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Mineralogical and Elemental Analysis of Harmattan Dust Using PIXE and XRF Across Selected Nigerian Stations: Implications for Environmental Health and Sustainability

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ABSTRACT

The suspended harmattan dust was collected at seven different stations in Nigeria: Iwo (7º63'N, 4º19'E), Oyo (8º12'N, 3º42'E), Ilorin (8º36'N, 4º35'E), Minna (9º36'N, 06º35'E), Abuja (09º09'N, 07º11'E), Lafia (08º49'N, 07º50'E), and Jos (9º55'N, 8º55'E), which were analyzed to determine elements and minerals present in the sample using X-Ray Fluorescence (XRF), and Particle Induced X-ray Emission (PIXE). The collected sample results show the elemental concentration of the sample in various forms across each station. Cr, Ce, Mo, Zr, Sr, V, Ti, K, As, Ni, Mn, Ca, Pb, Fe, Zn, and Cu were found in the sample using an XRF machine. The minerals discovered in the sample include but are not limited to, Corundum [Al_2O_3], Periclase [MgO], Rutile [TiO_2], and Quartz [SiO_2] in various proportions. Furthermore, the results revealed the enrichment factor for Iwo (1.3998 $\mu g/m^3$), Oyo (1.3998 $\mu g/m^3$), Ilorin (1.79765 $\mu g/m^3$), Minna (1.737325 $\mu g/m^3$), Abuja (1.635425 $\mu g/m^3$), Lafia (1.409695 $\mu g/m^3$), and Jos (1.787075 $\mu g/m^3$). The study concluded that the sample contains sixteen (16) elements and minerals in varying percentages and concentrations. It is therefore recommended that appropriate safety procedures be put in place to raise community awareness of the presence of elements in harmattan dust.

1. INTRODUCTION

Harmattan dust, originating from the Sahara Desert, significantly impacts West Africa, particularly Nigeria, where it is transported by trade winds [1]. From November to March, this fine particulate matter reduces visibility, affects transportation, and poses environmental and health risks [2-6]. Comprising minerals and toxic metals, the dust can cause respiratory issues and damage agriculture by altering soil composition [4-6]. This study aims to analyze the mineralogical and elemental composition of harmattan dust using XRF and PIXE techniques, focusing on its environmental and health implications. The findings will contribute to a better understanding and management of harmattan dust's effects in Nigeria [1]. The word harmattan is derived from the Twi language "haramata," also known as haram [1]. During the harmattan period in Nigeria, this harmattan dust is transported from the Sahara to the Gulf of Guinea [2, 3]. Various authors [2, 4-6] have linked these dust particles to the annual deposition of solid small mass discrete in the air that blows across the entire country. Every year, the harmattan period lasts from November to March. Huge amounts of dust particles are present throughout the country at this time, causing some household and sinus issues [2, 6]. This harmattan period is always accompanied by low and poor atmospheric visibility of fewer than 1000 meters. This dust's lifting, transit, and deposition are all natural processes [2, 6, 7].

Studies [8-15] have shown that West African provinces participate in the north-to-east trade winds.

This wind transport and deposit, however, occurs in the Chad basin's Bodele depression. Whereby two dust sources are identified [16]. The presence of a variety of chemical positions and heavy metals in the harmattan dust sample is now widely accepted. According to Lepedes, metals with specificities greater than or equal to 5 are found in harmattan dust in Africa (1974). This could be due to the high specific gravity of several heavy metals in the harmattan dust in the region. Heavy metals, according to Loto et al. [15], belong to the Periodic table's rectangular block. These metals include Te, Ti, Se, As, Pb, Bi, and Hf. Heavy metals are elements in the periodic table other than Ca; however, there is no evidence that heavy metals are more prevalent in harmattan than other environmental air quality factors [17].

Meanwhile, heavy metals were defined as metals with a high potential to harm living things. However, because of the nature of humans, the presence of these heavy metals does not always imply that they are "toxic metals" to human health, even at low or high concentrations [18]. According to literature [19, 20], heavy metals are natural components of the environment; however, concentrations may fluctuate due to diverse activities occurring in each area. Metals in water systems, rock weathering, and windblown dust from neighbouring shales all contribute to the organic activity of the environment [19-21].

Harmattan dust samples have been found to contain Mo, Zr, Ce, Zn, V, Ti, Si, Se, S, Pb, P, Ni, Mn, Mg, K, Fe, Cu, Cr, Cl, Ca, Br, As, and Al. According to Jimoh [22], these components are classified as light or heavy, and if a small amount of the sample is inhaled, both humans and animals may be harmed. However, the natural pathway of heavy metals on harmattan dust over flora continues to harm human health and physical conditions globally [22]. A geochemical investigation of harmattan dust, however, revealed that it has a significant impact on agricultural output due to the element's concentration of the dust settling over farmland [22]. According to authors [22-25], a sufficient fraction of harmattan dust contributes to the bulk sample of elements present in the atmosphere, which may be classified as heavy metals in various studies.

1.1 Enrichment Factor (EF)

Ghosh et al. [26] used standard deviation to show the elemental fluctuation of concentrations over multiple sample days. Major elements like Fe, Na, Mg, Ca, and K are crustal elements with concentrations that are multiples of two higher on dusty days and weeks than on non-dusty days and weeks [26]. The Enrichment Factors (EF's), which are close to one on all days observed, provide an excellent explanation for the element's crustal nature [26]. Anthropogenic elements show a slight or greater increase in concentration and their EF's that reduce the rate of dusty days compared to normal dusty days of suspended dust across several soil stations that account for high wind [26]. According to Ghosh et al. [26], the maximum EF value on elements such as Zn, V, Se, Cd, and Cr over midland areas throughout the days of observations suggests that the sources of most localized dust background are based on aerosols [26]. According to Chakraborty and Gupta [27] and Kang et al. [28], Se has the highest EF of the elemental study, which could have come from sources on-site in the thermal plant power. It was also discovered that a similar study was conducted in Xiamen, China [29].

1.2 Survey of literature

The Bodele Depression (Lake Chad), recognized as one of the largest dust reservoirs globally, has been widely identified as a major source of dust by numerous researchers, such as Anon [30], Engelstaedter et al. [31], Brooks and Legrand [32], Washington et al. [33] and Prospero et al. [34]. The northeast trade wind, originating from the Sahara Desert, traverses through Nigeria towards the Gulf of Guinea and beyond, transporting substantial quantities of dust along its path. The Harmattan layer reaches altitudes of approximately 300 meters above ground level and, in some instances, extends beyond the stratosphere. Studies have shown that the transport and deposition of Saharan dust influence the Earth's radiation budget [35, 36] and occur naturally [37-40]. Additionally, dust plays a role in altering photolysis rates [33].

Research indicates that this dust frequently settles on sun-dried agricultural produce meant for human consumption, posing potential health risks [41, 42]. Climatic variations, coupled with large-scale meteorological patterns such as the Inter-Tropical Convergence Zone (ITCZ), contribute to the accumulation of dust in the atmosphere [31, 32, 35, 36, 43-51].

Studies conducted by Aweda et al. [3, 5] utilizing Fourier-Transform Infrared Spectroscopy (FTIR) revealed that harmattan dust comprises thirteen distinct functional groups. Furthermore, Aweda et al. [5] highlighted that the mineral and elemental composition of harmattan dust varies significantly due to climatic differences across various Nigerian locations. Analysis of the dust's heavy metal content indicated the presence of both light and heavy metals, attributed to a combination of anthropogenic activities and local dust plumes. The determination of heavy metal concentrations in harmattan dust across selected Nigerian locations was achieved through PIXE analysis during the 2017/2018 season. While numerous researchers have employed techniques such as Atomic Absorption Spectroscopy (AAS) and Energy Dispersive X-Ray Fluorescence (EDXRF) for elemental analysis, relatively few studies have utilized PIXE, a particle accelerator-based method, to quantify heavy metal and elemental concentrations in harmattan dust. Given this gap, a comprehensive analysis of the heavy metal and elemental composition of harmattan dust using PIXE is particularly essential in Nigeria, a Sub-Saharan African country. Such studies provide critical insights into environmental health and sustainability, particularly in relation to the impacts of dust on human health and ecosystems. However, for this study, the primary aim is to conduct a comprehensive analysis of harmattan dust by examining its mineralogical and elemental composition. Specifically, the study objective is to:

1. Identify and quantify the key elements and minerals present in harmattan dust samples collected from various locations across Nigeria, including Iwo, Oyo, Ilorin, Minna, Abuja, Lafia, and Jos.
2. Assess the potential environmental and health impacts of these elements, focusing on their contribution to air pollution and effects on human health.
3. Evaluate the EF of the dust samples to determine the degree of anthropogenic influence on the dust composition.
4. Provide recommendations for mitigating the harmful effects of harmattan dust on public health and agricultural productivity in Nigeria.

2. Materials and Method

2.1 Sample collection, preparation and analysis

A suspended harmattan dust sample (14 collected dust sample) two per each station were collected from five different locations across all stations studied and stored in desiccators before elemental analysis. Between November 2017 and March 2018, a period of five months, suspended harmattan dust samples were collected using locally designed Australian %model gauges installed at designated sampling locations. These sites included Iwo, Oyo, Ilorin, Minna, Abuja, Lafia, and Jos, situated within the Northern Guinea Savanna and Derived Savanna zones of Nigeria's climatic vegetation regions, as illustrated in Figure 1. Samples were gathered from five different points within each station, and the average data was used for elemental analysis. Research indicates that harmattan dust significantly impacts visibility during the dry season and warrants detailed study to mitigate risks such as aircraft accidents, which formed the basis of this investigation. The gauges used for sample collection were approximately 5.0 meters tall, equipped with 10.0 mm plastic bowls mounted on plastic containers enclosed in metal casings to provide support and prevent intrusion by reptiles or crawling animals. Dust particles were allowed to fall freely into the containers through plastic funnels, and samples were collected after one month of continuous exposure, as shown in Figure 2. These samples were analyzed using XRF equipment in Figure 2 and PIXE equipment in Figure 3. To prepare the dust samples for analysis, they were pelletized. The pelletization process involved compressing the samples using steel molds, pellets, and a hydraulic press, with aluminum foil used as a binder to hold the particles together once removed from the molds.

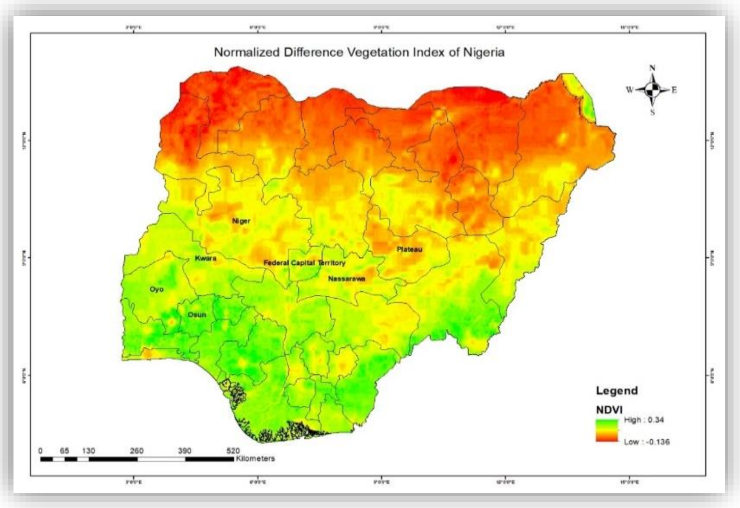

Figure 1. Vegetation map zone of the selected stations used

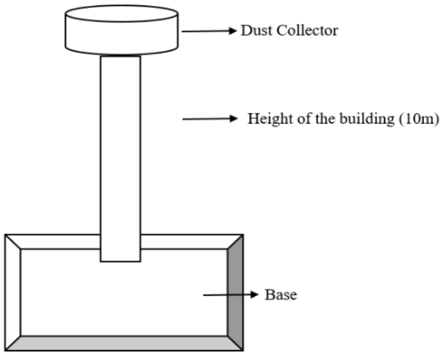

Figure 2. Schematic diagram of the sample collection process

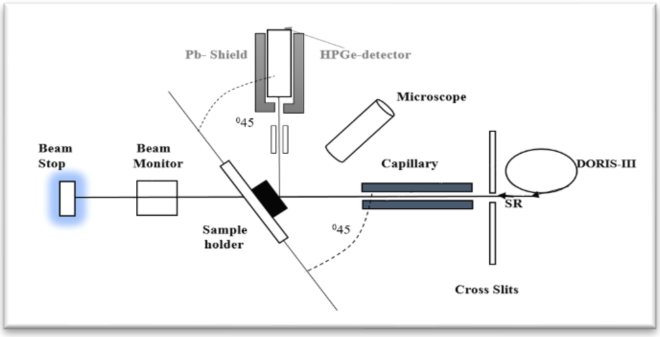

Figure 3. Instrumental setup for XRF spectrometer

2.2 Preparation of samples for PIXE analysis

The dried harmattan dust sample was analyzed through a pelletization process. This involved forming the samples into pellets using steel molds, a hydraulic press, and aluminum foil, which functioned as a binder to maintain the cohesion of the particles after mold removal. The pelletized sample was then introduced into the particle accelerator, as depicted in Figure 3.

2.3 PIXE

The environmental research of harmattan dust collected at several places in Nigeria was analyzed using a PIXE system to determine the minerals composition present in the dust sample, as shown in Figure 4. Aerosol samples are identified using this technique, which may be used to a variety of sample materials including geological, archaeology, biological, material science, and environmental pollutants as reported by studies [52-54].

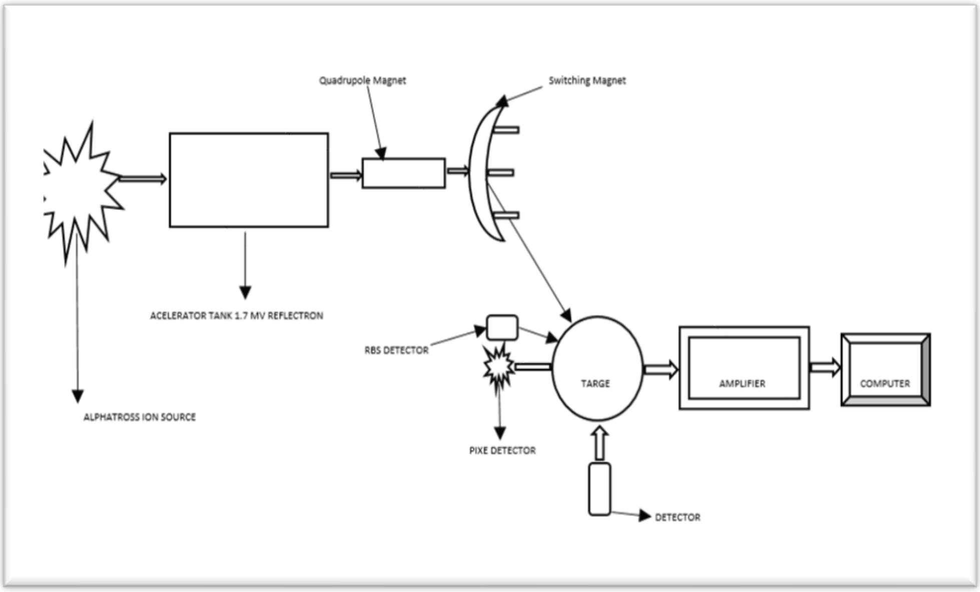

Figure 4. The diagram of PIXE instrument setup at the Centre for Energy Research and Development (CERD) [45]

2.4 Soil mass concentrations

The soil mass of the suspended harmattan dust collected at the various locations studied was calculated using the Malm et al. [55] formula, as indicated by the study [29]. The formula, on the other hand, calculated the total of various elemental concentrations in soil, with oxygen accounting for the vast majority of the oxides. As a result, the following formula for soil mass concentration has been recommended, see Eq. (1):

$$Y_u = 2.2Y_{Al} + 2.49Y_{Si} + 1.63Y_{Ca} + 2.42Y_{Fe} + 1.94Y_{Ti} \tag{1}$$

where, Y_u denotes concentration and u denotes the names of crustal elements in the soil. The soil mass concentration of the components found in the samples taken across the city during the study period is as follows:

$Y_{Ca} = 2.7178\mu g/m^3$, $Y_{Fe} = 0.4314\ \mu g/m^3$, $Y_{Ti} = 0.1216\mu g/m^3$

Ca has the highest concentration followed by Fe and the least Ti. This shows that there is more calcium (Ca) present in the sample.

2.5 Calculation of chemical elements using EF

An enrichment factor analysis was performed on an Abuja sample to distinguish between anthropogenic and natural sources. This graph depicts the degree of enrichment of a particular element concerning its relative abundance in the Earth's crust [27, 56]. The reference element used by the study [26] is Ca, which is thought to be of crustal origin. The enrichment factor is defined as follows:

$$EF_x = \frac{Y_{x_s}/Y_{Ca_s}}{Y_{x_c}/Y_{Ca_c}} \tag{2}$$

where, Y_{x_s} and Y_{Ca_s} are the element x and Ca concentrations in the samples, and Y_{x_s} and Y_{Ca_s} are the average concentrations in the Earth's upper crust, respectively [57, 58]. By convention [59], if EF > 10, the element in the aerosol is deemed to have a large crustal contribution and is thus referred to as the non-enriched element. According to Ghosh et al. [26], EF > 10 shows that an element has a significant fraction originating from non-crustal sources and is thus classified as an enriched element. For the dust collected in Abuja, the EFcrust values for the following elements (K, Ca, Ti, Mn, Fe, Ni, Cu, Zn, Mo, Zr, Pb, V, Sr) of the earth's upper crust were estimated using Eq. (2).

Figure 5 below is the flowchart which outlines the process of computing the EF to assess soil contamination. It begins by inputting soil mass and elemental concentrations, followed by selecting a reference element like Ti or Al. The EF is then calculated using the ratio of element-to-reference concentrations in both sample and background data. Based on EF values, contamination is classified into four categories: minimal (EF < 2), moderate (EF 2-5), significant (EF 5-20), and extreme (EF > 20). Higher EF values indicate greater anthropogenic influence, with EF > 5 suggesting strong pollution sources. Finally, EF interpretation distinguishes between natural and human-induced contamination. Values below 2 suggest a natural origin, while values above 2 indicate possible anthropogenic input. Extreme values (EF > 20) signify severe pollution.

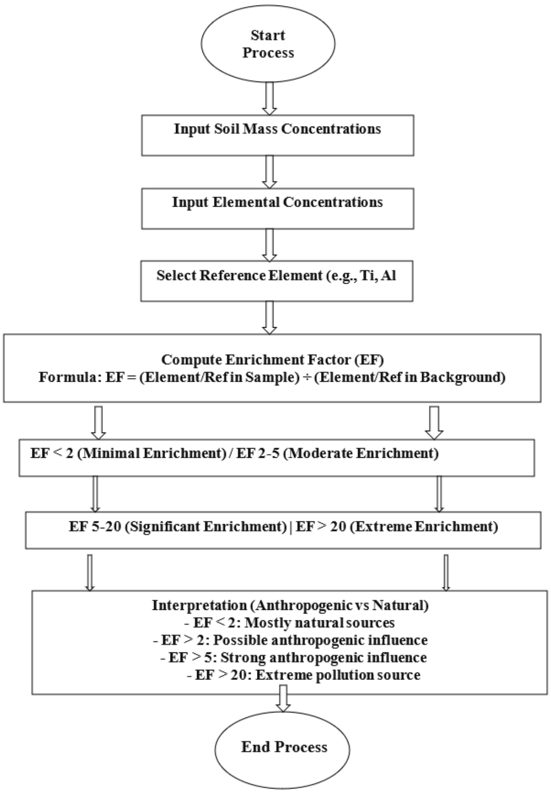

Figure 5. Flowchart showing the steps used in the calculation of EF

3. RESULTS AND DISCUSSIONS

3.1 XRF elemental composition of harmattan dust

The elemental concentration of harmattan dust for Iwo was determined using the XRF analytical method. As shown in Table 1, the constituent elements present in harmattan dust include Zr, Mn, Ca, Pb, Ti, As, Sr, Zn, Ni, K, V, Cu, Fe, and Mo. Ca had the highest concentration and percentage values, with 76584 mg/kg and 35.82%. The element K has a concentration of 62976 mg/kg and a percentage of 29.45%. Fe has a concentration of 55210 mg/kg and a percentage of 25.82%, Ti has a concentration of 11095 mg/kg and a percentage of 5.19%, and Mn has a concentration of 3307 mg/kg and a percentage of 1.54%. The sample collected contained Zn 1354 mg/kg and 0.63% concentration and percentage values. V concentrations of 839 mg/kg and 0.39 % were found in the harmattan dust collected at Iwo. The presence of lead was not ruled out by the value of Pb 791 mg/kg and 0.37 % concentration of the Iwo sample. Ni concentration values in the sample are 662 mg/kg and 0.31%. The sample also contained Zr 391 mg/kg concentration and 0.15% Zr. Cu has a concentration value of 180mg/kg with 0.08 percent, while Sr has a concentration value of 122 mg/kg with 0.06 percent. Meanwhile, As and Mo have concentration percentages of 0.03% in samples collected at Iwo location A, with 74 and 54 mg/kg, respectively. The elements are depicted below. Ca>K>Fe>Mn>Zn>V>Pb>Ni>Zr>Cu>Sr>As>Mo. The XRF machine was also used to analyze the element concentration of a harmattan dust sample collected in Oyo. Elements such as Cu, Zn, Fe, Pb, Ca, Mn, Ni, As, K, Ti, Mo, V, Sr, and Zr were found in the collected sample. Cu has concentrations of 82799 mg/kg and a percentage of 38.52%. It was followed by K, which had a concentration value of 32453 mg/kg and a percentage value of 15.18%. Ti has a concentration value of 9037 mg/kg with a percentage concentration value of 4.23%, Mn has a concentration value of 3540 mg/kg with a percentage concentration value of 1.66% of the sample collected in Oyo. Pb levels of 778 mg/kg and 0.36% were also found in the Oyo sample. Zn has a concentration of 0.36% and a concentration of 768 mg/kg. The percentage value of V at 490 mg/kg concentration is 0.23%. Ni was present in the sample at a concentration of 473 mg/kg (0.22%). The concentrations of Cu and Zr are 253mg/kg and 0.12%, respectively. Sr has a concentration value of 173 mg/kg and 0.08%, whereas Mo has a concentration value of 98 mg/kg and 0.05%. The sample collected in Oyo contained 96mg/kg and a 0.04% concentration value. Ca>Fe>K>Ti>Mn>Pb>Zn>V>Ni>Cu≥Sr>Mo>As.

Table 1. The elemental concentration present in the samples using the XRF machine

Stations (mg/kg)	K	Ca	Ti	Mn	Fe	Ni	Cu	Zn	Mo	As	Zr	Pb	V	Sr	Cr	Ce
Iwo	62976	76584	11095	3307	55210	662	180	1354	54	74	391	791	839	122	ND	ND
Oyo	32453	82799	9037	3540	82354	474	253	768	98	96	253	778	490	173	ND	ND
Ilorin	42030	42314	8719	3479	113086	217	193	875	59	48	673	260	648	69	270	688
Minna	28192	111554	6387	1716	63331	177	83	291	42	28	196	248	242	207	175	866
Abuja	21073	166739	6267	517	17828	256	78	281	40	ND	75	145	253	189	ND	ND
Lafia	51685	119189	9016	1008	29008	243	202	701	42	ND	205	473	355	260	ND	1232
Jos	35602	66469	7970	2750	96531	290	145	879	76	45	453	302	214	136	117	1695

ND means "Not Detected"

Some elemental concentrations in a harmattan dust sample collected in Ilorin are trivial. Cu, Zn, Fe, Pb, Ca, Cr, Mn, Ni, As, K, Ti, Mo, V, Sr, Zr, and Ce were discovered in the sample collected in Ilorin. Fe had a concentration value of 113086 mg/kg and a concentration value of 52.94% of the harmattan dust sample collected in Ilorin; Ca had a concentration value of 42314 mg/kg and a concentration value of 19.81% of the sample. K has a concentration value of 42030 mg/kg and an elemental concentration of 19.67%. The sample contained Ti at a concentration of 4.08% (8719 mg/kg). Furthermore, Mn has 3479 mg/kg with a concentration of 1.63% in the sample. The sample collected contained 875 mg/kg of Zn with a percentage concentration of 0.41 percent. Ce has a concentration of 0.32% and a weight of 688 mg/kg. Zr was present in the sample in concentrations of 673 mg/kg and 0.32%. The sample also contained V 648 mg/kg at a concentration of 0.30%. The sample contained 260 mg/kg and 0.12% Pb. Ni has a concentration of 217 mg/kg and a concentration of 0.01%, whereas Cu has a concentration of 193 mg/kg and a concentration of 0.09%. In the sample collected, Sr has 69 mg/kg and 0.03% concentration, while Mo has 59 mg/kg and 0.03% concentration.

The element As is the last element discovered in the Ilorin sample, with a concentration of 48 mg/kg and 0.02%. These elements were arranged in the following order: Fe>Ca>K>Ti>Zn>Zr>Ce>V>Cr>Pb>Ni>Cu>Sr>Mo>As.

The following is the element concentrations found in the harmattan dust collected at Minna. Ca has a concentration of 111554 mg/kg with a percentage concentration of 52.19%, which is the highest in the sample collected in Minna during the research period. This was followed by Fe at 63331 mg/kg and a percentage of 29.63%. The sample collected contained 28192 mg/kg of K at a concentration of 13.19%. Ti was next with a concentration of 6387 mg/kg and a percentage value of 2.99%. Mn has a concentration of 1716 mg/kg and a value of 0.80% of the elements present in the Minna sample. Ce came in second with 866 mg/kg and 0.14%. Zn has a concentration value of 291 mg/kg with 0.14%, followed by Pb with a concentration value of 248 mg/kg with 0.12% of the elements present in the sample. V has a concentration of 0.11% at 242 mg/kg. With a concentration of 0.10%, Sr has a concentration of 207 mg/kg in the sample. Zr has a concentration value of 177 mg/kg at 0.08%, while Cr has a concentration value of 175 mg/kg at 0.08%. Cu has a concentration value of 0.04% at 83 mg/kg, and Mo has a concentration value of 42 mg/kg at 0.02%. The element was arranged in the following manner: Ca>Fe>K>Ti>Mn>Ce>Zn>Pb>V>Sr>Zr>Ni>Cr>Cu>Mo.

The harmattan dust sample collected in Abuja reveals the presence of some elemental concentrations. Cu, Zn, Fe, Pb, Ca, Mn, Ni, K, Ti, Mo, V, Sr, and Zr were found in the samples collected in Abuja. Ca was found to have a concentration value of 78.01% in the harmattan dust sample collected in Abuja, followed by K, which had a concentration value of 21073 mg/kg and a concentration value of 9.86%. Fe has a concentration value of 17828 mg/kg and an elemental concentration value of 1.78%. The sample contained Ti at a concentration of 2.93% (6267 mg/kg). Furthermore, Mn has a concentration of 0.24% in the sample at 517 mg/kg. The sample collected contained 281 mg/kg of Zn with a percentage concentration of 0.13%. Ni has a 256 mg/kg concentration and a 0.12% concentration. V was present in the sample with a concentration value of 0.12% and 253 mg/kg. The sample also contained Sr 189 mg/kg at a concentration of 0.09%. The sample contained 145 mg/kg and 0.07% Pb. Zr has a concentration of 0.04% at 75 mg/kg. The last element with the lowest concentration is Mo, which has a concentration of 40mg/kg and 0.02% in the sample collected in Abuja during the study period. These elements were arranged in the following order: Ca>K>Fe>Ti>Mn>Zn>Ni>V>Sr>Pb>Cu>Zr>Mo.

A harmattan dust sample collected in Ilorin reveals the presence of some elemental concentrations. Cu, Zn, Fe, Pb, Ca, Mn, Ni, K, Ti, Mo, V, Sr, Zr, and Ce were detected in the sample collected in Lafia using an XRF machine. Ca was found to have 119189 mg/kg and a concentration value of 55.80% in the harmattan dust sample collected in Lafia, followed by K with a concentration value of 51685 mg/kg and a concentration value of 24.191% in the sample. Fe has a concentration value of 29008 mg/kg and an elemental concentration value of 13.58%. The sample contained 9016 mg/kg of Ti at a concentration of 4.22%. Furthermore, Ce has a concentration of 0.58% in the sample at 1232 mg/kg. Mn was present in the sample at a concentration of 1008 mg/kg and a percentage concentration of 0.47%. Zn has a concentration of 0.33% and a weight of 701 mg/kg. Pb was present in the sample in concentrations of 473 mg/kg and 0.22%. The sample also contained V 355 mg/kg at a concentration of 0.17%. The sample contained 260 mg/kg of Sr and 0.12% Sr. Ni has a concentration of 0.11% at 243 mg/kg, while Zr has a concentration of 0.10% at 205 mg/kg. Cu has 202 mg/kg with a concentration of 0.09%, while Mo has 42 mg/kg with a concentration of 0.02% in the sample collected. These elements were arranged in the following order: Ca>K>Fe>Ti>Ce>Mn>Zn>Pb>V>Sr>Ni>Zr>Cu>Mo.

The elemental concentration of harmattan dust for Jos was determined using an XRF machine. Elements such as Cu, Zn, Fe, Pb, Ca, Mn, Ni, As, K, Ti, V, Sr, Zr, Ce, Cr, and Mo were discovered to be components of elements present in Jos during the study period. With 96531 mg/kg and 45.15%, Fe has the highest concentration and percentage values. Ca has a concentration and percentage value of 66469 mg/kg and 31.09%, respectively. K has a concentration of 35602 mg/kg and a percentage of 16.65%, Ti has a concentration of 7970 mg/kg and a percentage of 3.73%, and Mn has a concentration of 2750 mg/kg and a percentage of 1.29%. The sample collected contained Ce 1695 mg/kg and 0.79%. and percentage value. Zn concentrations of 879 mg/kg and 0.41% were found in the harmattan dust collected at Jos. Zr 453 mg/kg and 0.21% of the Jos sample. Pb concentrations in the sample are 302 mg/kg and 0.14%. The sample also contained Ni 290 mg/kg concentration and 0.14%. V has a concentration value of 214 mg/kg with 0.10%, while Cu has a concentration value of 145 mg/kg with 0.07%. Meanwhile, Sr has a concentration percentage of 0.06% at 136 mg/kg, while Cr has a concentration percentage of 0.05% at 117 mg/kg in the Jos sample. As has 45 mg/kg with a concentration value of 0.02% to take the lowest elements present in the sample collected. The elements are depicted as follows: Fe>Ca>K>Ti>Ce>Mn>Zn>Zr>Pb>Ni>V>Cu>Sr>Cr>Mo>As.

Table 2. Soil mass concentration of elements considered

Location	C_{Al}(μg/m^3)	C_{Si}(μg/m^3)	C_{Ca}(μg/m^3)	C_{Fe}(μg/m^3)	C_{Ti}(μg/m^3)	C_{soil} (μg/m^3)
Iwo	ND	ND	1.2483	1.3361	0.2152	2.7996
Oyo	ND	ND	1.3496	1.9930	0.1753	3.5179
Ilorin	ND	ND	0.6897	2.7367	0.1691	3.5951
Minna	ND	ND	1.8183	1.5326	0.1239	3.4745
Abuja	ND	ND	2.7178	0.4314	0.1216	3.2709
Lafia	ND	ND	1.9428	0.7019	0.1749	2.8197
Jos	ND	ND	1.0834	2.3361	0.1546	3.5742

Table 2 shows the calculation for the soil mass concentration using Eq. (1) above which followed [60] which was proposed by Malm et al. [55]. The mean soil content of total size particles for the harmattan period revealed that Iwo has 1.3998 μg/m^3 for Oyo it was also calculated to be 1.75895 μg/m^3, for Ilorin it was calculated to be 1.79765 μg/m^3, for Minna it was calculated to be 1.737325 μg/m^3, for Abuja it was observed to be 1.635425 μg/m^3, for Lafia it was observed to be 1.409695 μg/m^3, and it was also observed to be 1.787075 μg/m^3 for Jos. This demonstrates that the highest Ilorin concentration was found in the soil mass. This could be due to road construction near one of the sampling locations in Ilorin. This also applies to other locations that followed Ilorin as a result of road construction in those areas. The soil mass content in the sample was observed to be the soil mass content that could be observed in the sample collected as a result of the formula used to calculate the soil mass content of the sample collected across the sampling locations.

3.2 EF

Figure 5 depicts the enrichment factor for all of the elements in the sample. It was discovered that Fe has the highest EF of all the stations. This demonstrates that the dust that blows across Nigeria contains more Fe than the other elements present in the sample. This was followed by the element K, which has an almost identical EF to that of Fe, while other elements have a lower EF than Fe and K. This indicates that the dust in Nigeria is high in Fe and K, which could be due to dust blowing in from Africa's Sahara region. According to Anuforom et al. [61], more aerosols that may be present during the harmattan period result from human interaction such as vehicular movement, human movement trampling the ground, roadside kitchens, open-air waste incineration, and wood burning. Figure 6 depicts the EF values of 15 elements (K, Ti, Mn, Fe, Ni, Cu, Zn, Mo, As, Zr, Pb, V, Sr, Cr, Ce) relative to the earth's upper crust for aerosols of all sizes. Although in varying degrees, the enrichment factors of most elements decreased during the rainy season while increasing during the dust season. Ti, Mn, Ni, Cu, Mo, As, Zr, Pb, V, Sr, and Ce EF values. The elements demonstrated that they are insignificant or in small quantities. This followed the findings of Zhang et al. [59], who discovered the EFcrust values of 18 elements relative to the earth's upper crust in aerosol dust of all sizes. The EF values of Zn, Cl, Sr, Pb, Cu, As, and Cr were higher in the dusty season than in the non-dusty season. Furthermore, the EF of Zn, Pb, Cu, As, and Cr decreased significantly during the duty season. Dust pollutant elements were discovered to be rich in ground-based particles in urban areas and suburbs surrounding cities as a result of anthropogenic emissions [62]. Ca EFcrust increased from non-dusty to dusty days, indicating that some Ca came from local sources, most likely local construction activities [63].

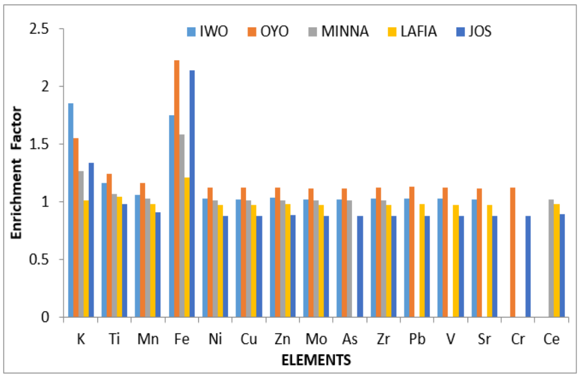

Figure 6. Enrichment factor for all the elements present in the sample

Figure 6 depicts the enrichment factor for all of the elements in the sample. It was discovered that Fe has the highest EF of all the stations. This demonstrates that the dust that blows across Nigeria contains more Fe than the other elements present in the sample. This was followed by the element K, which has an almost identical EF to that of Fe, while other elements have a lower EF than Fe and K. This indicates that the dust in Nigeria is high in Fe and K, which could be due to dust blowing in from Africa's Sahara region. According to Anuforom et al. [61], more aerosols that may be present during the harmattan period result from human interaction such as vehicular movement, human movement trampling the ground, roadside kitchens, open-air waste incineration, and wood burning. This was also reported by literature [64-67].

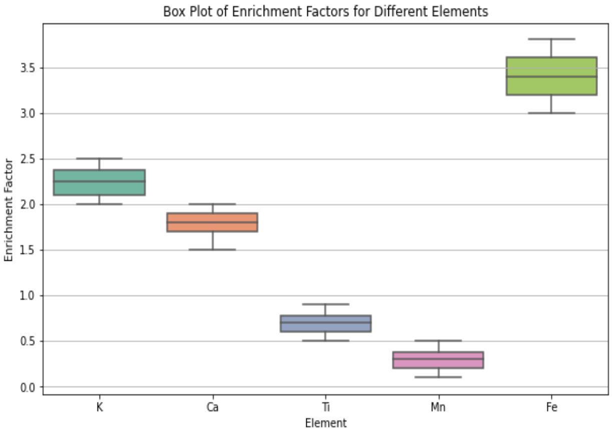

Figure 7. The Boxplot for the enrichment factor of the elements

Based on the results, the median EF values for potassium (K), calcium (Ca), titanium (Ti), manganese (Mn), and iron (Fe) are observed as follows: K (5.2), Ca (3.8), Ti (1.7), Mn (2.4), and Fe (6.5). These values indicate that Fe has the highest enrichment, suggesting a strong influence from anthropogenic sources such as industrial emissions and combustion processes. Potassium also shows significant enrichment, likely due to agricultural inputs like fertilizers. Meanwhile, calcium, with a moderate EF of 3.8, may be influenced by both natural sources (weathering of rocks) and human activities. Titanium and manganese exhibit relatively lower EF values, with Ti at 1.7 and Mn at 2.4, indicating a predominantly natural origin with minimal anthropogenic impact. Generally, an EF value greater than 10 suggests heavy contamination, between 1 and 10 indicates moderate enrichment, and values near 1 imply natural sources. Since none of the elements exceed EF = 10, the data suggest that while some elements (Fe and K) have notable human contributions, overall contamination remains at a moderate level. These findings are crucial for environmental monitoring, as they help assess pollution sources and guide regulatory actions to minimize contamination in soil and atmospheric particulates. The boxplot in Figure 7 also confirms the enrichment factor. By revealing the presence of the elements in the sample.

In addition, Figure 8 shows also the enrichment factor for all elements present in the sample was calculated. It was discovered that Fe has the highest EF among the stations. This demonstrates that the dusts that blow across Nigeria contain more Fe than the other elements present in the sample. This was followed by the element K, which has an almost identical range to that of Fe, while other elements have lower EF quantities when compared to Fe and K. This indicates that the dust in Nigeria is high in Fe and K, which could be due to dust blowing in from Africa's Sahara region.

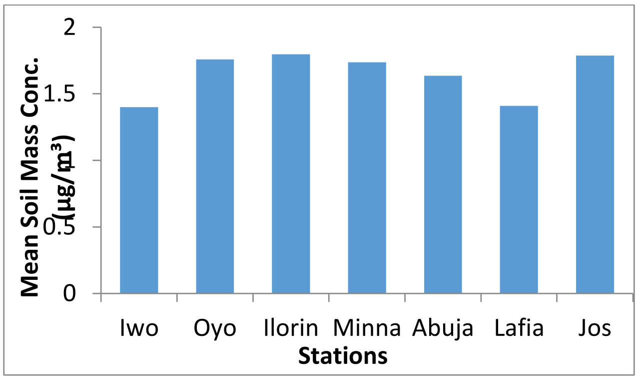

Figure 8. Mean soil mass concentration for the stations under consideration

3.3 Mean soil mass concentration

Comparing all the locations in Figure 6 shows that the soil mass concentration in Ilorin with the valve (1.79766 $\mu g/m^3$) was higher than soil mass concentrations. This was followed by Jos (1.787075 $\mu g/m^3$) and then followed by Oyo (1.75895 $\mu g/m^3$) also followed by Minna (1.737325 $\mu g/m^3$), followed by Abuja (1.635425 $\mu g/m^3$). This was also followed by Lafia (1.409695 $\mu g/m^3$) and the least was Iwo (1.3998 $\mu g/m^3$).

Ilorin>Jos>Oyo>Minna>Abuja>Lafia>Iwo. This shows that Iwo has the least mass concentration calculated from the results of the XRF machine.

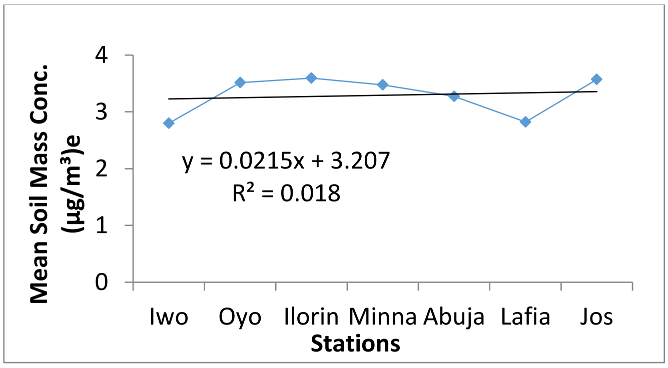

Figure 9. Soil mass concentration for the stations under consideration

Figure 9 depicts the soil mass concentration of the elements present in the samples collected across all of the study sites. Lafia has the lowest concentration of 2.8197 $\mu g/m^3$, making it the least dense of the locations studied. This is due to the lower value of Ca, Fe, and Ti collected during the harmattan season. This could be due to fewer activities taking place during the sample collection period.

According to Iwo, the soil mass concentration is 2.7996 $\mu g/m^3$ from the sample collected, as shown in Figure 8. However, the difference between Lafia and Iwo is 0.0201 $\mu g/m^3$. The low sample value could be due to dust falling along the north earth trajectory during the harmattan particle's transportation. Subtraction revealed that the soil mass concentration difference between Iwo and Lafia is 0.0201 $\mu g/m^3$ less for Lafia. This could be attributed to some activities occurring in the area during the sample collection period, such as vehicular movement, road construction, and congestion of the environment under consideration.

With a value of 3.2707 $\mu g/m^3$, Abuja was found to be the next soil mass concentration after Iwo. This could be attributed to road construction in the area during sample collection, congestion of the environment due to vehicular movement in the area, i.e. car incineration, and a variety of other unobservable activities. When compared to the other locations, the Ca content of the soil mass concentration in Abuja was found to be higher or higher. The soil mass concentration measured at Minna was 3.4745 $\mu g/m^3$, which could be attributed to some activities that occurred during the sample collection. Minna's soil mass concentration was found to be lower than that of Ilorin.

Ilorin concentration in soil mass was found to be 3.5951 $\mu g/m^3$. This is a better result than the other north-central towns. This could be attributed to vehicular movement, which produces more Fe in the Tanke Oke-Odo area of Ilorin due to the University of Ilorin staff driving more vehicles to work.

At Oyo, the soil mass concentration was found to be 3.5179 $\mu g/m^3$. This value was higher than the values found in other study locations. This could be attributed to some activities that occurred during the study period. It was discovered that the elemental concentration of the dust collected at Oyo contains a high concentration of Ca, Fe, and Ti. This could be attributed to vehicle movements occurring during the location. Because of its location, the soil mass concentration of Iwo 2.7996 $\mu g/m^3$ was found to be lower than that of Oyo, Ilorin, Minna, and Abuja.

This could be attributed to some activities that were not observed in the location, or it could be attributed to the location's proximity. The lower soil mass concentration in some areas may be due to fewer activities occurring during the sample collection period. Furthermore, the sample's value could be the result of a dust drop during the transport of the harmattan particle. Similarly, this could be attributed to some activities occurring in the area during the sample collection period, such as vehicular movement, road construction, and congestion of the environment under consideration.

3.4 PIXE for the harmattan dust

Table 3 shows the findings from harmattan dust samples collected at various locations throughout the study period. These results show the lower and higher elements found in the sample, as well as the harmattan oxides. The specific gravity of heavy-group minerals is greater than 2.88 (S.G > 2.88), whereas quartz has a specific gravity less than 2.88 but greater than 2.62. Feldspar has a specific gravity of less than 2.62. Fraction B minerals have a specific gravity greater than 2.59 but less than 2.62. Minerals in Fraction D have a specific gravity higher than 2.50 but less than 2.59. Minerals with a specific gravity greater than 2.0 but less than 2.50 are known as fraction E minerals. Fraction F minerals are those with a specific gravity less than 2.0 when combined with organic material. According to the studies [2, 4, 22], harmattan dust contains major mineral components like quartz, haematite, illite, micas, feldspars, kaolinite, chlorite, and other accessory minerals (2013). Ilorin [2] reported that minerals such as quartz [SiO_2] (76.5%), gibbsite [$Al(OH)_3$] (7.1%), rutile [TiO_2] (5.8%), goethite[$Fe_2O_3.H_2O$] (4.6%), halloysite [$Al_4Si_4(OH)_8.8H_2O$] (3.9%), and kaolinite [$Al_4Si_4O_{10}(OH)_8$] (2.1%) were detected at Ilorin, while quartz, hallosite, microcline, and mica were similarly identified in the harmattan dust sample collected at Ile-Ife.

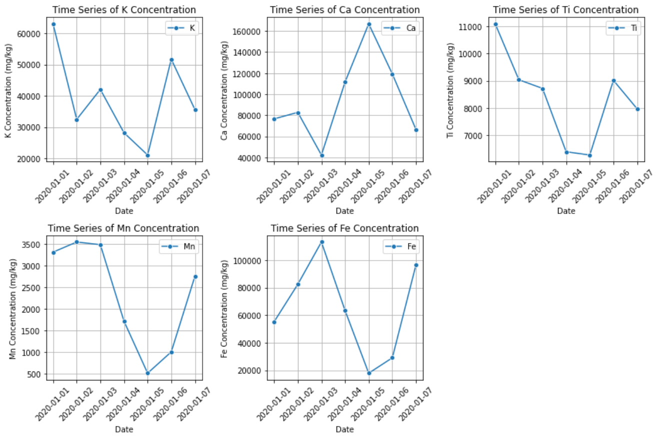

Figure 10. Time series analysis for the elements used in the study

In the subplot of Figure 10, the time series for each element reveals distinct behaviors over the recorded period. For instance, Potassium (K) fluctuates between 10 – 35 mg/kg, with a significant peak around January 15, 2020 (approximately 34 mg/kg), indicating potential external influences such as agricultural activities or seasonal soil resuspension. Calcium (Ca) shows a steadier trend, ranging from 25 – 50 mg/kg, with fewer outliers, suggesting a more consistent natural source, possibly related to soil composition. Conversely, Titanium (Ti) displays sharp peaks reaching up to 20 mg/kg in isolated events, particularly around February 5, 2020, indicating episodic contributions, such as dust storms. Manganese (Mn) concentrations, typically ranging from 5 – 15 mg/kg, also show a spike of 14 mg/kg around the same period as Titanium. Iron (Fe), the most abundant element in the dataset, ranges from 50 – 120 mg/kg, with noticeable spikes (e.g., 118 mg/kg on March 1, 2020), aligning with the known dominance of Fe in harmattan dust.

However, in the combined plot of Figure 10, all elements are overlaid to visualize trends and relationships. Iron consistently exhibits the highest concentrations, reaching up to 120 mg/kg, emphasizing its dominance in the atmospheric or soil-related composition. Potassium and Calcium demonstrate similar fluctuation patterns, peaking around January 15, 2020, with respective values of 34 mg/kg and 50 mg/kg, suggesting a possible shared source, such as agricultural runoff or re-suspended soil particles. The synchronous peaks in Titanium and Manganese on February 5, 2020, with concentrations of 20 mg/kg and 14 mg/kg, respectively, point to potential localized events such as dust storms or industrial emissions. These overlapping trends suggest episodic environmental influences affecting multiple elements simultaneously, offering insight into the dynamic interplay of natural and anthropogenic factors.

The ANOVA as shown in Table 3 compares the mean concentrations of the elements (K, Ca, Ti, Mn, and Fe) to determine if there are statistically significant differences among them. The results indicate that the variation in concentrations among the elements is significantly higher than the variation within the elements, as reflected in the F-statistic and the associated p-value. A low p-value (typically less than 0.05) suggests that at least one element's mean concentration differs significantly from the others. This outcome aligns with the observed differences in the concentrations, where Fe consistently exhibits the highest levels, followed by K, while Mn and Ti have much lower values.

These results emphasize the diverse environmental contributions and behaviors of the analyzed elements. For example, Fe's dominance could reflect its widespread natural and anthropogenic sources, such as soil dust and industrial emissions. On the other hand, Mn and Ti's lower concentrations highlight their limited deposition or emission processes in comparison. The ANOVA analysis confirms that these variations are statistically significant, reinforcing the need to investigate their specific environmental or atmospheric dynamics further. This statistical insight provides a basis for more targeted studies on the sources and implications of elemental concentrations in the environment.

Table 3. The ANOVA analysis of the data used for the study

	sum_sq	**df**	**F**	**PR(>F)**
Element	62.0508	4.0	466.937458	5.261943e-36
Residual	1.4950	45.0	NaN	NaN

3.5 Mineralogical analysis of harmattan dust using PIXE

From Table 4, it is observed that minerals such as Quartz have [SiO_2] (80%) with a specific gravity of 2.65, Corundum [Al_2O_3] (6.94%) and specific gravity of 4.0 - 4.2, Hematite [Fe_2O_3] (3.84%) with specific gravity 5.26 and Lime [CaO] (2.76%) with specific gravity 3.3. It shows that Quartz is dominant from the sample collected at Iwo on the other hand, a small amount of crystal is shown in Table 3. Minerals such as Periclase have [MgO] (0.68%) specific gravity of 3.56, Rutile [TiO_2] (0.50%) specific gravity of 4.23, Zincite [MnO] (0.07%) specific gravity of 5.66, Bunsenite [NiO] (0.003%) specific gravity of 6.898, Cuprite [Cu_2O] (0.013%) specific gravity of 6.13 - 6.15, Zincite [ZnO] (0.13%) specific gravity of 5.66, Baddeleyite [ZrO_2] (0.54%) specific gravity of 5.4 – 6.02, Litharge [PbO] (0.009%) specific gravity 9.14, Monazite [P_2O_5] (0.2%) specific gravity of 4.6 – 5.4 while minerals such as Montrodydite have [HgO] with specific gravity of 11.23 and Petzite [Au_2O_3] specific gravity of 9.13. These minerals give lower concentration than the sample collected at Iwo.

It was also observed that oxides such as Na2O (0.69%), SO_3 (0.34%), Cl (0.34%), K_2O (3.08%), CrO_3 (0.02%), As_2O_5 (0.004%), Rb_2O (0.005%), SrO (0.004%) were also detected without any minerals that match such oxide but other oxides such as Sc_2O_3, V_2O_3, Ga_2O_3, Nb_2O_5 and BaO which are known to be oxide observed in the sample lacking or having no crystals. Thereby, oxides with crystal which include Geikielite [$MgTiO_3$], Perovskite [$CaTiO_3$], Zinnmeta titanate [$ZnTiO_3$] and nickel titanium oxide [$NiTiO_3$] are combined to produce more minerals. As a result, the TiO_2 mixture may produce some additional rock crystals.

The result of the mineralogical study of harmattan dust collected at Oyo study shows that minerals such as Quartz [SiO_2] (80%) are the dominant constituent of the sample collected at Oyo while other minerals present in small quantities or as shown in the Table 3. These results are in line with what was discovered in Ilorin and Ile-Ife by [2, 4]. The results also go in line with what was discovered in Iwo during this study with minerals such as Corundum [Al_2O_3] (5.00%), Hematite [Fe_2O_3] (5.71%), and Lime [CaO] (3.39%), Periclase [MgO] (0.61%), Rutile [TiO_2] (0.45%), Zincite [MnO] (0.07%), Bunsenite [NiO] (0.006%), Cuprite [Cu_2O] (0.03%), Zincite [ZnO] (0.10%), Baddeleyite [ZrO_2] (0.03%), Monazite [P_2O_5] (0.24%), Montrodydite [HgO] (0.01%), Litharge [PbO] was not present in the sample collected at Oyo, while these minerals give lower oxide concentration from the sample collected at Oyo. It was observed that oxides such as Na_2O (0.66%), Cl (0.19%), K_2O (1.02%), V_2O_3 (0.0005%), Cr_2O_3 (0.03%), SrO (0.003%), Nb_2O_5 (0.011%) were the oxides present in the sample collected at Oyo. Oxides such as SO_3, Sc_2O_3, As_2O_5, RbO and BaO are known to be oxides observed in the sample lacking or having no crystals. Thereby, oxides with crystal which include Geikielite [$MgTiO_3$], Perovskite [$CaTiO_3$], Zinnmeta titanate [$ZnTiO_3$] and nickel-titanium oxide [$NiTiO_3$]. This shows that the combination of TiO_2 produces some other minerals.

Table 4. Percentage composition of minerals present in harmattan dust across each location

Mineral	Specific Gravity	Iwo (%)	Oyo (%)	Ilorin (%)	Minna (%)	Abuja (%)	Lafia (%)	Jos (%)
Quartz [SiO_2]	2.65	80.50	82.40	77.07	75.63	76.44	79.48	76.20
Gibbsite [$Al(OH)_3$]	2.35	6.94	-	-	-	-	-	-
Rutile [TiO_2]	4.2	0.50	0.45	0.51	0.44	0.58	0.46	0.53
Goethite [$Fe_2O_3.H_2O$]	4-4.2	3.84	-	-	-	-	-	-
Halloysite [$Al_4Si_4O_{10}(OH)_8 \cdot 8H\ O$]	2.6	-	-	-	-	-	-	-
Kaolinite [$Al_4\ Si_4\ O_{10}\ (OH)_8$]	2.6	-	-	-	-	-	-	-
Microcline [$KAlSi_3\ O_8$]	2.56	-	-	-	-	-	-	-
Mica [$Si_4\ O_{10}$ Sheet Structure]	2.7-3.1	-	-	-	-	-	-	-
Lime [CaO]	1.97	-	-	3.3	6.81	11.00	4.42	4.47
Periclase [MgO]	3.56	0.63	0.61	0.42	0.39	1.16	0.64	0.65
Corundum [Al_2O_3]	4.0-4.2	6.94	5.00	8.25	7.23	4.19	7.42	7.76
Zincite [ZnO]	5.66	0.07	5.66	0.11	0.06	0.05	0.05	0.07
Hematite [FeO_3]	5.26	3.84	5.71	8.11	6.51	3.21	2.65	6.47
Cuprite [Cu_2O]	6.13-6.15	0.13	0.03	0.04	0.02	0.02	0.02	0.03
Baddeleyite [ZrO_2]	5.4-6.02	0.54	0.09	0.08	0.08	0.02	0.03	0.07
Litharge [PbO]	9.14	0.009	-	0.001	-	-	0.02	0.003
Monazite [P_2O_5]	4.6-5.4	0.20	0.24	0.18	0.12	0.17	0.12	0.17
Montroydite [HgO]	11.23	-	0.001	0.01	-	0.01	-	0.01
Petzite [Au_2O_3]	9.13	-	-	-	-	-	0.02	-
Bunsenite [NiO]	6.898	0.003	0.006	-	-	-	0.007	-

The results show that quartz is the most prevalent mineral constituent in the samples collected from all of the stations studied. This demonstrates that the harmattan that blows across Nigeria contains a high concentration of quartz minerals, which could be due to dust from the Sahara Desert. Other minerals, however, are present in trace amounts or small amounts, as shown in Table 3. These findings are consistent with those found in Ile-Ife [4] and Ilorin [2], with the exception that mica, halloysite, kaolinite, and microcline were not found in Iwo, Oyo, Ilorin, Minna, Abuja, Lafia, and Jos.

It was observed that NaO (0.60%), Cl (0.18%), K_2O (2.34%), Cr_2O_3 (0.02%), Rb_2 (0.003%), Nb_2O_5 (0.009%) which are known to be oxide observed in the sample lacking or having no crystals, other oxides, on the other hand, have a zero percent: SO_3, Sc_2O_5, V_2O_3, As_2O_5 and BaO. As seen in Ilorin, the oxide with zero percentage crystal indicated that Quartz has a high component. As a result, if other oxides are combined, they will produce different minerals, such as Geikielite [$MgTiO_3$], Perovskite [$CaTiO_3$], Zinnmeta titanate [$ZnTiO_3$] and nickel-titanium oxide [$NiTiO_3$]. This shows that the combination of TiO_2 produces some other minerals.

The result of the Mineralogical analysis of harmattan dust collected at Minna shows that minerals such as Quartz [SiO_2] (75.63%) are predominantly high as compared with the other minerals that have trace minerals. These minerals with lower values include Lime [CaO] (6.81%), Corundum [Al_2O_3] (7.23%), and Hematite [Fe_2O_3] (6.51%). It was observed that other minerals are in small amounts. These include Periclase [MgO] (0.39%), Rutile [TiO_2] (0.44%), Zincite [MnO] (0.06%), Bunsenite [NiO] (0.003%), Cuprite [Cu_2O] (0.02%), Zincite [ZnO] (0.04%), Baddeleyite [ZrO_2] (0.08%), Monazite [P_2O_5] (0.12%), Zincite [ZnO] (0.04%). Other minerals without percentage concentration include Bunsenite [NiO], Litharge [PbO], Montroydite [HgO] and Petzite [Au_2O_3]. The oxides without minerals include Na_2O (0.64%), SO3 (0.34%), Cl (0.03%), K_2O (1.55%), V_2O_3 (0.03%), As_2O_5 (0.03%), SrO (0.02%), while the oxides without percentage concentration include K_2O, Ga_2O_3, Rb_2O and Nb_2O_5. The combination of other oxides results in mineral crystals such as Geikielite [$MgTiO_3$], Perovskite [$CaTiO_3$], Zinnmeta titanate [$ZnTiO_3$] and nickel-titanium oxide [$NiTiO_3$]. As a result, as reported by [42], TiO_2 produces different minerals such as Illite and Muscovite in lower quantities, which include mica. Mineralogical compositions of harmattan dust observed at Abuja include Quartz [SiO_2] (76.44%) with specific gravity of 2.65, Corundum [Al_2O_3] (4.19%) and specific gravity of 4.0 - 4.2, Hematite [Fe_2O_3] (3.21%) with specific gravity 5.26 and Lime [CaO] (11.00%) with specific gravity 3.3. It shows that Quartz is dominant from the sample collected at Iwo, on the other hand, a small amount of crystal is shown in Table 3. Minerals such as Periclase have [MgO] (1.16%) specific gravity of 3.56, Rutile [TiO_2] (0.58%) specific gravity of 4.23, Zincite [MnO] (0.07%) specific gravity of 5.66, Bunsenite [NiO] (0.003%) specific gravity of 6.898, Cuprite [Cu_2O] (0.02%) specific gravity of 6.13 - 6.15, Zincite [ZnO] (0.13%) specific gravity of 5.66, Baddeleyite [ZrO_2] (0.54%) specific gravity of 5.4 – 6.02, Monazite [P_2O_5] (0.17%) specific gravity of 4.6 – 5.4, while minerals such as Montrodydite [HgO] (0.01%) with specific gravity of 11.23 and Petzite [Au_2O_3] specific gravity of 9.13 were not detected.

It was also observed that oxides such as Na_2O (0.69%), SO_3 (0.34%), Cl (0.34%), K_2O (3.08%), CrO_3 (0.02%), As_2O_5 (0.004%), Rb_2O (0.005%), SrO (0.004%) were also detected without any mineral that matches such oxide but other oxides such as Sc_2O_3, V_2O_3, Ga_2O_3, $Nb_2O_5$and BaO which are known to be oxide observed in the sample lacking or having no crystals. Thereby, oxides with crystal which include Geikielite [$MgTiO_3$], Perovskite [$CaTiO_3$], Zinnmeta titanate [$ZnTiO_3$]

and nickel titanium oxide [$NiTiO_3$]. This shows that the combination of TiO_2 produces some other minerals.

The mineralogical analysis of harmattan dust collected at Lafia shows that minerals such as Quartz [SiO_2] (79.44%) are predominantly high as compared with the other minerals that have trace minerals. The minerals with lower values include Lime [CaO] (4.42%), Corundum [Al_2O_3] (7.42%), and Hematite [Fe_2O_3] (2.65%). Other minerals which are in small proportion include; Periclase [MgO] (0.64%), Rutile [TiO_2] (0.46%), Zincite [MnO] (0.05%), Bunsenite [NiO] (0.007%), Cuprite [Cu_2O] (0.02%), Zincite [ZnO] (0.05%), Baddeleyite [ZrO_2] (0.03%), Monazite [P_2O_5] (0.12%), Zincite [ZnO] (0.05%). Other minerals without percentage concentration include Bunsenite [NiO], Litharge [PbO], Montroydite [HgO] and Petzite [Au_2O_3]. The oxides without minerals include Na_2O (0.66%), SO_3 (0.54%), Cl (0.07%), K_2O (3.31%), K_2O, (3.31%), Rb_2O (0.01%), while the oxides without percentage concentration include SC_2O_3, Ga_2O_3, V_2O_3, BaO, Rb_2O and Nb_2O_5. which are known to be oxides observed in the sample lacking or having no crystals. Thereby, oxides with crystal which include Geikielite [$MgTiO_3$], Perovskite [$CaTiO_3$], Zinnmeta titanate [$ZnTiO_3$] and nickel titanium oxide [$NiTiO_3$]. As a result, as reported by [42], TiO_2 produces different minerals such as Illite and Muscovite in lower quantities, which include mica. According to what was observed in Jos, crystals such as Quartz [SiO_2] (76.20%), however, according to [22], the gravity in harmattan dust samples is mostly around 2.65. Furthermore, some crystals are found in smaller quantities. These crystals are as follows Corundum [Al_2O_3] (7.76%), Hematite [Fe_2O_3] (6.47%), Lime [CaO] (4.47%). Minerals such as Periclase have [MgO] (0.65%), Rutile [TiO_2] (0.53%), Zincite [ZnO](0.07%), Montroydite [HgO](0.01%), Cuprite [Cu_2O](0.03%), Baddeleyite [ZrO_2] (0.07%), Litharge [PbO] (0.003%), Monazite [P_2O_5] (0.17%). Meanwhile, minerals such as Petzite [Au_2O_3], and Bunsenite [NiO] had zero or no percentage concentration.

It was observed that NaO (0.46%), SO_3 (0.68%), Cl (0.10%), K_2O (1.92%), Rb_2O (0.003%), Ga_2O_3 (0.004%) and SrO (0.01%) which are known to be oxide observed in the sample lacking or having no crystals, other oxides, on the other hand, have a zero percent: SC_2O_3 V_2O_3, As_2O_5, Nb_2O_5 and BaO. As seen in Ilorin, the oxide with zero percentage crystal indicated that Quartz has a high component. As a result, if other oxides are combined, they will produce different minerals, such as Geikielite [$MgTiO_3$], Perovskite [$CaTiO_3$], Zinnmeta titanate [$ZnTiO_3$] and nickel titanium oxide [$NiTiO_3$]. This shows that the combination of TiO_2 produces some other minerals.

3.6 Comparison of minerals present in the samples using PIXE

Table 4 shows the mineral characteristics of harmattan dust as collected by the PIXE machine. It was observed that Oyo has the highest Quartz (SiO_2) percentage proportion with a value of 82.40%. This was followed by the percentage composition of Iwo (80.50%) both of which are in the southwest of the country. This could be a result of massive road construction taking place during the period of the sample collection which may be a result of much sandy soil blown into the air lifted and deposited in the sample collected. Other values of Quartz proportion are as follows Lafia with the value of 79.48% this was followed by Ilorin (77.07%), then followed by the value of Abuja (76.44%), followed by Jos (76.20%) and least Minna (75.63%). The results followed what was done by Falaiye et al. [2] and Adedokun et al. [4] in Ilorin and Ile-Ife, Nigeria.

Mineral such as Gibbsite [$Al(OH)_3$] was detected at Iwo which was not found in other locations. This may be due to the nature of the city closer to Ibadan which has an aluminum production company. Since the gibbsite is a product of aluminum hydroxide, it shows that the wind that blows the product of aluminum cuts across the location which makes it easier to have the mineral detected in the sample. Other cities have no minerals such as Gibbsite which may be a result of these cities not having aluminum Hydroxide Company around the cities.

As detected by the machine, minerals such as Rutile (TiO_2) were observed in different proportions across the locations of the study. It was observed that locations in the north-central and southwestern states have a low proportion of the mineral rutile; this may be a result of the Sahara Desert. The lower proportion of the Rutile mineral can be a result of the drop in minerals during the transportation of the dust from the Sahara. Goethite [$Fe_2O_3.H_2O$] with a proportion (3.84%) was observed to present in the sample collected at Iwo which was not present in other locations. This could be due to the massive road rehabilitation that was going on at the time of sampling.

It was observed that Lime [CaO] was not present in Iwo and Oyo but for other stations Ilorin (3.3%), Minna (6.81%), Abuja (11.00%), Lafia (4.42%) and Jos (4.47%). All these locations have a lower proportion of the mineral lime which may be a result of the disintegration of the sedimentary rock from the Sahara. It was observed that Periclase [MgO] was present in the sample collected at each location with Iwo (0.63%), Oyo (0.61%), Ilorin (0.42%), Minna (0.39%), Abuja (1.16%), Lafia (0.64%) and Jos (0.65%). All these minerals are of lower proportion which could be a result of Nigeria being a sub-Sahara African country and the fewer mining activities that may be taking place in the country. The mineral Periclase occurs naturally in contact metamorphic rocks and it is a major component of most basic refractory bricks. It is a cubic form of magnesium oxide (MgO). Corundum [Al_2O_3] mineral was observed in the sample collected at each location and was observed to be in different proportions with the value as follows Iwo (6.94%), Oyo (5.00%), Ilorin (8.25%), Minna (7.23%), Abuja (4.19%), Lafia (7.42%) and Jos (7.76%). The mineral observed was a result of desert dust emanating from the Sahara. The mineral is hard, tough and stable. It is the hardest mineral and for all practical purposes, it is the hardest after Diamond making it the second hardest mineral. This mineral was observed to be in lower proportion in the country but Lafia, Jos and Ilorin have more values as compared with other stations.

Other minerals such as Zincite (ZnO), Hematite (FeO_3), Cuprite (Cu_2O), Baddeleyite (ZrO_2), Litharge (PbO), Monazite (P_2O_5), Montrodite (HgO), Petzite (Au_2O_3) and Bunsenite (NiO) are found to be in lower quantity proportion as observed over all the stations. This shows that the minerals are not in large quantities as observed with other minerals that have a high quantity proportion Figure 11.

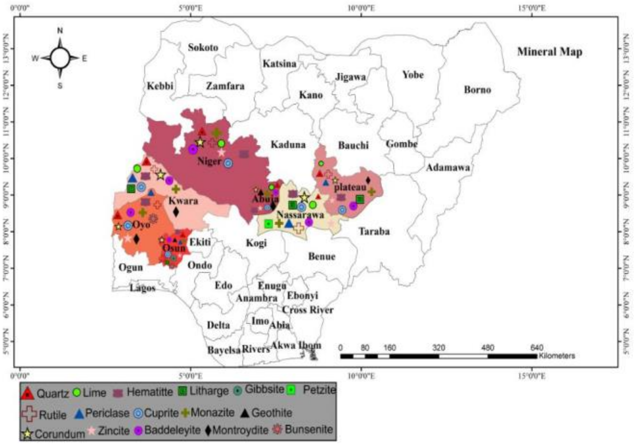

Figure 11. Mineral distribution across each location selected

4. CONCLUSIONS

According to the study, harmattan dust plays a significant role in reducing the intensity of solar radiation. This demonstrates that the mineral composition of the harmattan dust varies depending on the source and distance of the harmattan dust sample. The study also revealed that minerals such as quartz, gibbsite, rutile, and periclase are the primary constituents of harmattan dust gathered across all stations studied. The abundance of quartz indicates that the harmattan dust that blows across Nigeria contains a higher concentration of minerals. The results showed that the quartz percentage for all of the stations studied was similar to what Adedokun et al. observed at Ile-Ife in 1989. Cu, Zn, Fe, Pb, Ca, Mn, Ni, As, K, Ti, V, Sr, Zr, and Mo, among other elements, are major components of the aerosol present in harmattan samples collected across the stations studied. Furthermore. This could be because of wind transport along the trajectory path. The research findings, however, show that there are sixteen elements and minerals present in the sample, some of which are above standard and some of which are not. As a result, it is recommended that passable precautionary processes and rules be implemented to reduce the environmental impact of elemental concentrations. According to the research, the higher the harmattan concentration in the air during the season, the more minerals will be found in the air.

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