INTERNATIONAL JOURNAL OF LATEST TECHNOLOGY IN ENGINEERING, MANAGEMENT & APPLIED SCIENCE (IJLTEMAS)
ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026

Investigating Atmospheric Metal Pollution in Khartoum North (Bahri), Sudan Using Laser-Induced Breakdown Spectroscopy

[1]Hind Ahmed Eisa, [2,*]Abdelrazig Mohamed Abdelbagi, [1]Ahmed H. Elfaki

[1]Sudan University for Science and Technology, Science College, Khartoum

[2]Department of Physics, College of Science, Shaqra University, Saudi Arabia.

[2]Omdurman Islamic University, Faculty of Science, Omdurman, Sudan

DOI : https://doi.org/10.51583/IJLTEMAS.2026.150700135

Received: 10 August 2024; Accepted: 15 August 2024; Published: 22 August 2026

ABSTRACT

In the present study, aerosol samples were collected from an outdoor industrial area and selected streets in Khartoum North. Air pollution is a massive problem due to its harmful health effects on human populations. This study investigates the distribution of heavy metals and associated health risks in three diverse areas of Khartoum North city in central Sudan.

Laser-Induced Breakdown Spectroscopy (LIBS) was used to analyze the aerosol samples, and an Inductively Coupled Plasma (ICP) spectrometer was employed to validate the measurements. The analysis of pollution-related conflicts over air quality in Khartoum is conducted using LIBS and ICP techniques, which provide new insights into the effects of industrial and sub-Saharan dust on human health.

The results showed good agreement between the two techniques. Examining how these elements are distributed in the environment helps identify pollution sources, track their movement through the atmosphere, and assess their ecological impact. The results highlight significant variations in heavy metal concentrations across the studied regions, with sandstorms in the area exhibiting higher pollution levels. Principal component analysis (PCA) revealed distinct metals: Cu1.9 $\mu g/m^3$, Cr 0.47 $\mu g/m^3$, Fe 36.86 $\mu g/m^3$, Ca 87.44 $\mu g/m^3$, and Pb 6.87 $\mu g/m^{3,}$ indicating contributions from anthropogenic emissions, traffic activities, Saharan dust, and natural sources. To present the t-test values for the elements from 8.3 to 11.09, with the highest Cr value of 79.46 and a PCA mean variance % of 64.99, the study highlights the ingredient concentrations. However, this task shows that the average concentrations of elements in Khartoum North's ambient air are more consistent with global statistics from similar regions in many countries.

Keywords: Air pollution, Soil dispersion, Laser-Induced Breakdown Spectroscopy, Elements.

INTRODUCTION

Atmospheric air is a complex and dynamic mixture of solid, liquid, and gaseous particles from both natural and human sources. Air quality valuation requires monitoring heavy metal pollution, and industrial emissions are the primary source of these heavy metals [1]. Growing amounts of solid, liquid, or gaseous materials in ambient air, both indoors and outdoors, cause environmental pollution. Directly emitted aerosols, such as dust, air pollutants, and smoke, are either formed in the air or emitted. Major contributors include traffic emissions, industrial activities, and anthropogenic activities [2]. Several factors contribute to the increasing concentration of solid, liquid, or gaseous substances in ambient air, leading to environmental contamination [3]. These sources release harmful substances into the atmosphere, significantly raising pollution levels and impacting ecosystems and public health. Gaseous pollutants in the natural atmosphere, such as carbon monoxide, sulfur dioxide, and ammonia, are affected by solar radiation.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026

These pollutants originate from various sources, which can have harmful effects on human health, plants, and animals [4]. The damage caused by ambient air pollution primarily affects human well-being through its direct adverse health effects on exposed populations [5]. These processes release large quantities of pollutants, including particulate matter and carbon oxides, which collectively degrade air quality and pose risks to human health and the environment [6]. Environmental pollution causes poor health and reduced life expectancy. If heavy metals are ingested or inhaled at sufficiently high levels, they can be toxic [7].

Khartoum North City is in the sub-Saharan region of central Sudan, near the confluence of the White and Blue Nile. Aerosol loading across the sub-Saharan region is typically higher than which is observed at many other latitudes, largely due to intense dust emissions and biomass burning activities. A comparison of Sahara dust and windblown city dust with other arid and desert environments is preferable [10]. Muntasir A. Ibrahim et al. detected aerosol optical depth pollution in Khartoum city. They used satellite platforms to quantify atmospheric air quality for nitrogen dioxide (NO_2), Sulphur dioxide (SO_2), and carbon monoxide [8]. Using Sentinel-5P satellite data processed in Google Earth Engine, some writers have examined the impact of studying on air quality in Khartoum, Sudan, concentrating on major pollutants: Aerosol Optical Depth (AOD), Carbon Monoxide (CO), Nitrogen Dioxide (NO_2), and Sulphur Dioxide (SO_2). This study reveals the complex multi-pollutant effects on Khartoum's air quality by combining high-resolution satellite data with sophisticated spatial and temporal analysis methods [9].

According to recent data, Bolpur, a semi-urban area in West Bengal, India, Kolkata, an urban area, and Durgapur, an industrial complex, are being investigated for the distribution of particle-bound heavy metals and related health hazards. The findings show regional differences in heavy metal concentrations, with industrial areas exhibiting higher levels due to traffic, industrial emissions, and natural sources. Current research on soil indicates that heavy metals are detrimental and pose a major risk to human health. The overall risk from all heavy metals exceeded the US EPA's limit [10]. With Cd, Cr, Cu, Ni, and Pb exceeding their WHO/FAO limits, Sudan's averages for all heavy elements, taken together, surpassed their corresponding average common range in soils. The purpose of this study was to collect baseline data on the population of Khartoum North's exposure levels to various elements. The levels of the elements in air pollution and the appropriate selection of these elements reflect environmental contamination and population activities in the region, which are critical for public health decision-making [11].

MATERIALS AND METHODS

Khartoum North is situated in Sudan's semi-arid region, with geographic coordinates of approximately 32.77° E longitude and 15.78° N latitude. Due to its location in the sub-Saharan region of North Africa, the city is frequently affected by wind-blown soil dust and sandstorms. Khartoum North's geographical location and climatic conditions result in the influence of both long-range transported Saharan dust and locally generated wind-blown dust [9]. The mineral dust core composition of the dust in Khartoum North's semi-arid environment is probably comparable to that of other desert-blown aerosols [12]. Consequently, comparing its aerosol composition with that found in other arid and desert environments is warranted. A mix of transported Saharan dust and locally generated dust or pollution aerosols creates region-specific signatures in the Khartoum North area, originating from sub-Saharan or distant desert sources [13].

Finding a baseline for elemental exposure levels is the aim of this investigation. Samples were taken approximately one meter above the ground surface. To capture spatial variations in pollution levels, sampling sites were selected based on expected contamination from different pollution sources and proximity to major streets. Air samples were collected from various areas of the city, including residential neighborhoods and the suburban oil refinery region. Sampling was conducted during the non-rainy season (summer and winter) to minimize the influence of precipitation on airborne particulate concentrations. From each of the ten collection points, three samples were procured. The thirty samples in total, representing averages from different places and sites in this study, were examined. This study represents the first attempt to use a sample collection method over two hours at a flow rate of 201 mL/min connected to a vacuum pump. These elements, in conjunction with the LIBS elemental measurement technique, are used to evaluate the effects of heavy metals associated with outdoor air pollution. The research focuses on contamination resulting from various anthropogenic activities in Sub-

Saharan Africa, with particular emphasis on Sudan [10]. Component measurements in air samples are important for assessing environmental contamination [14]. Valuation of the appropriate combination of these elements is essential for effectively managing healthcare, making informed public health decisions, and implementing primary prevention strategies [15]. In this investigation, samples can be taken from the polluted region during the dry season. The collection of atmospheric samples was done outdoors at a height of 1.5 meters above street level in Khartoum North. To collect airborne particulate matter, a flow meter was used to measure flow rates at the start and end of each run. A thin layer was prepared on the nuclear pore filter (Ammonium Tetramethylene Dithiocarbamate (ATDC) using a standard sample of each element of interest. Standard solutions are created using metal oxides or high-purity compounds. Depending on the type of characterization needed and the nature of the material, different procedures are employed. Two milliliters of a 4% w/v solution of freshly prepared Ammonium Tetramethylene Dithiocarbamate (ATDC), filtered through filter paper, were pipetted from a mixture of solutions to create a series of concentrations ranging from 20 to 100µg/ml. Using a vacuum pump, a thin-film standard was produced by filtering a mixed solution of the metal (ATDC) precipitate through a Nuclepore track-etched polycarbonate membrane. Aerosol particulate matter was collected using Nuclepore membrane filters that were 0.47 µm in pore size, 47 mm in diameter, and 10 µm in thickness, and that demonstrated good mass stability.

The solution was then added to each concentration. Plotting concentration (an independent variable) versus counts per second produced a linear calibration curve. The slope, intercept, and regression line parameters from the calibration graph were then used to calculate the elemental composition of the air samples [16].

We analyzed environmental pollution samples from three locations with LIBS to detect hazardous elements in airborne pollutants. The filter papers containing the collected samples were measured for various metals using a LIBS spectrometer. The nitrogen pulsed laser was used as the irradiation source. It was focused on the sample to create plasma for the emission of spectral lines. The irradiation source was a nitrogen pulsed laser operating at 337.1 nm with an energy of 400 mJ. The laser beam was directed onto the material until plasma formation occurred, accompanied by the emission of distinct spectral lines. The emission spectra of the air samples were acquired with a 0.5 µs – 2 µs delay after the direct laser-pulse irradiation measurement. A USB2000 spectrometer was used to record the emitted spectra, which were subsequently, analyzed using the National Institute of Standards and Technology (NIST) Atomic Spectra Database and the Handbook of Basic Atomic Spectroscopic Data. However, it was compared with the high-resolution wavelength selection capability of inductively coupled plasma spectroscopy (ICP) [17]. This approach significantly enhances the investigation and measurement of elements in outdoor ambient air. The most sensitive emission lines, or fingerprint wavelengths, for element identification were found within the 300–1150 nm range, based on data from the National Institute of Standards and Technology (NIST) database and reference spectra. The LIBS spectral fingerprints of air filter paper samples collected from various locations around Khartoum North city were divided into three areas. Statistica software was used for statistical analysis and evaluation of factors associated with pollution emission sources.

RESULTS AND DISCUSSION

The concentration of the unknown element in the outdoor air sample was predicted using linear regression analysis. Laser-induced breakdown spectroscopy (LIBS) enables elemental concentration analysis with high wavelength resolution. Samples were collected from local and residential sites, including refinery areas, to determine the relative contributions of different pollution sources. Laser-induced breakdown spectroscopy (LIBS) was used to demonstrate its capability for accurate environmental pollution monitoring and elemental analysis, enabling the detection of Cu, Cr, Fe, Ca, and Pb. The initial analysis examined the distribution of elements in the region's air pollution. Fig. 1 presents the analysis of average elemental concentrations in samples collected from Khartoum North using LIBS, compared to ICP. To assess and identify the sources of air pollution, quantitative techniques were applied to investigate aerosol samples collected from different parts of the city. The data of results are shown in Fig. 2, which illustrates the contributions of elements in the Khartoum North ambient air [18]. Table 1 shows a comparison of average elemental concentrations from LIBS and ICP spectroscopy analysis for 10 locations in Khartoum North, including the standard deviation (±SD) and lower detection limit (LOD) under study. Table 1 presents the correlation transformation variables for the elements in the outdoor ambient air in the Khartoum North sites. Table 2 compares t-test values, and the outdoor samples of the elements

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026

are obtained using the extracted principal component analysis. Table 3 presents a comparison of elemental concentrations from worldwide data for the same region as the current study.

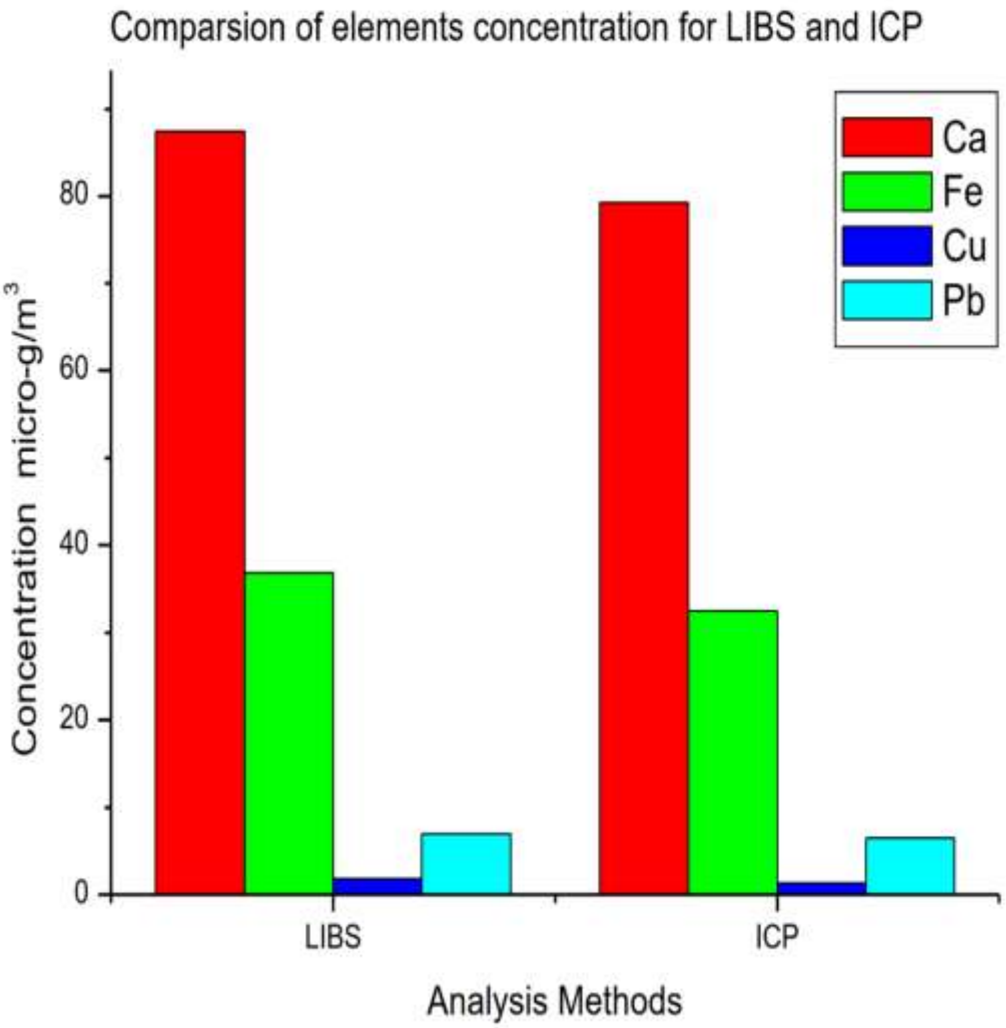

Figure 1. Comparison graph of element concentration using LIBS and ICP methods

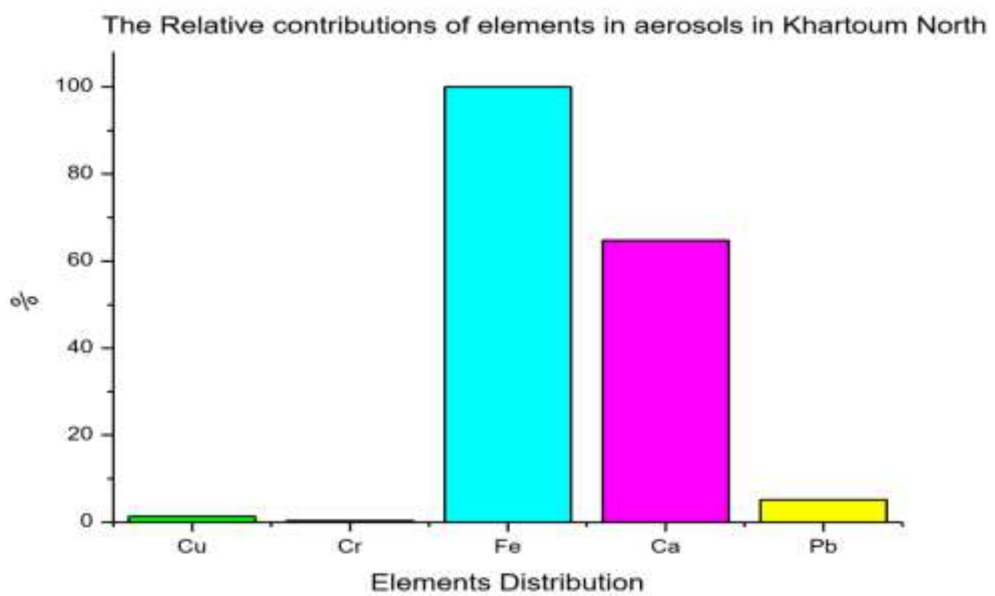

Figure 2: Relative contributions of elements to Khartoum North air pollution.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026

Table1. Comparison of LIBS and ICP of elements in μg/m^3, for 10 samples representing locations, including ±SD and lower detection limit (LOD).

Element	LBIS	SD	LOD	ICP	SD	LOD
Cu	1.81	±0.406	0.0012	1.327	±0.406	0.0033
Fe	36.89	±3.2	0.401	32.497	±3.2	0.366
Ca	87.44	±6.446	2.218	79.227	±6.447	2.219
Pb	7.0	±0.932	0.001	6.496	±0.83	0.001

Table 2 Correlation transformation variables of the elements' concentration in Khartoum North.

Elements	Cu	Cr	Fe	Ca	Pb
Cu	1.000				
Cr	.531	1.000			
Fe	.667	.572	1.000		
Ca	.662	.614	.525	1.000	
Ph	.706	.447	.573	.812	1.000

Table 3 T-test and Extraction Method: Principal Component Analysis.

Element	Sites N	t-test	Communalitis Extraction	Component Matrix	Rotated Component Matrix	Dim- nsion 1	Dim- nsion 2	Mean
Cu	10	9.174	.896	-.639-	-.381-	.812	.695	.754
Cr	10	79.458	.852	.106	-.195-	.512	.638	.575
Fe	10	11.094	.571	.745	.747	.596	.522	.559
Ca	10	9.522	.659	.715	.801	.757	.622	.689
Pb	10	8.307	.847	.877	.920	.717	.486	.601
Active Total	_	_	_	_	_	4.128	3.671	3.90
% of Variance	_	_	_	_	_	68.79	61.19	64.99

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Table 4 presents a comparison of element levels (μg/m^3) in global data from the same region as the current investigation.

Locations	Cu	Cr	Fe	Ca	Pb
Yarkant, Takla Makan (desert), China, L. Makra, (2002)	< 3	0.49	49.7	118.2	_
Manesar, India Kumari et al., 2021 2022-2023	0.11	0.256	18.47	_	0.381
Gisr Al Soltan, Egypt, 2025 Hazem A. Soliman1	_	0.424	_	_	4.034
Mumbai, India, 2012 D.G. Gajghate	-	0.003	3.5	3.07	0.13
Khartoum Bahri presents a study	1.9	0.47	36. 86	87.44	6.87

DISCUSSION

According to the results, soil in the study area may be a significant natural source of particulate matter, which influences both anthropogenic emission contributions and ambient air pollution concentrations [19]. Quantitative methods for aerosols from various locations within city sites were employed to assess the sources of atmospheric pollution. The goal of the current study is to identify and measure the elemental composition of air pollutants from diverse sources that contribute to varying element concentrations at local sampling locations [20]. Calcium and Iron are found in high concentrations, with average elemental concentrations added by LIBS and ICP analyses, revealing an average difference of 10.2% ± 0.546% between the measured concentrations. The limit of detection (LOD) differed by 0.130 between the two methods. This close agreement demonstrates the reliability of the analytical approaches and highlights their effectiveness for elemental contents in outdoor air pollution.

The data validation results are presented in Figure 2, which illustrates the relative contributions of the detected elements in the outdoor air in Khartoum North, notably highlighting higher concentrations of Ca and Fe than those of the other measured elements**.** Saharan sand dust, vehicular exhaust, and soil degradation are significant contributors to atmospheric pollution (21). The mobilization of soil particles into the air is increased by wind, man-made anthropogenic factors from land surfaces, and construction operations [22]. Table 1 shows a comparison of average elemental concentrations from LIBS and ICP spectroscopy analyses for 10 locations in Khartoum North, including the standard deviation (±SD) and lower detection limit (LOD) under study.

Table 2 shows the correlation between the elements' content data from the aerosol at the Khartoum North sites. The strong correlation among Ca, Fe, and Pb indicates the presence of element sources in the study area, whereas Cu is likely associated with multiple combustion sources. The association observed between Cu and Cr, with a moderate correlation, suggests that these elements originate from a single common source in the region, possibly an oil refinery. The refinery's combustion process generates fine particulate matter and metal-containing aerosols that can be transported to residential and commercial areas.

The dataset's complexity and items with comparable behavior were grouped using principal component analysis (PCA) and the contributions of elements in the area [23]. High commonalities for Cu, Cr, and Pb observed in the principal component extraction (Table 3) suggest that these elements are likely derived from a common source. Both the component matrix and the rotated component matrix exhibit strong validations for these metals, indicating their association with a single dominant pollution source. Moreover, the principal component analysis results for the active total variables ranged from 3.671 to 4.128, with an average variance of 64.99% for all elements. Table 4 compares the elemental analysis of element levels in international data from a similar area to the present study [25].

The PCA results were corroborated by correlation analysis, which demonstrated a strong link between pieces from similar sources [25]. High correlations between calcium and iron, for instance, supported their shared association with soil and dust suspension, whereas correlations involving lead suggested that activities are connected to combustion. The results of elements present in airborne particles, such as trace elements, originate from natural sources, soil dust, human activities, and fuel combustion. This suggests more irregular fluctuations in emissions, which could be linked to disruptions brought on by sandstorms and the Khartoum North region's non-rain season. Conversely, high values and increased variability indicate occasional high-emission events, which represent localized problems in residential areas. The distribution of trace metals in ambient air may have long-term effects on contaminated ecosystems, underscoring the need for comprehensive evaluations that consider environmental pollution.

CONCLUSION

The study presents the most effective contemporary analytical method for identifying heavy metals in air samples. Overall, the study indicates that soil dispersion, industrial activity, car emissions, and refinery fuel combustion are all significant contributors to Khartoum North's air pollution, which is caused by both natural and man-made sources, as well as desert dust contamination. Iron, along with other trace metals, is often associated with industrial emissions as a marker of these anthropogenic sources when detected at elevated levels in airborne particles.

This task shows that the average concentrations of Cu, Cr, Fe, Ca and Pb in Khartoum North's ambient air are more consistent with global statistics for similar regions in many countries. Thus, pollution degrades local air quality and contributes to broader environmental pollution by damaging ecosystems worldwide, and, in Khartoum North, it is not an isolated issue: it reflects a global pattern, though rising emissions degrade air quality and feed into climate change, creating a cycle that demands integrated environmental and climate action. This clearly supports the idea that industrial areas significantly contribute to ambient atmospheric contamination.

Furthermore, source-apportionment results highlight the need for targeted interventions to reduce industrial and refinery-associated metal concentrations. The evidence from principal component analysis and contributions shows that refinery and industrial operations release substantial amounts of heavy metals into the environment. Examination of ambient outdoor air provides important information about the influence of air pollution in the local area. This research project provides baseline data on urban air quality. The findings are valuable to the Ministry of Environment and Urban Planning and may also contribute to global valuations of climate change. The databases are used to validate the findings on outdoor atmospheric air quality and air pollution for locals, and the detected environmental toxins in the area can be highly useful for future research.

ACKNOWLEDGEMENT

The author(s) gratefully acknowledge Khartoum University, represented by the Physics Department, which offered facilities for standard sample preparation and XRF support for this research work.

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