, 26^0C - 29^0C, 29^0C - 32^0C, & > 32^0C
Soil acidity (Nopriani et al., 2023)	pH ≤ 6,5, 6,5 ≤ pH ≤ 7,5, & pH ≥ 7,5
Diversity of vegetation life forms	1, 2, 3, 4, 5, & 6

2.5 Method of collecting data

Data collection conducted in the study was divided into two, namely primary and secondary data collection. The primary data used were the absolute location and relative location of vegetation objects, distance from the center of the eruption, altitude, air temperature, soil temperature, soil acidity, and distribution of vegetation composition. Meanwhile, the secondary data used were NDVI values, altitude, land cover, air temperature, and surface temperature from 2004 to 2024, as well as the administrative boundaries of the research area (Table 2).

Table 2. Research data

No	Data	Data types	Source
1.	Absolute location of vegetation objects	Primary	Field survey using handheld GPS
2.	Relative location of vegetation objects	Secondary	Interviews with local figures and field surveys
3.	Administrative boundaries of the research area	Primary	Geospatial Information Agency (BIG) and Open Street Map (OSM)
4.	Distance of vegetation objects from the spray center	Primary	Field survey
5.	NDVI value	Secondary	Image processing of Sentinel-2 10 m resolution, Landsat 8 OLI/TIRS, and Landsat 7
6.	Land cover	Secondary	Sentinel-2 LULC 10 m resolution image processing and field survey
7.	Height	Secondary	DEMNAS data processing
8.	Slope	Secondary	DEMNAS data processing
9.	Air temperature	Primary	Field survey
10.	Surface temperature	Primary	Field survey
11.	Soil acidity (pH)	Primary	Field survey
12.	Vegetation composition	Primary	Field survey

2.5.1 Secondary data collection

Secondary data collected in this study are in the form of institutional data. Institutional data is data obtained through several related agencies to support the sustainability of the research, namely the Geospatial Information Agency, the Central Statistics Agency, and several other related agencies. Topographic Map of Indonesia on a scale of 1:25,000, source: Ina-Geoportal page of the Geospatial Information Agency. National Digital Elevation Model (DEMNAS) data, source: Ina-Geoportal page of the Geospatial Information Agency. Digitization of the Lapindo mud region through Landsat 8 Operational Land Imager (OLI) imagery in 2024, source: EarthExplorer page managed by the United States Geological Survey (USGS). Landsat 7 Operational Land Imager (OLI) imagery in 2004, 2006, and 2024, source: United States Geological Survey (USGS). Data on the physical condition of the research area from local agencies and figures.

2.5.2 Primary data collection

Primary data collection was carried out during field survey activities and recording related to the research. The implementation of the field survey was carried out through photograph-based or by observing and documenting in the form of photos of each vegetation growing around the Lapindo Mud region. Field surveys were also conducted to verify secondary data obtained through agencies and related literature sources. The primary data collected was in the form of data on the types of life forms of vegetation biodiversity in the Lapindo Mud region. Data were collected through a field survey conducted for three days at 08.00-10.00 WIB on March 25-28, 2024 in the Lapindo Mud region which covered several villages in three sub-districts, namely Porong District, Jabon District, and Tanggulangin District. Primary data collection was taken during the transition from the dry season to the rainy season so that it was assumed to represent both seasons.

Table 3. Primary data

Primary Data	Source
Vegetation objects	Field survey observation
Coordinate points	Field survey observation and Handheld GPS
Air temperature	Field survey observations and Kestrel 5000
Surface temperature	Field survey observation and Soil Analyzer
Soil acidity (pH)	Soil Analyzer
Relative location of vegetation objects	Interview with local figures

2.6 Sampling method

2.6.1 Vegetation sampling methods

The sampling technique used in this study was taken through the transect and plot methods. The transect sampling method is the creation of a transverse line in the research area with the aim of determining the relationship between vegetation changes and environmental changes (Nopriani et al., 2023). The line transect method can estimate the number of objects around it, especially for animals and vegetation objects. In addition, this method is used to determine the type of vegetation in an area (Plumlee et al., 2008). Based on the 11 station points, 67 observation plots were obtained. From the observation plot, vegetation samples were taken randomly with the criteria of vegetation life forms that grow naturally at the observation point. Each sample discovery was recorded through observation and documentation of the type of life form.

2.6.2 Informant collection method

The informant's answers in this study were used to support the physical characteristics and environmental changes that occurred due to the Lapindo mud phenomenon. Informants were taken through snowball sampling which is a nonprobability sampling method (Prasetyo et al., 2021). Sampling in snowball sampling is carried out in a chain or multi-level manner by rotating from one informant to another (Prasetyo, 2023). In determining the sample, initially one or two people were selected, then the researcher would look for the next informant through information provided by the previous informant (Salwati et al., 2013).

2.7 Data processing

2.7.1 Height data processing

The altitude area is one of the aspects used in this study to examine the biodiversity that grows on it. According to Junghuhn's Climate Theory, vegetation grows based on different altitude variations. The altitude variations formed in the Lapindo mud are made to explain the suitability of plant biodiversity with Junghuhn's Climate Theory. The data used in processing altitude data in the Lapindo Mud region is the National Digital Elevation Model (DEMNAS) data with a spatial resolution of 0.27-arcsecond and the EGM2008 vertical datum obtained through the Geospatial Information Agency data portal, namely the tanahair.indonesia.go.id page. The data is processed using the ArcGIS Pro device through several stages, namely cutting DEMNAS based on the Lapindo Mud region vector polygon, classifying altitude based on the specified altitude area classification, and converting the DEMNAS data for the Lapindo Mud region into a shapefile format so that the altitude area can be visualized in the form of a height map of the Lapindo Mud region.

2.7.2 Land cover data processing

Land cover is the object most affected by the 2006 Lapindo Mud phenomenon. The entry of Lapindo Mud content in the form of toxic heavy metal elements tends to damage land cover so that specific changes occur. Before the emergence of the phenomenon, land cover in the Lapindo Mud region was dominated by agriculture, plantations, wild vegetation, facilities and infrastructure, industrial areas, and residential areas. However, various land covers and human activities in them were destroyed by the Lapindo Mud phenomenon to cover three sub-districts, namely Porong, Tanggulangin, and Jabon Sub-districts (Purnomo et al., 2018). The data used in making the visualization of the Lapindo Mud region land cover map is Sentinel-2 Landuse/Landcover (LULC) satellite imagery data with a spatial resolution of 10 meters WGS84 projection which is Level-1C data (ToA reflectance) and obtained through Google Earth Engine (GEE) script code processing. The series of spatial data processing in question includes cutting LULC raster data based on the vector polygons of the research area, namely the Lapindo Mud region, reclassification of each type of land cover that has been determined above the research area, downloading data in shapefile format to facilitate analysis and processing of spatial data, and creating a land cover map layout.

2.7.3 Normalized difference vegetation index (NDVI) processing

Normalized Different Vegetation Index (NDVI) is a quantitative index that represents greenness and is used to measure density and assess changes in plant health. The values indicated in this index range from -1 to +1 (Rowe & Speck, 2005). In this study, NDVI is calculated as the ratio between the measured reflectance of the near infrared band and the red band. The waves detected in these two bands are able to capture the photosynthetic activity in each pixel. The Sentinel-2 band extraction in the research area is then carried out in the next stage in the form of radiometric calibration to convert the digital number (DN) value into radians which are converted back into reflectance values and are considered to represent the actual value of the earth's surface object (Hanung et al., 2016). The radiometric calibration is run by GEE automatically to produce accurate NDVI until it is continued to enter the NDVI computation stage with the following formula.

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)} \quad \text{(Eq. 1)}$$

With the following description:
NDVI: Normalized Different Vegetation Index
NIR: Near infrared band
Red: Red band

The calculations obtained through the computation are analyzed periodically according to the time period specified in this study, namely from 2004, 2006, and 2024. At the visualization and analysis stage, the periodic graph produced through GEE can display variations in NDVI values temporally which represent changes in vegetation density and health. In addition, the NDVI values in the research area, namely the Lapindo Mud region, are visualized into a map with a color legend representing each NDVI value interval.

Table 4. Classification of greenness level of NDVI value

NDVI Value	Greenness Level
-1 ≤ NDVI < 0	No vegetation, water bodies, built-up land, and cloud cover
0 ≤ NDVI < 0,25	Greenness is very low
0,25 ≤ NDVI < 0,50	Low greenness
0,50 ≤ NDVI < 0,75	Low greenness
0,75 ≤ NDVI ≤ 1	Low greenness

The results of NDVI processing are used to identify changes in vegetation density that occur in the Lapindo Mud region periodically, namely in 2004, 2006, and 2024, by utilizing Landsat 7 ETM + imagery. The NDVI value in the Lapindo Mud region is classified according to vegetation density from -1 to +1, which indicates land conditions ranging from non-vegetated to highly green, as shown in Table 4. The closer to the value of +1, the higher the level of greenness, indicating that the vegetation tends to be healthy and has a high density.

2.7.4 Interpolasi inverse distance weighting (IDW)

Inverse Distance Weighting (IDW) interpolation is a spatial method used to estimate the value of a variable at an unmeasured location based on measured values taken around it. This interpolation has the principle that closer data points are estimated to be greater than the influence of more distant data points (Salganik & Doughlas, 2007). The value at an unmeasured location is calculated as an average based on the measured data around it using the following formula.

$$z_0 = \sum_{i=1}^{n} w_i . z_i$$

(Eq. 2)

Description:
z0 : Estimated point value
wi : Weight factor of point -i
zi : Value of estimated point -i

The collection of physical aspect data at each observation point of this study is considered to represent the surrounding area so that IDW interpolation in this study is used to provide an overview of the distribution of physical aspects (air temperature, surface temperature, and soil acidity) in the research area as a whole. This interpolation produces a map to determine the estimated value of physical aspects in areas that are not sampled.

2.8 Analysis method

2.8.1 Quantitative descriptive analysis

Quantitative descriptive analysis is used to analyze data by providing an overview of the data that has been taken in the field (Sugiyono, 2015). This analysis is used to describe sample data in a population of research objects. In this study, the sample data taken were vegetation samples around the Lapindo Mud region. Vegetation in the Lapindo Mud region experienced very significant changes due to sudden extreme changes that occurred in the environment. Various spatio-temporal aspects of the environment are the basis for the adaptability of vegetation in it. Physical aspects that include several variables in the Lapindo mud region are measured through previously determined parameters. Changes in vegetation biodiversity occurred significantly due to the emergence of the Lapindo hot mud phenomenon which is toxic to living things around it. The changes that occurred will be analyzed spatially, namely the identification of spatial distribution patterns of vegetation after the Lapindo mud disaster. Thus, this study uses a quantitative descriptive analysis approach to explain the distribution of vegetation caused by the Lapindo mud disaster causing primary succession.

2.8.2 Multiple linear regression analysis

The analysis method used in this study is analysis which is one of the statistical analysis techniques to identify the relationship between two or more quantitative variables (Saputra et al., 2016). In this study, the analysis used is multiple linear regression analysis. This is because the data used is data in interval and ratio scales that are quantitative, and are multivariate or have more than one factor that affects the dependent variable. Thus, multiple linear regression analysis is used to analyze the effect of the distance of the Lapindo mudflow center, air temperature, surface temperature, and soil pH on the diversity of vegetation life forms. The variables measured in this study are the distance of the mudflow center (X1), air temperature (X2), surface temperature (X3), and soil acidity (X4). From these variables, they will be linked to the diversity of vegetation life forms which is the main focus of this study.

3. Results and Discussion

3.1 Physical aspects supporting vegetation growth

3.1.1 Air temperature

Based on data measurements taken at the field survey stage at each observation point, the air temperature taken in the research area has a variable value ranging from 32.00^{0}C to 36.25^{0}C. It can be seen at observation point B which is the closest point to the Lapindo mudflow, it has a temperature value of 35.4^{0}C. However, there was a high air temperature value again at observation point J, which is an observation point with a greater distance than point B. As seen in Figure 6, the air temperature has a random distribution pattern and does not depend on the distance to the center of the Lapindo mudflow. At observation point B which is the closest observation point to the Lapindo mud, which is 548 m away, it has a high temperature of up to 36.25^{0}C. However, high temperatures again occurred at observation points G, H, J, and K which are further away, namely 2206 to 3399 m from the center of the mudflow. In addition, lower temperatures are actually at observation points that are quite close to the center of the mudflow. This proves that the distance to the center of the Lapindo mudflow does not have a significant effect on the distribution of air temperature in the study area (Servina, 2019). Based on the researcher's findings, high air temperatures occur in land cover dominated by built-up land, such as settlements and road networks (Setiawan, 2022). Conversely, air temperatures will be lower when land cover in the form of built-up areas decreases (Setiawan, 2013). Thus, air temperature is more influenced by land cover than by distance to the center of the Lapindo mudflow (Sriyono, 2019).

3.1.2 Surface temperature

In Figure 7, it can be seen that the surface temperature also experiences the same distribution pattern as the air temperature, namely having a random distribution pattern with a temperature value ranging from 31.00^{0}C to 35.99^{0}C. The surface temperature is not affected by the distance to the center of the Lapindo mudflow, but is influenced by the air temperature and land cover around it. At observation point B, there was a high surface temperature reaching 35.99^{0}C. This is due to the land cover which is only filled with pure Lapindo mud and limestone boulders used as embankments. High temperatures also occurred again at observation points H, J, and K with a relatively further distance compared to observation point B, which ranged from 2218-3399 m from the center of the Lapindo mudflow. At these three observation points, land cover is dominated by built-up areas in the form of settlements and road networks so that the surface temperature is relatively high. In addition, the minimal vegetation at these three points also affects the high temperature. At other points, such as observation points C, D, E, F, and G, the surface temperature is lower, reaching 31.00^{0}C. This is due to land cover dominated by vegetation and water bodies (Sungkowo et al., 2015). The presence of vegetation causes a decrease in surface temperature due to the activities of the vegetation, such as evapotranspiration and reflection of sunlight (Supriatna, 2018).

3.1.3 Soil acidity

Based on the primary data in the visualization soil acidity has a gradient distribution pattern, which is spread gradually following the distance to the center of the Lapindo mudflow, with a value of 4.7 to 6.3. The closer to the center of the Lapindo mudflow, the lower the soil acidity will be, which means that the soil will be increasingly acidic as it approaches the center of the mudflow. This is in line with several previous studies which stated that Lapindo mud contains heavy metal compounds on a high scale, such as Aluminum (Al), Iron (Fe), Arsenic (Ar), and Lead (Pb). According to several previous studies, soil acidity is influenced by the activity of Hydrogen ions in compounds contained in the soil. In this study, high content of heavy metal compounds was found in Lapindo mud, thus indirectly affecting soil acidity (Sutarno & Setyawan, 2015). The closer to the center of the Lapindo mudflow, the more acidic the soil will be, which is influenced by the content of heavy metal compounds (Thohiron & Prasetyo, 2012).

3.2 Impact of lapindo mud on the environment

Lapindo mud, which is a hot mud phenomenon with high toxicity, causes environmental changes or succession in accordance with the research of Tjitrosoepomo (1985) who studied the succession of Lapindo mud which was still in its early stages in 2013. Two informants who contributed to this study, namely FJ and his colleague as a Lapindo mud tour guide, helped researchers in exploring the area affected by Lapindo mud to the location of the center of the eruption (Trisilowaty, 2012). The exploration was carried out by tracing the Lapindo mud embankment and observing the biodiversity of vegetation growing at Station A. Then, continued with exploration to the central embankment of the Lapindo mud eruption which is one of the observation stations in this study, namely Station B. Observations made in the area affected by Lapindo mud did not find any vegetation growing. However, near the center of the eruption, vegetation with a type of life form in the form of trees was seen (Tunstall, 2008). It can be seen that the trees are homogeneous and planted in rows following the embankment (Ulfindrayani et al., 2019). According to the statement of Informant FJ and his colleague, this tree grew because it was deliberately planted by the government which functions to help guests of government agencies and researchers who come so that monitoring the Lapindo mud phenomenon can be done more comfortably. This tree can grow because the soil is mixed with the natural soil of Sidoarjo Regency with an alluvial type (Verawati et al., 2023). However, no vegetation was found growing on the Lapindo mud that was not mixed with soil or other materials (Wahyuni et al., 2021).

On the Lapindo mud embankment, there are several vegetation with life form types in the form of herbs, bushes, vines, and epiphytes. According to the statement of informant FJ, this embankment can be overgrown with vegetation of this type of life form because the embankment was made with alluvial soil and a collection of limestone fragments built by one of the Gresik factories in collaboration with the Sidoarjo Regency Government

(Pemkab). At Station B, researchers found that the vegetation that grew was a type of tree life form vegetation. According to statements by FJ (54) and IR (59), there is no vegetation that can grow on pure Lapindo mud. However, this tree grew due to planning made by the local government which functioned for the convenience of surveyors and researchers from various agencies in monitoring Lapindo mud (Widiarti, 2018).

3.3 Vegetation changes

The area affected by the Lapindo mud was initially an area dominated by settlements, agriculture and plantations, and industrial areas in the form of factories. This information was supported by the testimony of FJ (54), as one of the victims affected by the Lapindo mud who currently works as a tour guide. Before the emergence of the Lapindo mud, the majority of people depended on the agricultural, plantation, and industrial sectors for their livelihoods. According to FJ, and 10 other informants, the agricultural activities in the affected area were rice fields, sugar cane, and secondary crops. In addition, there were also plantations dominated by various vegetables, such as kale and spinach. In addition, there were also fruit plantations dominated by watermelon and melon (Widodo, 2012).

The area is outside the area affected by the Lapindo mud to the south. The area was initially a local community settlement that was voluntarily abandoned (Widoretno, 2010). This was because the groundwater consumed daily was contaminated with heavy metals so that it could not be used (Wijaya et al., 2021). In addition, the smell of compounds caused by the Lapindo mudflow was strong enough that the local people decided to migrate to various areas. In the end, the former community settlement area was purchased by the government and allocated as a greening area and vegetation growth area (Wijaya, 2019). The transition of the built-up area to the vegetation growth area acquired by the government was not well maintained. It can be seen in Figure 10 that there is a lot of wild vegetation found with types of life forms of herbs, bushes, trees, bushes, and climbing vegetation that fill the area.


Fig. 1. Residential transition land

The land use change that was originally a community settlement also occurred in the outer area affected by the Lapindo mud in the west. As in the southern part, the community in the western part also migrated due to groundwater contamination, increased air temperature, and pungent odors (Wistiani, 2014). The residential land was then purchased by the Sidoarjo Regency Government (Pemkab) and shifted from a settlement to a vegetation area (Wan, 2020). Unlike the southern part which was deliberately left by the Sidoarjo Regency Government (Pemkab) to be overgrown with wild vegetation, the western part of the outer area affected by the Lapindo mud was planted with corn plantations (Zea mays) which are included in the type of herbaceous life form (Wu et al., 2017). During the observation of the western part, researchers found that the corn plantations that were planted were not well maintained (Yuliana et al., 2015). There was a drought and a lot of wild vegetation grew in the corn fields (Zannah & Sudarti, 2021). The wild vegetation that grew included herbs, shrubs, and climbing vegetation.

Fig. 2. Corn fields (zea mays) in the western part of the outer area affected by Lapindo mud

Changes in vegetation biodiversity due to the emergence of the Lapindo mud phenomenon are also supported by several informants who stated that agricultural areas and activities, as well as plantations, were reduced due to sinking in the area affected by the Lapindo mud. In addition, other informants also stated that vegetation in the outer area affected by the Lapindo mud was not as fertile as before and the land became barren.

"The average job before the Lapindo mudflow was as a farmer, because the vast rice fields that were affected, were drilled. Hectares of 3 sub-districts" (NF, 54 years old)
"The form of land use that was utilized was agriculture. There were rice fields, sugar cane, secondary crops ..." (MZ, 42 years old)
"After the Lapindo mudflow, the impact reached 2-3 km. Agriculture and plantations were lost. Then the plants around it were also barren" (NH, 52 years old)

Based on the observations and statements of the informants, it is proven that there was a significant change in vegetation biodiversity in the research area. In the area affected by the Lapindo mud, all vegetation biodiversity, including agriculture and plantations, was lost due to sinking.

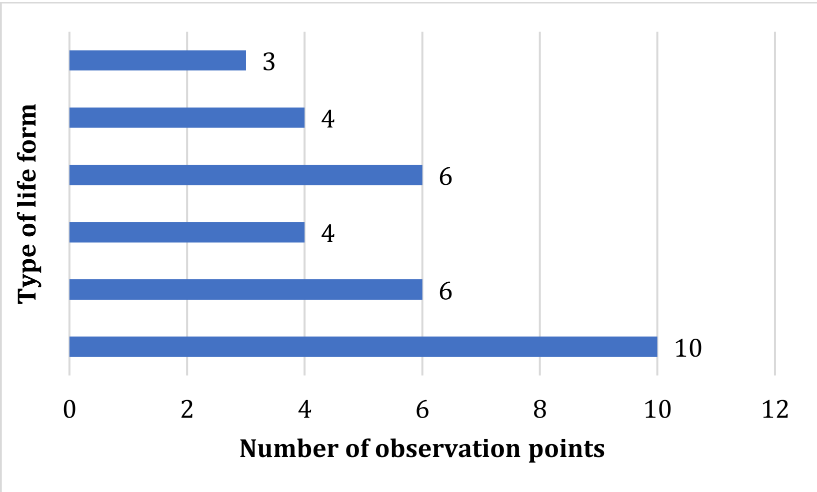

Fig. 3. Bar chart of types of natural vegetation life forms that grow

Based on field surveys conducted at each station, researchers found six types of vegetation life forms including aquatic vegetation, epiphytes, vines, trees, shrubs, and herbs. In Figure 5.7, it can be seen that vegetation that grows with the herbaceous life form type almost fills all observation points. Of the 11 observation points, this type of life form grows at 10 observation stations, which means that herbs have a growth percentage of 90% in the research area. The next vegetation that grows the most is vegetation with the shrub and vine life form types which fill 6 of the 11 observation points with a percentage of 54%. Then, followed by tree and epiphytic vegetation that grows at 4 observation points, and aquatic vegetation that grows at 3 observation points, which means that these three vegetation grow in the research area with a percentage below 50%.

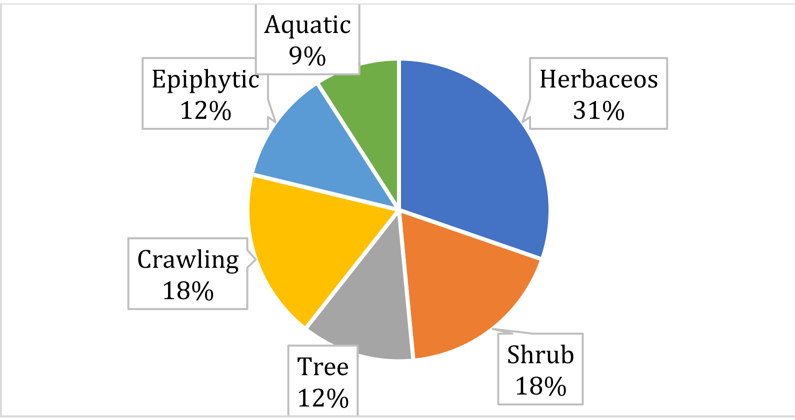

Fig. 4. Pie chart of vegetation life form percentage

Based on Figure 4, herbs are the most abundant vegetation in the research area with a percentage of 31%. The herbs that grew in this study were grass vegetation that managed to survive and grow in various habitat conditions, and with various conditions, including extreme environments, such as infertile soil, high soil temperature and acidity, and extreme drought (Mcilroy, 1976). Based on field data, the research area has an acidity value ranging from 4.7 to 6.3 which has a gradient distribution pattern. This is due to the lower soil pH value as the distance to the Lapindo mudflow center increases. The closer to the Lapindo mudflow center, the lower the soil acidity, which means the soil will be more acidic as the distance approaches the Lapindo mud. In Figure 4, it can be seen that herbs have a random distribution pattern, independent of the distance to the eruption center or soil pH. This proves Mcilroy's theory (1976) that herbs can grow in various environmental conditions.

Table 5. Representative group of family types of vegetation life forms

Life form types	Family group representative
Herbs	Poaceae
Bush	Melastomataceae
Creeping	Convolvulaceae
Tree	Musaceae
Epiphyte	Bryophyta
Aquatic	Pontederiaceae

In this study, each type of life form of vegetation that grows naturally in the research area is represented by a family group. In herbaceous vegetation, the family group that grows is vegetation originating from the Poaceae family which is grass. Based on the data processing carried out, it was found that there was a random pattern in the distribution of the diversity of life forms of vegetation due to the emergence of Lapindo mud. According to several previous studies and informant testimonies, vegetation cannot grow in pure Lapindo mud. This occurs at observation point B which is located in the area affected by Lapindo mud with a distance of 548 m from the center of the eruption. At this point, no vegetation was found growing naturally. However, vegetation can grow if the pure mud is added with a mixture of other planting media which also depends on the adaptability of each type of vegetation. Although vegetation cannot grow naturally at observation point B, the local government is reforesting the observation point which functions to provide comfort for monitoring and research activities related to Lapindo mud. The planting media used is alluvial soil mixed with Lapindo mud. This proves that vegetation can grow if the planting media used is a mixture of pure Lapindo mud with other planting media.

In Figure 15, it can be seen that observation point F has the highest vegetation diversity which is visualized in dark green. This point is 1513 m from the center of the Lapindo mud eruption. Observation point F has a higher diversity of life forms compared to observation points with a greater distance from the center of the eruption, such as points H, I, J, and K, which are 2218, 2342, 3470, and 3399 m from the center of the mudflow. This proves that the distance of the observation point to the center of the Lapindo mudflow does not affect the diversity of vegetation life forms in the surrounding environment. Through validation and identification of the research area, the diversity of vegetation life forms is not based on the center of the Lapindo mudflow, but rather depends on the land cover and the relative location where the vegetation grows. At observation point F which has the highest vegetation diversity, the land cover that meets it is quite varied, namely built-up areas in the form of settlements, road networks, unbuilt land, empty land, mixed plants, and water bodies in the form of rainwater drainage. This causes the growth of natural vegetation that meets the six life form coverages in this study, namely herbs, shrubs, vines, trees, epiphytes, and aquatic. Meanwhile, other observation points that are further away with less diversity of vegetation life forms, such as observation points G and H, are dominated by built-up land cover in the form of settlements and road networks.

4. Conclusions

In the results of data analysis using regression tests, it was found that distance has a greater influence on air temperature than on surface temperature. Meanwhile, distance has the greatest influence on soil acidity. This is also supported by spatial data in the form of air temperature distribution, surface temperature, and soil acidity. Air temperature and surface temperature have random distribution patterns and are not determined based on the distance to the center of the Lapindo mudflow. However, there is a difference in soil acidity which has a lower value when approaching the center of the Lapindo mudflow, which proves that acidity will increase as the distance to the center of the mudflow approaches. In addition, based on statistical calculations, the distance to the center of the mudflow and the physical characteristics of study area do not have a significant effect on the diversity of vegetation spread across the Lapindo mud region.

Based on the analysis carried out, the life form of natural vegetation in this study has a random distribution pattern that occurs due to the intervention of the surrounding population. This distribution is not influenced by the distance to the center of the Lapindo mudflow and physical characteristics, but is influenced by the type of land cover where the vegetation grows, such as water bodies overgrown with aquatic vegetation and empty land overgrown with wild herbaceous vegetation. Land cover dominated by built-up areas, such as settlements and road networks, has relatively little diversity of natural vegetation life forms. Meanwhile, land cover dominated by unbuilt land and water bodies has high diversity of vegetation life forms and meets the six types of life forms determined in this study. In addition, there is no vegetation that grows naturally in pure Lapindo mud so that the local government planted tree a vegetation by mixing alluvial soil in the mud embankment area.

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