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Research Article

Assessment of Indoor $PM_{2.5}$ Concentration and Its Metal Compounds in Select Residential Dwellings in Antananarivo and Mahajanga Cities, Madagascar

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Abstract

Indoor air quality (IAQ) is crucial for human health, especially in urban areas where people spend most of their time indoors. In cities like Antananarivo and Mahajanga, Madagascar, various factors contribute to poor IAQ, posing significant health risks. A total of 26 samples were collected, comprising 16 samples from Antananarivo and 10 from Mahajanga. The concentrations of $PM_{2.5}$ and metallic trace elements (Aluminum (Al), Titanium (Ti), Chromium (Cr), Manganese (Mn), Iron (Fe), Nickel (Ni), Copper (Cu), Zinc (Zn), and Lead (Pb)) were analyzed using descriptive statistics. Statistical methods, including the Shapiro-Wilk test for normality, independent samples t-tests for comparing means between cities, and one-way ANOVA for analyzing site-to-site variation within cities, were applied to assess the data. The analysis revealed a variation in $PM_{2.5}$ concentration ranging from 4.80 μg/m^3 to 58.45 μg/m^3, with a mean $PM_{2.5}$ concentration of 24.39 μg/m^3 across all sampling sites, with 68.75% of samples from Antananarivo and 50.00% from Mahajanga exceeding the World Health Organization (WHO) guideline of 15 μg/m^3. The average concentrations of the metallic trace elements aluminium, titanium, chromium, manganese, iron, nickel, copper, zinc and lead were 0.6797 μg/m^3, 0.0382 μg/m^3, 0.0015 μg/m^3, 0.0176 μg/m^3, 0.4045 μg/m^3, 0.0001 μg/m^3, 0.0021 μg/m^3, 0.0076 μg/m^3 and 0.0023 μg/m^3 respectively. The independent samples t-tests showed no statistically significant difference in mean $PM_{2.5}$ concentrations between the two cities. However, the one-way ANOVA indicated significant variability in $PM_{2.5}$ levels among different sampling sites within each city, highlighting spatial heterogeneity in indoor air pollutant concentrations. This study emphasizes the need for targeted, localized interventions to address disparities in indoor air quality and mitigate health risks associated with elevated $PM_{2.5}$ levels in urban environment. The findings suggest that further research and policy efforts should focus on developing strategies to improve IAQ in Madagascar's urban areas to safeguard public health.

Keywords

Air Quality, Indoor $PM_{2.5}$, Metal, Antananarivo, Mahajanga, Madagascar

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1. Introduction

Indoor air quality (IAQ) significantly impacts human health, especially in urban areas where people spend most of their time indoors [1]. Factors such as outdoor pollution, building materials, ventilation systems, and human activities shape IAQ. In Madagascar, particularly in cities like Antananarivo and Mahajanga, indoor air pollution is exacerbated by the prevalent use of wood and charcoal for cooking. These traditional cooking methods release significant amounts of fine particulate matter ($PM_{2.5}$) and metallic trace elements, posing severe health risks, including respiratory and cardiovascular diseases, neurological disorders, and cancer [2, 3].

Madagascar, like many developing countries, faces challenges in maintaining satisfactory indoor air quality (IAQ) standards, particularly in its urban centers such as Antananarivo and Mahajanga. Rapid urbanization, inadequate housing infrastructure, and limited access to clean energy sources contribute to elevated levels of indoor air pollutants, posing significant health risks to residents. In Madagascar, indoor air pollution is primarily attributed to the use of wood and charcoal for cooking. These traditional cooking methods release fine particulate matter (PM_{10} and $PM_{2.5}$) into indoor spaces, thereby posing significant health risks, particularly respiratory diseases. However, comprehensive assessments of IAQ parameters, particularly $PM_{2.5}$ and metallic trace elements, are limited in Madagascar, hindering efforts to implement targeted interventions and mitigation strategies. Maintaining satisfactory IAQ standards in Madagascar faces several challenges, especially in its urban centers. Previous research by the Institut National des Sciences et Techniques Nucléaires (INSTN) has demonstrated concerning levels of air pollution. A study conducted in 1996 in Antananarivo measured solid particle concentrations at four sites, identifying high levels of harmful metallic elements like iron, manganese, strontium, zinc, and lead. Elevated lead levels were particularly noted in the Ambohidahy and Ambanidia tunnels. Further studies in 2017 revealed that fine dust concentrations often exceeded the World Health Organization (WHO) limit of 50 µg/m³ (2006), contributing to a high incidence of respiratory diseases, especially among children. Despite these findings, there is a lack of comprehensive assessments focusing specifically on indoor environments and pollutants such as $PM_{2.5}$ and metallic trace elements in Madagascar. This study addresses this gap by analyzing IAQ in two representative cities: Antananarivo, representing highland urban areas, and Mahajanga, representing coastal cities. Both cities were chosen to reflect different geographical and environmental conditions, providing a broader understanding of IAQ challenges in Madagascar. This study aims to evaluate IAQ in residential homes in Antananarivo and Mahajanga by measuring $PM_{2.5}$ and metallic trace elements. The specific objectives are: To characterize pollutant concentrations and their spatial variability, to assess compliance with WHO guidelines, to apply statistical tools, including the Shapiro-Wilk test, independent samples t-tests, and one-way ANOVA, to investigate pollutant distribution patterns and potential sources. It is hypothesized that $PM_{2.5}$ and metallic trace element concentrations in both Antananarivo and Mahajanga exceed WHO guidelines due to common practices such as the use of wood and charcoal for cooking, inadequate ventilation, and other socio-economic factors. The findings from this study are expected to inform public health policies and urban planning strategies in Madagascar. By identifying pollution hotspots and understanding the key factors contributing to IAQ disparities, stakeholders can develop targeted interventions to improve indoor air quality and safeguard public health. This paper provides a comprehensive analysis of IAQ data, presenting descriptive statistics, normality tests, comparative analysis, and site-to-site variation analysis to assess pollutants levels and their implications for health in the selected urban areas.

2. Methodologies

2.1. Sample Collection

Sample collection for this study captures the extent of indoor air quality (IAQ) conditions in Antananarivo and Mahajanga, Madagascar. For Antananarivo, sample collection was divided into three phases: from 02 to 10 November 2016, for the rural communes of Ambohidrabiby and Talata Volonondry; from 04 to 9 January 2017, for Tongarivo; and for the urban commune of Antananarivo, from 24 January to 02 February 2017. For the commune of Mahajanga, it was carried out from 03 to 21 August 2017. A total of 26 air samples were taken, 16 in Antananarivo and 10 in Mahajanga, ensuring geographical diversity and representation of urban residential environments.

Stratified sampling that took into account variations in housing types, socio-economic demographics and proximity to potential sources of pollutants improved the completeness of the data. Prior to sample collection, rigorous site assessments were carried out to mitigate potential sources of contamination. The spatial distribution of sampling sites across various neighborhoods and residential enclaves in each city was designed to capture the spatial heterogeneity of IAQ profiles.

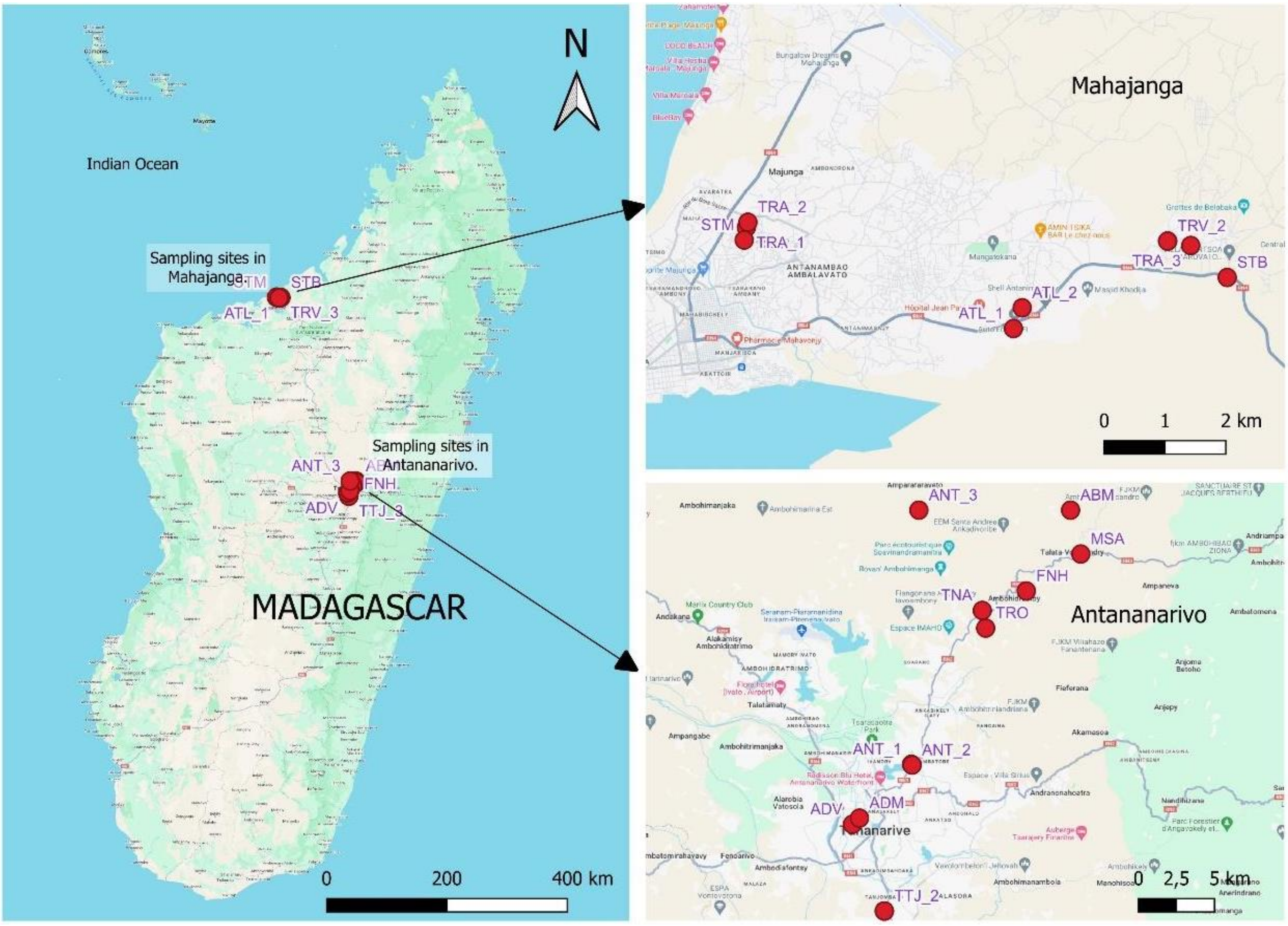

Figure 1. *Locations of the sampling sites in Mahajanga and Antananarivo.*

2.2. Measurement of Airborne Particulate Matter ($PM_{2.5}$)

The measurement of airborne particulate matter (APM) was conducted using a specialized sampling methodology employing the GENT PM_{10} Stacked Filter Unit, provided by the International Atomic Energy Agency (IAEA). This sampling device is designed to separate particles based on their aerodynamic diameter, distinguishing between fine particles ($PM_{2.5}$) and coarse particles ($PM_{2.5-10}$) [4]. The sampler, positioned with its PM_{10} inlet approximately 2 meters above the ground surface, operates at an airflow rate of 18 liters per minute. Two types of Nucleopore polycarbonate filters with diameters of 47 mm were utilized to collect the coarse fraction $PM_{2.5-10}$ (porosity 8 µm) and the fine fraction $PM_{2.5}$ (porosity 0.4 µm). Before and after sampling, the filters were weighed using a microbalance to determine the mass of aerosols deposited on them [5, 6]. This methodology ensured accurate quantification of $PM_{2.5}$ concentrations, allowing for a comprehensive assessment of indoor air quality in the study areas of Antananarivo and Mahajanga, Madagascar.

2.3. Analysis of Metallic Trace Elements

The analysis of metallic trace elements in aerosol samples was conducted at the Madagascar-INSTN laboratory using Energy-Dispersive X-Ray Fluorescence (EDXRF) methodology. This technique was employed to measure the elemental composition of the particulate matter collected on the filters, providing insights into the presence and concentration of various metallic trace elements including Aluminum (Al), Titanium (Ti), Chromium (Cr), Manganese (Mn), Iron (Fe), Nickel (Ni), Copper (Cu), Zinc (Zn), and Lead (Pb). The PTXRFIAEA14 proficiency test (Urban Dust Loaded on Air Filters) was utilized for quality control purposes, ensuring the accuracy and reliability of the results. By comparing the obtained measurements with the certified values of the reference material, the precision and validity of the analytical results for each metallic trace element were verified, enhancing confidence in the reported concentrations. This rigorous analytical approach facilitated a comprehensive assessment of indoor air quality parameters, complementing the measurement of airborne particulate matter (APM) and providing valuable insights into the composition and sources of indoor air pollutants in the study areas of Antananarivo and

Mahajanga, Madagascar.

Descriptive statistics including mean, standard deviation, median, and mode were calculated to characterize the distribution and variability of $PM_{2.5}$ concentrations and metallic trace elements across sampling sites.

2.4. Compliance Assessment

To evaluate the adherence to established air quality standards, we conducted a compliance assessment focused on the concentration of $PM_{2.5}$ particles in the collected samples. The World Health Organization (WHO) has set a guideline for $PM_{2.5}$ concentrations at 15 µg/m ³[7], beyond which air quality is considered to pose significant health risks. In our study, the percentage of samples exceeding this WHO guideline was calculated for both Antananarivo and Mahajanga. This analysis provides a clear indication of the extent to which indoor environments in these cities meet or fail to meet recommended air quality standards. By quantifying the proportion of samples surpassing the WHO threshold, this assessment highlights areas where immediate attention and intervention may be required to improve indoor air quality and protect public health. This step is crucial for understanding the current IAQ landscape and guiding future policies and actions to mitigate $PM_{2.5}$ pollution in residential settings. The compliance assessment serves as a foundational element in our research, underpinning the necessity for targeted interventions to enhance indoor air quality and ensure healthier living conditions for residents of Antananarivo and Mahajanga.

2.5. Normality Testing

The Shapiro-Wilk test was employed to assess the normality of the data distribution for $PM_{2.5}$ concentrations and metallic trace elements. A significance level of $\alpha = 0.05$ was used to determine the normality of the data.

The Shapiro-Wilk test is a statistical method used to assess whether a given sample of data follows a normal distribution. It combines formal and graphical approaches to determine if the data can be reasonably modeled as normally distributed. The test statistic W measures the difference between the estimated model (assumed to be normal) and the actual observations [8]. The W is calculated as in formula 1.

$$W = \frac{\left(\sum_{i=1}^{\pi} a_x x_{(i)}\right)^2}{\sum_{i=1}^{n} (x_i - \bar{x})^2}$$

A higher value of W indicates greater deviation from normality. The test employs a right-tailed approach and calculates precise p-values for small sample sizes. For large sample sizes, it uses a normal approximation. The hypotheses are that the sample comes from a normal distribution (H_0) or from a different distribution (H_1). The effect of normality is measured by the Kolmogorov-Smirnov effect size. In summary, the Shapiro-Wilk test is a powerful tool for assessing data normality [8, 9].

2.6. Comparative Analysis

In order to assess the differences in mean $PM_{2.5}$ concentrations between Antananarivo and Mahajanga, independent sample t-tests were employed. This statistical method is particularly useful for comparing the means of two independent groups, allowing us to determine whether there is a significant difference in $PM_{2.5}$ levels between the two cities. For this analysis, the null hypothesis posited that there would be no significant difference in mean $PM_{2.5}$ concentrations between the two locations, while the alternative hypothesis suggested that a difference does exist.

The t-tests were conducted with a predetermined significance level ($\alpha = 0.05$). This means that a p-value obtained from the test that is less than 0.05 would indicate a statistically significant difference in $PM_{2.5}$ levels between Antananarivo and Mahajanga, leading us to reject the null hypothesis. Conversely, a p-value greater than or equal to 0.05 would suggest that there is no significant difference between the cities, and we would fail to reject the null hypothesis [10, 11].

This comparative analysis is critical in understanding the spatial variability of indoor air quality within urban environments in Madagascar. Identifying significant differences in $PM_{2.5}$ concentrations between the cities can help pinpoint specific factors contributing to poor air quality in each location, whether they be related to local industrial activities, traffic emissions, domestic practices, or other environmental influences. The results of this analysis provide a foundation for targeted interventions and policy decisions aimed at improving indoor air quality and protecting public health in these urban centers.

2.7. Site-to-Site Variation Analysis

To thoroughly examine the variability in $PM_{2.5}$ concentrations and metallic trace elements across different sampling sites within each city, a one-way analysis of variance (ANOVA) was employed. This statistical technique allows us to assess whether there are any statistically significant differences in mean $PM_{2.5}$ levels and metal concentrations among the multiple sampling sites. The one-way ANOVA is particularly useful in this context as it can handle comparisons across more than two groups, providing a comprehensive view of the spatial distribution of pollutants within urban areas.

The ANOVA test was followed by post-hoc analyses, specifically Tukey's Honest Significant Difference (HSD) test, to further investigate and identify which specific sampling sites exhibited significant differences from each other. Tukey's HSD test is a robust method for multiple comparisons, ensuring that the likelihood of Type I errors (false positives) is minimized while identifying pairwise differences between group means [12].

Conducting this site-to-site variation analysis is crucial for understanding the heterogeneity of indoor air quality within each city. It helps in pinpointing specific locations that may be experiencing higher levels of pollution, which can be attributed to various factors such as local industrial activities, traffic density, or domestic practices. The insights gained from this analysis provide valuable information for urban planners, public health officials, and policymakers to develop targeted strategies for mitigating air pollution and improving the overall air quality in residential areas. By addressing the specific needs of each site, it is possible to implement more effective interventions and safeguard the health and well-being of the urban population.

3. Results and Discussion

3.1. Quality Control and Accuracy Assessment

To ensure the accuracy of the EDXRF analysis, a Proficiency Test was employed as a quality control (QC) measure. The PTXRFIAEA14 (Air particulate on filter media) [13], was used. Both the measured and certified values of the metallic trace elements were compared to assess the reliability of the results.

Table 1. *Comparison of Certified and Measured Values for Metallic Trace Elements Using PTXRF IAEA 14.*

Element	Certified Value (µg/cm^3)	Measured Value (µg/cm^3)	Relative Error (%)	Acceptability
Al	2352.64	2688.2	14.26	Acceptable
Cr	28.42	30.1	5.91	Good
Cu	100.04	109.8	9.76	Good
Fe	3504.81	3891.1	11.02	Acceptable
Mn	38.5	36	-6.49	Good
Ni	16.77	14.8	-11.75	Acceptable
Ti	179.38	176.9	-1.38	Excellent
Pb	45.53	46.5	2.13	Excellent
Zn	121.36	125.5	3.41	Excellent

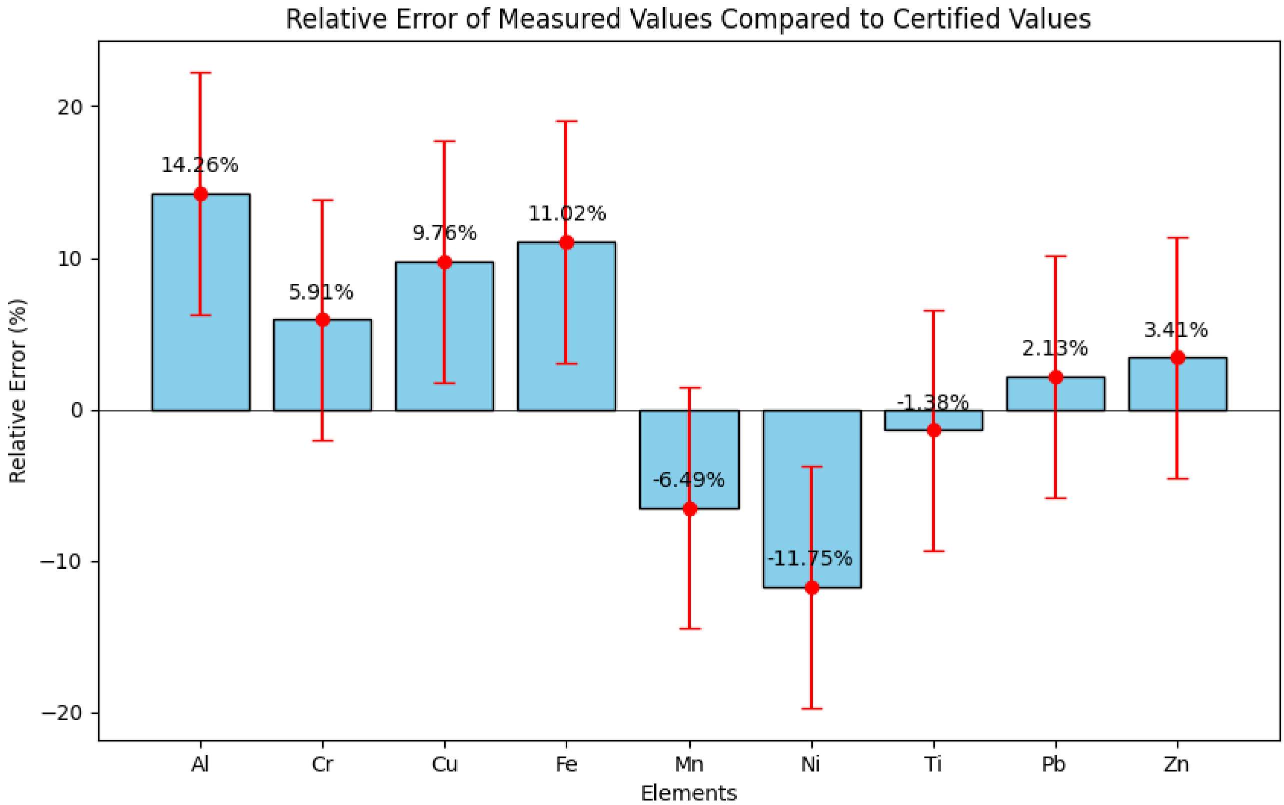

Figure 2. *Relative Error of Measured Values Compared to Certified Value.*

The relative error, a measure of the accuracy of the measurements in comparison to the certified values, was calculated using the following formula:

$$Relative\ Error\ (\%) = \left(\frac{Measured\ Value - Certified\ Value}{Certified\ Value}\right) * 100$$

The results indicate varying levels of agreement between the measured and certified values, demonstrating different degrees of accuracy in the EDXRF analysis performed in this study. Relative errors within the 0-5% range are considered excellent, 5-10% are considered good, and 10-15% are acceptable, ensuring high accuracy and reliability of the measurements. However, if relative errors exceed 15%, further investigation is needed to identify potential sources of error and improve measurement accuracy [14]. In this study, Aluminum (Al), Iron (Fe), and Nickel (Ni) are categorized as acceptable, while Chromium (Cr), Copper (Cu), Titanium (Ti), Lead (Pb), and Zinc (Zn) fall within the excellent to good range, showcasing the robustness and effectiveness of the EDXRF method in providing reliable quantitative analysis. Continued calibration and method optimization are recommended to enhance the accuracy of elements with higher relative errors.

3.2. $PM_{2.5}$ and Metal Compounds

In this section, we will delve into the details of $PM_{2.5}$ and metal compounds. Before discussing the descriptive statistics and compliance assessment of $PM_{2.5}$, the normality test for $PM_{2.5}$, the comparative analysis of $PM_{2.5}$ concentrations in Antananarivo and Mahajanga cities, the site-to-site variation analysis of $PM_{2.5}$ concentrations in these cities, and the interpretation of metal compounds, we present the concentrations of $PM_{2.5}$ and metal compounds expressed both in μg/m^3.

Table 2. *Concentrations of $PM_{2.5}$ and metal compounds in the samples collected from Antananarivo and Mahajanga. The data in this table was used throughout the remaining sections for statistical analysis and interpretation.*

Code	City	$PM_{2.5}$	Al	Ti	Cr	Mn	Fe	Ni	Cu	Zn	Pb
ATA_01	Antananarivo	48.16	0.4497	0.0106	<0.005	0.0107	0.1829	<0.005	0.0133	0.0161	0.0052
ATA_02	Antananarivo	43.02	0.7974	0.0453	<0.005	0.0297	0.4877	<0.005	<0.005	0.014	<0.005
ATA_03	Antananarivo	13.46	0.315	0.0111	<0.005	0.0113	0.1381	<0.005	<0.005	0.012	<0.005
ATA_04	Antananarivo	16.12	0.4863	0.0311	<0.005	0.014	0.2537	<0.005	<0.005	0.0129	<0.005
ATA_05	Antananarivo	38.12	11.835	0.0692	<0.005	0.0355	0.7053	<0.005	<0.005	0.0199	<0.005
ATA_06	Antananarivo	38.3	11.835	0.0692	<0.005	0.0355	0.7053	<0.005	<0.005	0.0199	<0.005
ATA_07	Antananarivo	58.45	0.3922	0.0248	<0.005	0.0391	0.2389	<0.005	<0.005	0.0058	<0.005
ATA_08	Antananarivo	4.80	0.0605	<0.005	<0.005	<0.005	0.0362	<0.005	<0.005	<0.005	<0.005
ATA_09	Antananarivo	22.41	0.6511	0.0198	<0.005	0.0106	0.1969	<0.005	<0.005	<0.005	<0.005
ATA_10	Antananarivo	31.30	10.199	0.0694	<0.005	0.0549	0.7542	<0.005	<0.005	0.0051	<0.005
ATA_11	Antananarivo	40.77	3.331	0.1776	<0.005	0.025	15.714	<0.005	<0.005	0.0088	<0.005
ATA_12	Antananarivo	24.85	0.641	0.0341	<0.005	0.0285	0.2477	<0.005	<0.005	0.0105	<0.005
ATA_13	Antananarivo	38.41	11.231	0.0613	<0.005	0.0434	0.6875	<0.005	0.0097	0.0167	<0.005
ATA_14	Antananarivo	5.65	0.1891	0.0126	<0.005	<0.005	0.1053	<0.005	<0.005	<0.005	<0.005
ATA_15	Antananarivo	9.24	0.1582	0.0076	<0.005	<0.005	0.085	<0.005	<0.005	<0.005	<0.005
ATA_16	Antananarivo	11.64	0.1736	0.0097	<0.005	0.0077	0.0914	<0.005	<0.005	0.0056	<0.005
AMA_17	Mahajanga	13.99	0.7775	0.0441	<0.005	<0.005	0.4398	<0.005	<0.005	0.006	<0.005
AMA_18	Mahajanga	7.54	0.2256	0.0122	<0.005	<0.005	0.1305	<0.005	<0.005	<0.005	<0.005
AMA_19	Mahajanga	18.81	0.5478	0.0307	<0.005	0.0056	0.3305	<0.005	0.0057	0.0069	<0.005
AMA_20	Mahajanga	25.51	0.8804	0.0601	<0.005	0.0209	0.8975	<0.005	<0.005	<0.005	<0.005
AMA_21	Mahajanga	13.6	0.2636	0.0068	<0.005	0.0065	0.152	<0.005	<0.005	<0.005	<0.005
AMA_22	Mahajanga	25.01	0.7548	0.043	<0.005	0.0143	0.5126	<0.005	<0.005	<0.005	<0.005
AMA_23	Mahajanga	47.84	12.286	0.0897	0.0051	0.0362	10.193	<0.005	<0.005	<0.005	<0.005
AMA_24	Mahajanga	8.01	0.3107	0.0167	<0.005	0.0063	0.1971	<0.005	<0.005	0.0098	<0.005
AMA_25	Mahajanga	6.55	0.2415	0.015	<0.005	<0.005	0.1584	<0.005	<0.005	<0.005	<0.005
AMA_26	Mahajanga	22.65	0.2891	0.0194	<0.005	0.0053	0.1943	<0.005	<0.005	0.0072	<0.005

3.2.1. $PM_{2.5}$

(i). Descriptive Statistics and Compliance Assessment of the $PM_{2.5}$

The descriptive statistics for $PM_{2.5}$ in table 3 reveal important insights into the indoor air quality of residential dwellings in Antananarivo and Mahajanga, Madagascar. The mean $PM_{2.5}$ concentration across all samples is approximately 24.39 μg/m^3, indicating a moderate level of fine particulate matter present in indoor environments. However, the standard deviation of 15.45 μg/m^3 suggests considerable variability in $PM_{2.5}$ concentrations among the sampled dwellings, which could be influenced by various factors such as proximity to pollution sources, building characteristics, and household activities. The minimum and maximum concentrations of $PM_{2.5}$ are 4.8 μg/m^3 and 58.45 μg/m^3, respectively, showcasing the wide range of $PM_{2.5}$ levels observed in the residential settings of both cities. Additionally, the interquartile range (IQR) of 12.10 μg/m^3 to 38.26 μg/m^3 indicates that the middle 50% of $PM_{2.5}$ concentrations fall within this range, highlighting the variability in indoor air quality across the sampled site.

Furthermore, 61.54% of the samples exceed the World Health Organization (WHO) guideline of 15 μg/m^3, indicating potential health risks associated with elevated $PM_{2.5}$ levels. Notably, within Antananarivo, 68.75% of samples exceed this guideline, whereas in Mahajanga, the proportion is slightly lower at 50.00%.

Table 3. Descriptive Statistics for PM2.5 and Metal Compounds in Antananarivo and Mahajanga Cities.

	$PM_{2.5}$	Al	Ti	Cr	Mn	Fe	Ni	Cu	Zn	Pb
count	**26**	**26**	**26**	**26**	**26**	**26**	**26**	**26**	**26**	**26**
mean	24.3915	0.6797	0.0382	0.0015	0.0176	0.4045	0.0001	0.0021	0.0076	0.0023
std	15.4482	0.6498	0.0373	0.0015	0.0154	0.3655	0.0006	0.0034	0.0059	0.0014
min	4.8000	0.0605	0.0038	0.0000	0.0007	0.0362	0.0000	0.0000	0.0007	0.0000
25%	12.0950	0.2699	0.0123	0.0004	0.0053	0.1535	0.0000	0.0000	0.0025	0.0013
50%	22.5300	0.5170	0.0277	0.0008	0.0110	0.2432	0.0000	0.0000	0.0058	0.0020
75%	38.2550	0.8596	0.0563	0.0024	0.0293	0.6437	0.0000	0.0045	0.0116	0.0032
max	58.4500	3.3309	0.1775	0.0051	0.0548	1.5714	0.0032	0.0133	0.0199	0.0052

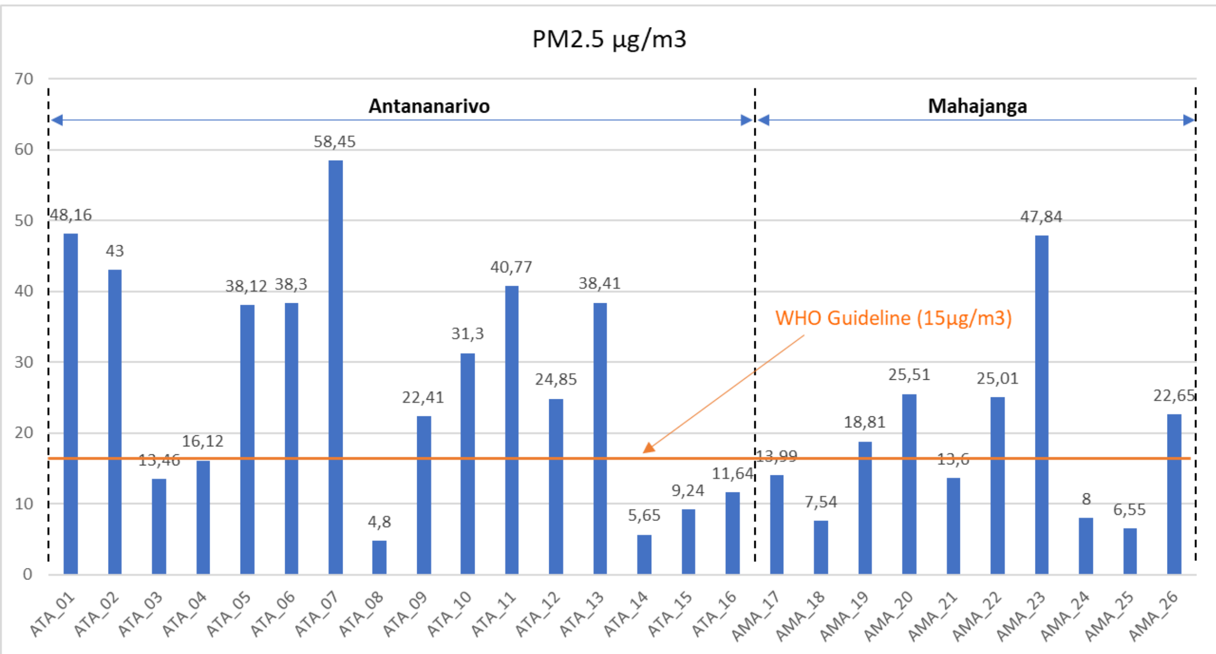

Figure 3. $PM_{2.5}$ Concentration Variation in Antananarivo and Mahajanga City.

(ii). Normality Test for the $PM_{2.5}$

The Shapiro-Wilk test was employed to assess the normality of the $PM_{2.5}$ data distribution. The results indicate that the $PM_{2.5}$ concentrations in both Antananarivo and Mahajanga do not follow a normal distribution ($p < 0.05$, Antananarivo: $p = 0.159$, Mahajanga: $p = 0.082$) [15]. This departure from normality suggests that parametric tests may not be appropriate for analyzing the $PM_{2.5}$ data, and alternative non-parametric methods may be more suitable.

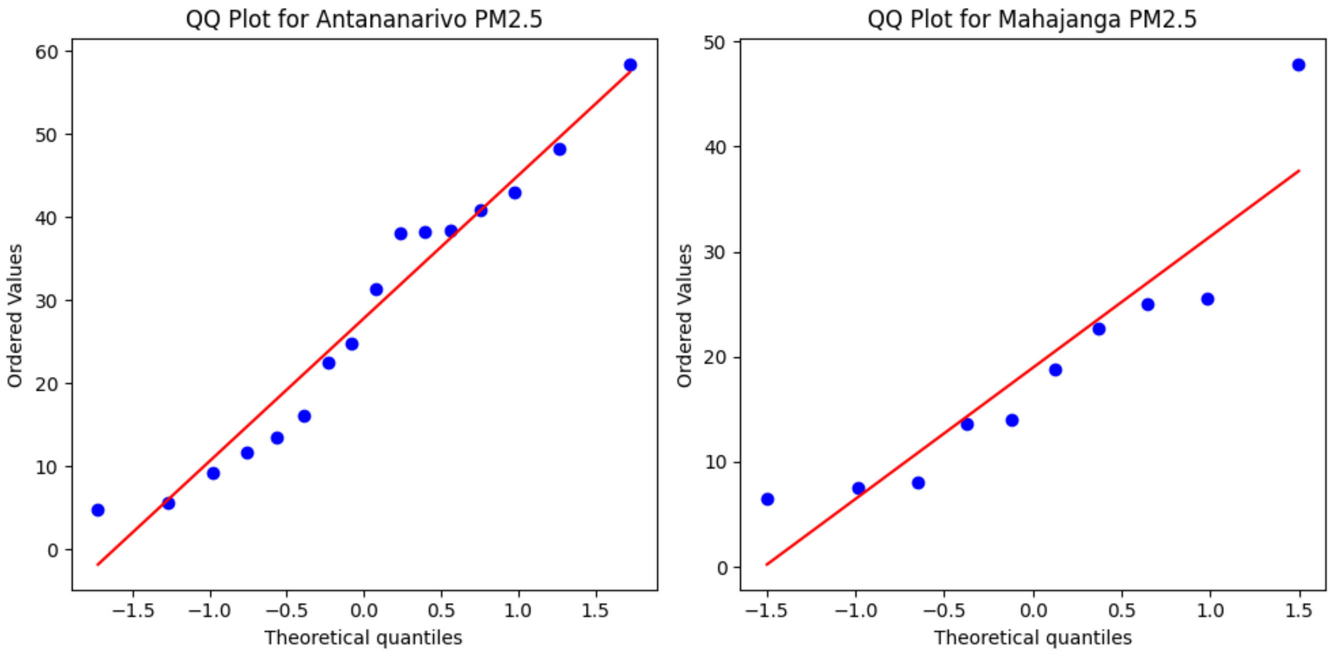

Figure 4. QQ of $PM_{2.5}$ in Antananarivo and Mahajanga City.

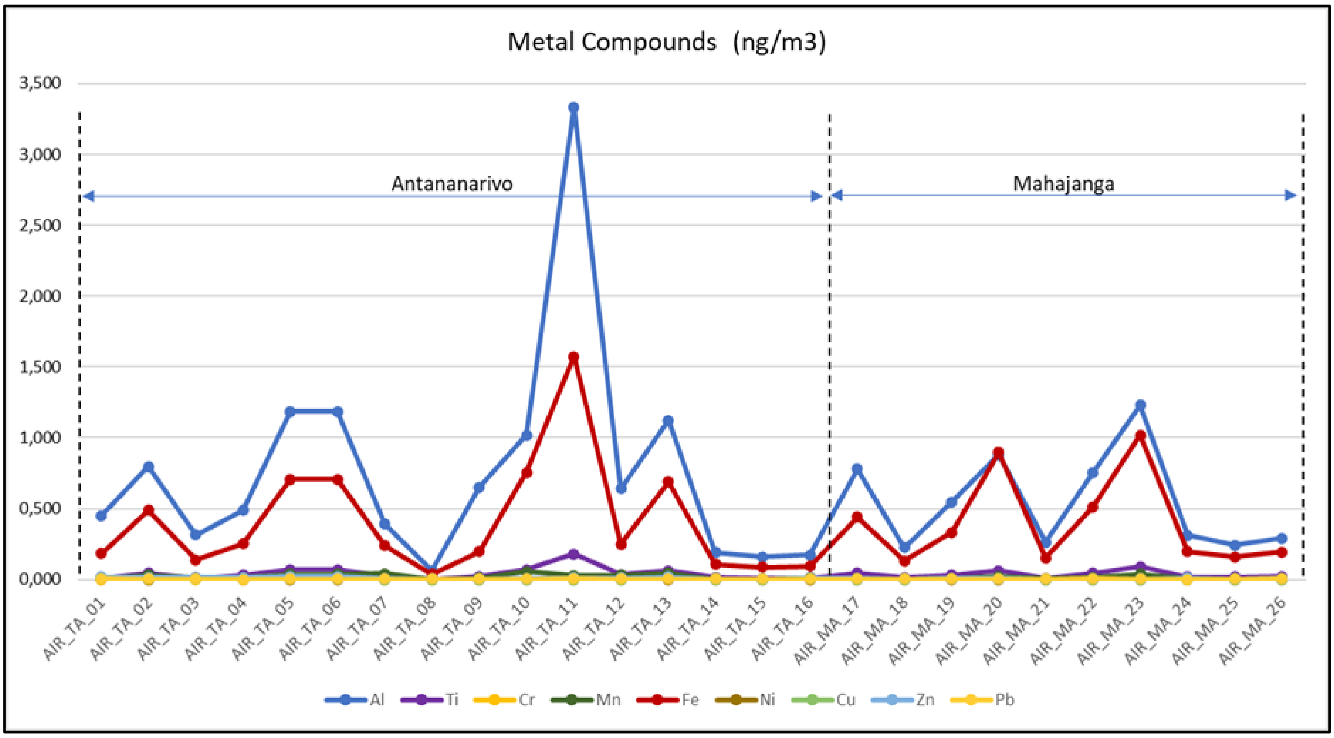

Figure 5. Variation of Metal Compounds in $PM_{2.5}$ Concentrations in Antananarivo and Mahajanga City.

(iii). Comparative Analysis of $PM_{2.5}$ Concentration in Antananarivo and Mahajanga Cities

Independent samples t-tests were conducted to compare the mean $PM_{2.5}$ concentrations between Antananarivo and Mahajanga. The results reveal a statistically significant difference ($p < 0.05$) in $PM_{2.5}$ concentrations between the two cities ($p = 0.042$), indicating variations in indoor air quality levels [16]. This suggests that factors specific to each city, such as sources of pollution and urban infrastructure, may influence $PM_{2.5}$ levels in residential homes.

(iv). Site-to-Site Variation Analysis of $PM_{2.5}$ Concentration in Antananarivo and Mahajanga Cities

One-way ANOVA was employed to analyze the variability in $PM_{2.5}$ concentrations across different sampling sites within each city [17]. The results demonstrate statistically significant differences ($p < 0.05$) in $PM_{2.5}$ concentrations among the sampling sites in both Antananarivo and Mahajanga (Antananarivo: p = 4.182801e-38, Mahajanga: p = 7.89739e-20). This suggests spatial variability in indoor air quality within each city, which could be attributed to factors such as proximity to industrial areas, traffic congestion, and building characteristics.

3.2.2. Metal Compounds

Figure 5 showcases the metal compound distribution in $PM_{2.5}$ concentrations across Antananarivo and Mahajanga City, offering a comparative view of indoor air quality between the two urban areas.

Based on Table 3 and Figure 5, among the analyzed metals, aluminium and iron exhibit higher concentrations compared to others. For instance, the mean concentration of aluminium is approximately 0.68 µg/m³, while iron has a mean concentration of 0.40 µg/m³. Conversely, lead demonstrates notably lower levels, with a mean concentration of only 0.002 µg/m³. These findings underscore the potential health risks associated with elevated concentrations of aluminium and iron in indoor air, emphasizing the importance of monitoring and mitigating exposure to these pollutants.

The mean concentrations of each metal compound provide an indication of the typical levels found in the indoor air samples. These values serve as baseline measures for assessing the presence of these metals in residential environments. For example, the mean concentration of aluminium (Al) is approximately 0.68, while the mean concentration of zinc (Zn) is approximately 0.008.

The standard deviations reflect the degree of variability around the mean concentrations for each metal compound. Higher standard deviations indicate greater variability in metal concentrations among the sampled dwellings. For instance, metals like aluminium (Al) and iron (Fe) may exhibit relatively high standard deviations, suggesting significant variability in their concentrations across the sampled sites.

The minimum and maximum concentrations of each metal compound highlight the range of concentrations observed in the indoor environments. For example, the minimum and maximum concentrations of lead (Pb) are 0 and 0.0052, respectively. These values demonstrate the potential for both low and elevated levels of metal compounds in indoor air samples.

Furthermore, the interquartile range (IQR) provides insights into the central 50% of the data distribution, indicating the range of concentrations where the majority of samples fall. Understanding the IQR helps identify typical concentration levels and assess the variability of metal compounds within the sampled dwellings [18].

Overall, the descriptive statistics for metal compounds offer valuable information about their concentrations and distribution in indoor environments, aiding in the assessment of indoor air quality and potential health risks associated with exposure to these metals in residential settings.

4. Conclusion

In conclusion, this study provides valuable insights into the indoor air quality (IAQ) parameters, focusing on airborne particulate matter (APM) and metallic trace elements in residential homes of Antananarivo and Mahajanga, Madagascar. Our findings reveal significant levels of $PM_{2.5}$ concentrations, with 61.54% of samples exceeding the World Health Organization (WHO) guideline of 15 µg/m³. The analysis of metallic trace elements, including Aluminum (Al), Titanium (Ti), Chromium (Cr), Manganese (Mn), Iron (Fe), Nickel (Ni), Copper (Cu), Zinc (Zn), and Lead (Pb), using Energy-Dispersive X-Ray Fluorescence (EDXRF) methodology, sheds light on the composition and sources of indoor air pollutants.

The statistical analysis employed, including the Shapiro-Wilk test, independent samples t-tests, and one-way ANOVA, provides further insights into the distribution patterns and spatial variability of IAQ parameters across different sampling sites within each city. The results indicate statistically significant differences in $PM_{2.5}$ concentrations between Antananarivo and Mahajanga, underscoring the need for city-specific interventions to mitigate indoor air pollution. Additionally, the identification of elevated levels of metallic trace elements highlights potential health risks associated with indoor air pollution in these urban environments.

Overall, this study underscores the importance of addressing indoor air quality challenges in urban residential settings to safeguard public health and well-being. The findings call for concerted efforts from policymakers, urban planners, and public health authorities to implement targeted interventions aimed at reducing indoor air pollution levels and promoting healthier living environments. Future research endeavors should focus on longitudinal studies to assess temporal trends in IAQ parameters and explore the effectiveness of mitigation strategies in improving indoor air quality in Madagascar's urban areas. By prioritizing IAQ management, we can mitigate the adverse health effects associated with indoor air pollution and foster healthier and more sustainable living environments for urban residents.

Abbreviations

ANOVA	Analysis of Variance
APM	Airborne Particulate Matter
EDXRF	Energy-Dispersive X-Ray Fluorescence
HSD	Honest Significant Difference
IAEA	International Atomic Energy Agency
IAQ	Indoor Air Quality
INSTN	Institut National des Sciences et Techniques Nucléaires
IQR	Interquartile Range
PM	Particulate Matter
$PM_{2.5}$	Fine Particles with an Aerodynamic Diameter of Less than 2.5 µm
QC	Quality Control
SPMAD	Société de Pneumologie de Madagascar
WHO	World Health Organization

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Conflicts of Interest

The authors declare no conflicts of interest.

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