RESEARCH ARTICLE

Correlation between Precipitation over the Andralanitra Landfill and PM2.5 and PM10 Concentrations in the City of Antananarivo, Madagascar

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Abstract: This study examines the correlation between particulate matter (PM2.5 and PM10) concentrations in the city of Antananarivo and precipitation over the constantly burning open landfill (Andralanitra), located 12 km from the city. Statistical analysis was conducted using daily PM2.5 and PM10 concentration data from air quality monitoring stations (November 2023 to October 2024) and daily precipitation data from the Andralanitra landfill. The results indicate a weak negative correlation between the daily concentrations of PM2.5 and PM10 and the daily precipitation levels. The correlation is stronger for PM10 than for PM2.5, likely due to the differences in particle size: PM10 particles are more affected by precipitation. Additionally, monthly precipitation levels at Andralanitra show a moderate negative correlation with the monthly concentrations of PM2.5 and PM10. Seasonal variations also influence the overall concentrations of PM, and an increase in precipitation intensity at Andralanitra leads to a reduction in the number of days considered polluted. These findings emphasize that air pollution caused by particulate matter (PM2.5 and PM10) is directly influenced by precipitation levels at Andralanitra.

Keywords: PM2.5, PM10, Pearson correlation coefficient, washing effect of precipitation

1 Introduction

Andralanitra is an open dump located 12 km east of downtown Antananarivo. Due to the lack of proper waste management, thick smoke from landfill fires rises constantly over the site [1].

A study by INERIS (Institut National de l'Environnement Industriel et des Risques) revealed that the smoke from these fires is mainly composed of asphyxiating pollutants, toxic compounds, and irritating pollutants, including particulate matter (PM) [2]. The concentration of particulate matter, specifically PM2.5 (particles with a diameter lesser than 2.5 μm) and PM10 (particles with a diameter lesser than 10 μm), significantly increases during landfill fires, which can severely affect public health [2, 3]. Exposure to these particles can cause respiratory and cardiovascular issues [4, 5].

The fact that thick toxic smoke is constantly released from the Andralanitra landfill constitutes a major public health problem that cannot be ignored. This raises an important question: "Do the fumes from the Andralanitra landfill have a significant impact on the overall air quality of Antananarivo, or is their effect negligible?" This study aims to answer this question.

Due to the lack of available data, we are unable to carry out a direct study between smoke from the Andralanitra landfill and PM2.5 and PM10 concentrations in the city of Antananarivo. However, an indirect study can be carried out based on the impact of rainfall on landfill fires and on the principle of washing effect of precipitation. Washing effect of precipitation is a physical phenomenon that describes the effect of precipitation on the concentration of particulate matter in the air. Previous studies have shown that an increase in precipitation leads to a decrease in PM2.5 and PM10 concentrations [6, 7]. Precipitation over the landfill impacts the amount of PM (PM2.5 and PM10) present in the landfill smoke. Since PM can travel long distances through diffusion, the smoke from the Andralanitra landfill affects the PM concentrations in the city of Antananarivo [8]. Therefore, there is an indirect relationship between precipitation over the Andralanitra landfill and PM2.5 and PM10 concentrations in Antananarivo. This study seeks to explore this relationship.

This work presents a statistical analysis of the relationship between precipitation over the Andralanitra landfill and PM2.5 and PM10 concentrations in Antananarivo.

2 Methodology

2.1 Objective

This study aims to statistically establish a relationship between precipitation at Andralanitra and the concentrations of PM2.5 and PM10 in the city of Antananarivo. By doing so, it will indirectly demonstrate that the smoke from the Andralanitra landfill significantly affects the overall PM2.5 and PM10 concentrations across the city.

2.2 Study Area

The study area is located in the city of Antananarivo, the administrative and economic capital of Madagascar. Situated in the Highlands at an altitude of 1,250 meters, Antananarivo experiences a subtropical climate, with a rainy season from November to March and a dry season from April to October, including a southern winter from June to August. With an estimated population of 1,391,433 in 2022, Antananarivo is the most populated and polluted city in the country [9].

Located on the outskirts of the city, the Andralanitra landfill is the only public waste disposal site in Antananarivo. It handles the entire city's solid waste, amounting to approximately 1,200 m^3 of household waste per day. The landfill, considered saturated, contains around 2,100,000 m^3 of waste [10]. Due to the lack of waste compaction, inadequate management of gases from decomposition, and fires set by informal waste pickers, a thick toxic smoke continuously escapes from the landfill [1, 10].

2.3 Data

The study period extends from November 2023 to October 2024. Two main datasets were used in this study.

2.3.1 Daily PM2.5 and PM10 Concentration Data of Antananarivo

These data represent the average concentrations of PM2.5 and PM10 over 24 hours for the entire city of Antananarivo, from November 2023 to October 2024. They were calculated based on information provided by the city's air quality monitoring stations.

The data from the monitoring stations were collected from the PurpleAir website. In collaboration with the Centre National de Recherche sur l'Environnement (CNRE) of the Malagasy government, PurpleAir has access to the data collected by these stations.

On the PurpleAir website, for the Antananarivo location [11], the following parameters were selected:

Data layer: Raw PM2.5 (μg/m^3) (for PM2.5) and Raw PM10 (μg/m^3) (for PM10).
Apply conversion: No
Averaging period: 1 day
Base map type: Detailed
Show outside: Checked
Show inside: Checked
Show sensors reporting or modified within: All time
Preferred units: Metric.

Using these parameters, we selected the following monitoring stations: Mada AQ Ambatobe 2, Mada AQ Amboditsiry 2, Météo Madagascar 001 DGM Ampandrianomby, and the Centre National de Recherche sur l'Environnement. Only data from these stations were used for this study, as, among the stations with the necessary data, only these had a reliability rate of 100%.

Each station provided two datasets concerning the 24-hour average concentrations of PM2.5 and PM10, covering the period from November 2023 to October 2024. By averaging these two datasets and eliminating outliers, we determined the daily concentrations of PM2.5 and PM10 for each monitoring station during the study period.

For any given day, the average PM concentrations (PM2.5 and PM10) were calculated from the data provided by the four monitoring stations for that day. By performing this operation over the 366 days of the study period, we obtained the daily concentrations of PM2.5 and PM10 for the city of Antananarivo, from November 2023 to October 2024, as illustrated in Figure 1.

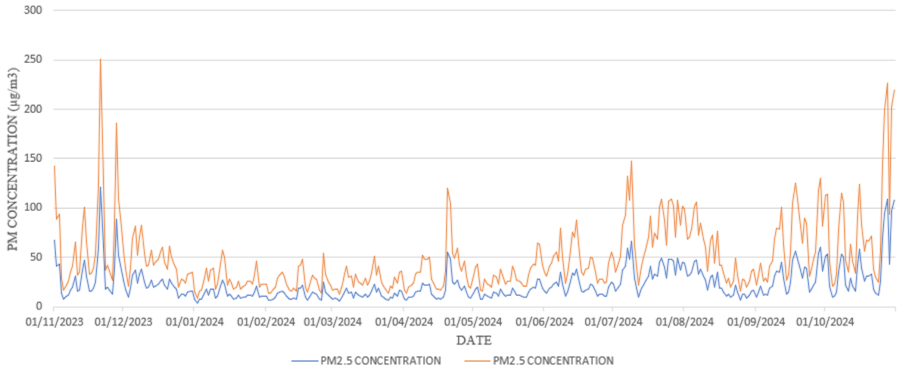

Figure 1 Daily concentrations of PM2.5 and PM10 in the city of Antananarivo from November 2023 to October 2024

The monthly concentration was calculated by averaging the daily concentrations over the course of one month.

In this study, we follow the standards set by the World Health Organization (WHO) in 2021, which state that a day is considered polluted if the daily average concentration of PM2.5 exceeds 15 μg/m^3 or if the daily average concentration of PM10 exceeds 45 μg/m^3 [12].

2.3.2 Daily Precipitation (RR) in Andralanitra

These data represent the daily average precipitation recorded at the location of the Andralanitra landfill over the period from November 2023 to October 2024. They were obtained through NASA's POWER (Prediction Of Worldwide Energy Resources) project.

To collect these data, we used the NASA POWER website [13], selecting the following parameters:
Single point
User Community: Renewable energy
Temporal Level: Daily
Location: Latitude: -18.9123; Longitude: 47.5772
Time Extent: November 1, 2023, to October 31, 2024
Parameters: Precipitation.

The data obtained through NASA POWER are illustrated below in Figure 2.

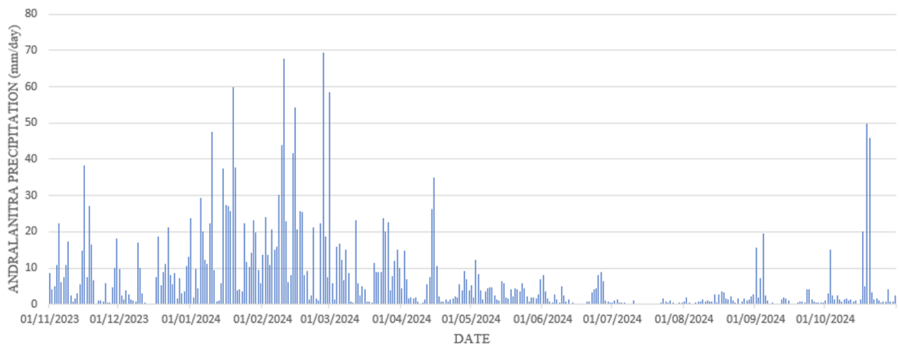

Figure 2 Precipitation recorded at the location of the Andralanitra landfill from November 2023 to October 2024

The monthly precipitation was calculated by averaging the daily precipitation over the course of a month.

For this study, the intensity of precipitation was categorized as follows:
Very Light Rain: 24-hour precipitation < 1 mm
Light Rain: 1 mm $\leq$ 24-hour precipitation < 11 mm
Moderate Rain: 11 mm $\leq$ 24-hour precipitation < 31 mm
Heavy Rain: 31 mm $\leq$ 24-hour precipitation < 71 mm.

2.4 Methods

We used correlation analysis to study the relationship between daily PM2.5 and PM10 concentrations of Antananarivo and the precipitation data recorded at the Andralanitra landfill.

2.4.1 P-Value

The p-value, which ranges from 0 to 1, indicates the probability that the null hypothesis is correct. The null hypothesis states that there is no relationship between the two variables. In this study, we set the significance level at P = 0.01. If P is less than 0.01, the null hypothesis is rejected, indicating a significant relationship between the two variables.

2.4.2 Pearson Correlation Coefficient

To assess the strength of the linear relationship between precipitation at Andralanitra and PM2.5 and PM10 concentrations in Antananarivo, we calculated the Pearson correlation coefficient (r). The formula is given below [14].

$$r\ (x, y) = \frac{Cov\ (x, y)}{\sigma x.\sigma y} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}\ (x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}\ (y_i - \bar{y})^2}} \tag{1}$$

Where:
x: daily precipitation at the Andralanitra landfill site
y: daily PM concentration (PM2.5 or PM10) in Antananarivo
$\bar{x}$: average daily precipitation at the Andralanitra landfill site during the study period
$\bar{y}$: average daily PM concentration (PM2.5 or PM10) in Antananarivo during the study period
r (x, y): Pearson correlation coefficient between x and y
Cov (x, y): covariance between the variables x and y
σx: standard deviation of the variable x
σy: standard deviation of the variable y.

3 Results and Discussion

3.1 Monthly Variation of Precipitation at Andralanitra and PM (PM2.5 and PM10) Concentrations

Figure 3 reveals a clear trend: monthly concentrations of PM2.5 and PM10 tend to be higher during the dry season, when precipitation over Andralanitra is low. In contrast, concentrations are lower during the rainy season, when precipitation over Andralanitra is more abundant.

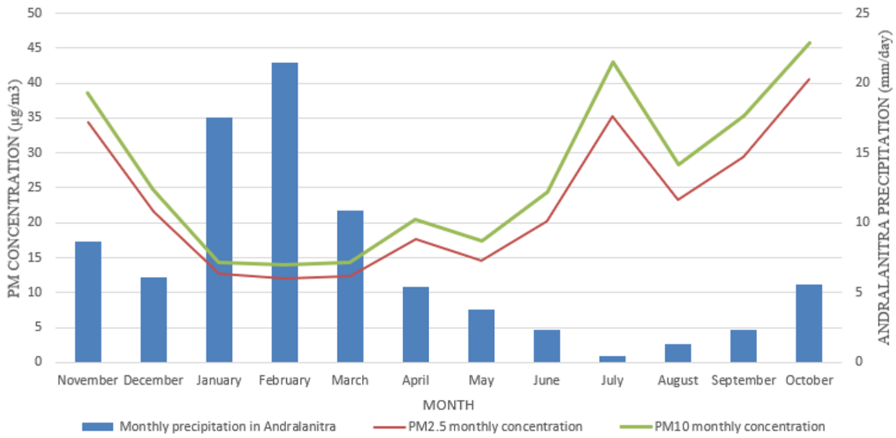

Figure 3 Influence of monthly precipitation at Andralanitra on the monthly concentrations of PM2.5 and PM10

Between June and August, a peak in the monthly concentrations of PM2.5 (35.32 μg/m^3) and PM10 (42.97 μg/m^3) is observed, coinciding with a significant decrease in precipitation ($\leq$ 2.29 mm). Conversely, between January and March, the monthly concentrations of PM2.5 (12 μg/m^3) and PM10 (13.92 μg/m^3) reach their lowest levels, accompanied by a sharp increase in rainfall ($\geq$ 10.88 mm). This variation is explained by the fact that the landfill receives three times more rainfall during the rainy season. The heavy precipitation during this period largely extinguishes the landfill fires, significantly reducing particulate matter emissions [6]. Additionally, the washing effect of precipitation diminishes the particulate matter concentration in the landfill smoke.

Through the analysis of the data in Figure 3, we obtained the following results: for PM2.5 (r = -0.527, P = 0.003) and for PM10 (r = -0.572, P = 0.001). These values indicate a moderate negative linear correlation between the monthly precipitation at Andralanitra and the monthly concentrations of PM (PM2.5 and PM10). More precisely, a decrease in monthly precipitation at Andralanitra leads to an increase in the monthly concentrations of PM2.5 and PM10.

Between September and October 2024, PM2.5 and PM10 concentrations increased, despite a rise in precipitation over the Andralanitra landfill. This trend appears to contradict previous observations and raises questions about the factors influencing particulate matter dynamics in the region.

A study by the U.S. Environmental Protection Agency in 2021 found that wildfires, bushfires, and biomass burning produce three main pollutants: ozone, carbon monoxide, and particulate matter (PM2.5 and PM10) [15].

The rise in PM2.5 and PM10 concentrations could be linked to the wildfire season, which is particularly active in September and October in the Antananarivo region. During this period, numerous vegetation fires were recorded in the capital and surrounding areas, devastating several thousand hectares.

Among the most significant events, the Angavokely Forest Reserve, located 40 kilometers east of Antananarivo, was severely affected by a fire that lasted several days in September 2024 [16]. Similarly, in November 2024, a major fire destroyed thousands of hectares of bushland in the Ankazobe district [17]. These fires are just two examples among many that occurred during this period.

3.2 Relationship between Andralanitra Precipitation and the Number of Polluted Days

Table 1 shows the relationship between precipitation in Andralanitra and the number of polluted days.

Table 1 Precipitation Intensity and Number of Polluted Days

Precipitation intensity	PM2.5 polluted days	PM10 polluted days
Very light rain (RR in 24 h $<$ 1 mm)	99	36
Light rain (1 mm $\leq$ RR in 24 h $<$ 11 mm)	91	17
Moderate rain (11 mm $\leq$ RR in 24 h $<$ 31 mm)	24	0
Heavy rain (31 mm $\leq$ RR in 24 h $<$ 71 mm)	5	0

The number of polluted days decreases with increased precipitation intensity. For PM2.5, the number of polluted days is 19.8 times higher during very light rain periods than during heavy rain periods. During very light rain, PM2.5 concentrations remain elevated and persist longer, which increases the number of days with polluted air. In contrast, during heavy rain periods, the rain helps to remove pollutants from the air, thereby reducing the number of polluted days. For PM10, polluted days only occur when precipitation is less than 11 mm/day. This indicates a clear relationship between the number of polluted days and precipitation intensity. In other words, air pollution related to PM (PM2.5 and PM10) is directly influenced by the level of precipitation in Andralanitra.

Regardless of the type of precipitation, the number of days polluted by PM2.5 is always higher than that of PM10. From November 2023 to October 2024, there were 219 days with PM2.5 pollution, compared to just 53 days for PM10. This suggests that PM2.5 pollution is far more persistent than PM10 pollution. Therefore, we can conclude that PM10 particles are more affected by precipitation than PM2.5, likely due to their larger size, which makes them more easily removed from the air by rain.

3.3 Correlation between Daily Precipitation in Andralanitra and Daily Concentrations of Pm2.5 and Pm10 in Antananarivo

Table 2 shows that the P-values for both PM2.5 and PM10 are below 0.01. The null hypothesis is therefore rejected, indicating a correlation between daily precipitation at Andralanitra and daily PM2.5 and PM10 concentrations.

Table 2 Correlation between daily precipitation at Andralanitra and daily concentrations of PM2.5 and PM10

Variables	Pearson correlation coefficient (r)	P-value
Daily precipitation at Andralanitra and daily PM2.5 concentration	-0.249	$1.93.10^{-33}$
Daily precipitation at Andralanitra and daily PM10 concentration	-0.266	$9.42.10^{-41}$

The Pearson correlation coefficients values lead to two conclusions:

(1) The negative coefficients indicate that an increase in daily precipitation at Andralanitra leads to a decrease in PM2.5 and PM10 concentrations.

(2) According to Cohen's guidelines, the correlation strength between daily precipitation at Andralanitra and daily PM2.5 concentrations is weak. In other words, there is a weak linear relationship between these two variables ($r < 0.3$). The same applies to daily precipitation at Andralanitra and daily PM10 concentrations ($r < 0.3$). These low correlation coefficients can be partly explained by the fact that Andralanitra precipitation indirectly affects the overall PM concentration (PM2.5 and PM10). Precipitation influences the amount of smoke emitted by the landfill, which, through diffusion, impacts the overall PM concentration in the city of Antananarivo. Other external factors also influence PM concentrations, including: forest fires, bushfires, and other types of biomasses burning [15], relative air humidity [18], precipitation over the city of Antananarivo and monitoring stations (atmospheric washing effect) and wind, through atmospheric diffusion.

$|r\ (PM\ 10, RR)| > |r\ (PM\ 2.5, RR)|$, which indicates that the correlation between Andralanitra precipitation and PM10 is stronger than with PM2.5. This difference in sensitivity is likely due to the particulate matter size. PM10, being larger, are more easily captured and carried by raindrops, leading to a reduction in their concentration in the air. In contrast, PM2.5 particles, being smaller and lighter, tend to stay suspended in the atmosphere for a longer time, even during precipitation.

Precipitation in Andralanitra has a weak and negative impact on PM2.5 and PM10 concentrations. This suggests that smoke from the landfill also affects the overall levels of particulate matter (PM2.5 and PM10) in the city of Antananarivo. Due to the non-transitive nature of Pearson's correlation coefficient, it is not possible to directly determine the strength of the correlation between the smoke from the Andralanitra landfill and the particulate matter (PM) concentrations in Antananarivo just by using the r (PM2.5, RR) and r (PM10, RR) values.

Our results show that the Andralanitra landfill significantly contributes to air pollution in Antananarivo. As a result, it represents a major health risk for the population. To tackle this issue, the competent authorities have decided to establish a pilot plant for the treatment and recovery of organic waste. This project will help reduce the pollution generated by the landfill, but it will remain insufficient to fully tackle the problem. More effective, large-scale solutions, such as the construction of a waste-to-energy incineration facility, will need to be considered. The danger posed by the Andralanitra landfill is too serious to be ignored.

4 Conclusion

This study is a statistical analysis of the relationship between precipitation over the Andralanitra landfill and the concentrations of PM2.5 and PM10 in the city of Antananarivo. The correlation analysis clearly shows that precipitation at Andralanitra is strongly linked to the overall concentrations of PM2.5 and PM10. The main conclusion of this study can be summarized as follows:

(1) Monthly precipitation at Andralanitra shows a moderate negative correlation with the monthly concentrations of PM2.5 and PM10.

(2) Seasons influence the overall concentrations of PM2.5 and PM10 in the city.

(3) An increase in the intensity of precipitation in Andralanitra leads to a decrease in the number of polluted days. Air pollution caused by PM (PM2.5 and PM10) is directly influenced by precipitation levels in Andralanitra.

(4) According to Cohen's guidelines, the daily concentrations of PM2.5 and PM10 both show a weak negative correlation with daily precipitation in Andralanitra. These low r values can be explained by the fact that precipitation in Andralanitra indirectly affects the overall concentrations of PM2.5 and PM10.

(5) The correlation between Andralanitra precipitation and PM10 is stronger than with PM2.5.

This difference in sensitivity is likely due to the size of the particulate matter. PM10 is more sensitive to precipitation than PM2.5.

(6) There is a correlation between landfill emissions and overall concentrations of PM2.5 and PM10. The smoke from the Andralanitra landfill pollutes the air in Antananarivo.

Conflicts of interest

The authors declare that they have no conflict of interest.

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