

Contamination level, health risk assessment and Monte Carlo probabilistic models of trace metals in outdoor dust in different functional areas in Ondo City, Southwestern, Nigeria.

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Abstract

This study assesses the contamination level and health risk implications of trace metals in settled outdoor dust across the functional areas in Ondo City, southwestern Nigeria. Dust samples were collected from educational, residential, commercial, market, and recreational areas, and analyzed for Trace metals (Cu, Pb, Cr, Mn, Ni, Cd, Zn, and As) using ICP-MS technique. The Geo-accumulation Index (I_{geo}) revealed varying levels of contamination, ranging from unpolluted for Mn, As, Zn, and Cr, to highly contaminated for Cu and Ni, and extremely polluted for Cd and Pb. Despite PLI values indicating low overall contamination ($PLI < 1$), localized ecological risks were notable. Health risk assessments were conducted based on estimated average daily doses through ingestion, dermal contact, and inhalation exposure pathways. While Hazard Quotient and Hazard Index values for non-carcinogenic effects were below unity across all areas, carcinogenic risk assessment revealed elevated values for Cd, especially in educational areas. For more realistic risk evaluation, a Monte Carlo Simulation (MCS) approach was applied using Oracle Crystal Ball. The probabilistic MCS results showed that the 95th percentile cancer risk for children in educational areas reached 2.97E-03, exceeding the USEPA's acceptable threshold of E-04. Sensitivity analysis identified Cd, As, and Ni as the major risk drivers, particularly affecting children in school environments and adults in commercial areas. These findings highlight the need for immediate public health interventions, particularly in educational settings. The study provides critical data to support urban environmental policy, exposure mitigation, and the protection of vulnerable populations in Nigerian cities.

Keywords: *Trace metals; Exposures; Hazard Quotient; Non-Carcinogenic Risk, MCS*

Introduction

The deterioration in environmental quality that is currently been witnessed in urban centers had been attributed to increased and diverse anthropogenic activities,

like rapid urbanization, industrialization, vehicular emission, uncontrolled waste generation and combustion and infrastructural development. These anthropogenic activities had led to introduction of various pol-

lutants such as dust, smoke, particulate matter, polyaromatic hydrocarbons (PAHs), gaseous pollutants, fumes and trace metals into the entire ecosystem (Wang et al., 2013). Among the pollutants, urban dust is complex solid particles that settle on ground surfaces in urban areas after mobilization in the air and resuspension by wind action. It had been reported to be a useful matrix for characterizing the pollution status of the urban environment (Wang et al., 2013). They consist of both organic and inorganic chemical substances that can cause severe health implications and trigger adverse health effects among the healthy group (Li et al., 2013; Mihankhah et al., 2020). The remobilization and the resuspension of previously settled dust had also contributed to toxic metal pollution and degradation of environmental components, particularly air, soils, and water (Jing and Andrea, 2008). Apart from adverse health implication, the aesthetic appearances and values of materials could also be reduced by the dust in the environment (Ogundele et al., 2018). Heavy metal is one of the oldest toxins known to man and they are available in the dust constituents with varying chemical concentration and composition. They are the group of metals and metalloids with relatively high densities ($> 4 \text{ gcm}^{-3}$), atomic numbers and atomic weights in the periodic table (Maigari et al., 2016). They can also occur as trace metals, including Pb, Cd, Zn, Cu, and Cr, and particularly hazardous due to their toxicities, persistence in the environment, and carcinogenic properties. The potential toxicities of trace metals and their deleterious health implications had been reported by several authors (Olujimi et al., 2014; Ma et al., 2019; Ogundele et al., 2018; 2020; Wang et al., 2013; Wan et al., 2016; Ali et al., 2017). Studies had indicated the exposure routes of trace metals in the polluted dust as dermal absorption of particles that stick to exposed skin, direct ingestion of airborne substrate of the particles, and the inhalation of suspended particles through the mouth and nose (Olujimi et al., 2014; Ogundele et al., 2019). Once they enter human body, they have the potential to affect the central nervous system, disrupt respiratory system, cause cardiovascular disorder, and weaken reproductive systems (Li et al., 2013; Ma and Singhirunnusorn, 2012). The toxicological studies had indicated that trace metals had no beneficial physiological benefits for growth and development in human. Their potential and deleterious health implications in the human body are numerous. Some of the adverse health implications of trace metals are cancer, teratogenicity, and mutagenesis (Lienesch et

al., 2000; Cook et al., 2005). Many detrimental health outcomes that are associated with exposure to dust-borne metals include kidney dysfunctions, skin lesions, vascular damage, birth defects, intellectual disability, gastrointestinal issues, reproductive systems problems and nervous system disorders. Excessive and long-term exposure to trace metal is associated with high complication and high cancer risk (Balali-Mood et al., 2012; Cao et al. 2016; Ogundele et al., 2019). The health implications of trace metals are not reversible once they occur in human body. The environmental implication of terrestrial and aquatic ecosystems due to the heavy metal pollution is a major environmental concern that has consequences for public health. Trace metals affect the entire ecosystem, most especially, the reduction of the rate of photosynthesis in green plant (Bao et al., 2019) and high concentration of dust that deteriorate the good air quality that is require for human wellbeing and survival (Ma and Singhirunnusorn, 2012). They constitute a major environmental problem to all the components of ecosystem even at low concentrations. In addition, they do not undergo biodegradation once they are released into the environment from both natural and anthropogenic sources; can exhibit long lasting period in and remain in the environment for years; can bioaccumulate in the living tissue and system; can also impose both short and long-term burden on environmental quality (Osipova et al., 2015; Wan et al., 2019). The impact of heavy metal contamination in the settled dust and the attendant health risks are important factors in environmental quality and assessment. A detailed risk assessment which involves establishing the capacity of a risk source to introduce pollutants into the environment, determining the quality of risk agents that came in contact with the human and environment and then quantifying the health implications of the contact or exposure is of great relevance (Ayaz et al., 2023). Outdoor dust consists of fine particulate matter capable of being transported over long distances through atmospheric processes, particularly by wind. The dust particles can act as carriers for various environmental pollutants, including toxic trace metals, which tend to accumulate in urban environments due to anthropogenic activities. Assessing the concentration and composition of trace metals in outdoor dust is therefore critical for understanding pollution dynamics, identifying potential health hazards, and developing effective environmental management strategies in urban settings. Such assessments are particularly important in developing nations where rapid urbanisation and inadequate pollution con-

trol contribute to environmental and public health risks. While extensive studies have been conducted on metal contamination in outdoor dust in developed countries, similar investigations in Sub-Saharan Africa, including Nigeria, remain limited. For instance, Aguilera et al. (2022) examined heavy metal contamination (Cu, Pb, Zn, Fe, and Mn) in urban dust in Mexican cities and discussed their ecological and human health implications. Delgado-Iniesta et al. (2022) assessed the risk posed by street dust trace metals in Madrid, Spain, while Chu et al. (2023) reviewed heavy metal concentrations and health hazards in indoor and outdoor dust globally. However, in Nigeria, increasing dust generation and resuspension, particularly during the dry season, when solar radiation and wind intensity are high, has become a growing concern, yet remains poorly characterized in terms of metal content and related health risks. Given the complex nature of exposure to environmental contaminants, this study not only aims to quantify the concentrations of trace metals in outdoor dust across functional areas in Ondo City, Southwestern Nigeria, but also to evaluate pollution characteristics, estimate average daily exposure doses through ingestion, inhalation, and dermal routes, and assess associated carcinogenic and non-carcinogenic risks. To strengthen the accuracy and reliability of the health risk assessment, the study further incorporates Monte Carlo Simulation (MCS), which is a probabilistic risk modelling approach that accounts for uncertainty and variability in exposure parameters. Unlike deterministic

models, which yield point estimates that may underestimate or overestimate risk, MCS enables the generation of a full distribution of potential risk outcomes by simulating thousands of possible exposure scenarios (Omeje et al., 2022; Orosun et al., 2023). This makes it particularly suitable for urban environments where exposure conditions and contaminant distributions are highly heterogeneous. By identifying not only mean risk values but also worst-case and most probable risk scenarios, MCS provides a more reliable basis for environmental health decision-making. The use of this technique in the present study ensures a comprehensive risk assessment framework that aligns with international best practices in environmental toxicology and public health.

Materials and Methods

Study area and sampling

The study was conducted in the southwest Nigerian city of Ondo. The city's boundaries are $4^{\circ} 50' 30.0984''$ E and $7^{\circ} 6' 0.0180''$ N on the geographic grid reference. In Ondo State, Ondo City is the second-biggest city. It is distinguished by its tropical climate, which has two different seasons: the dry season, which lasts from November to March of the following year, and the wet season, which lasts from April to October of the same year. Ondo City experiences an average annual temperature of 26.42°C and 182.94 mm of precipitation. The National Institute of Education Policy and Administration (NIEPA), Ondo City Stadium, Wesley Univer-

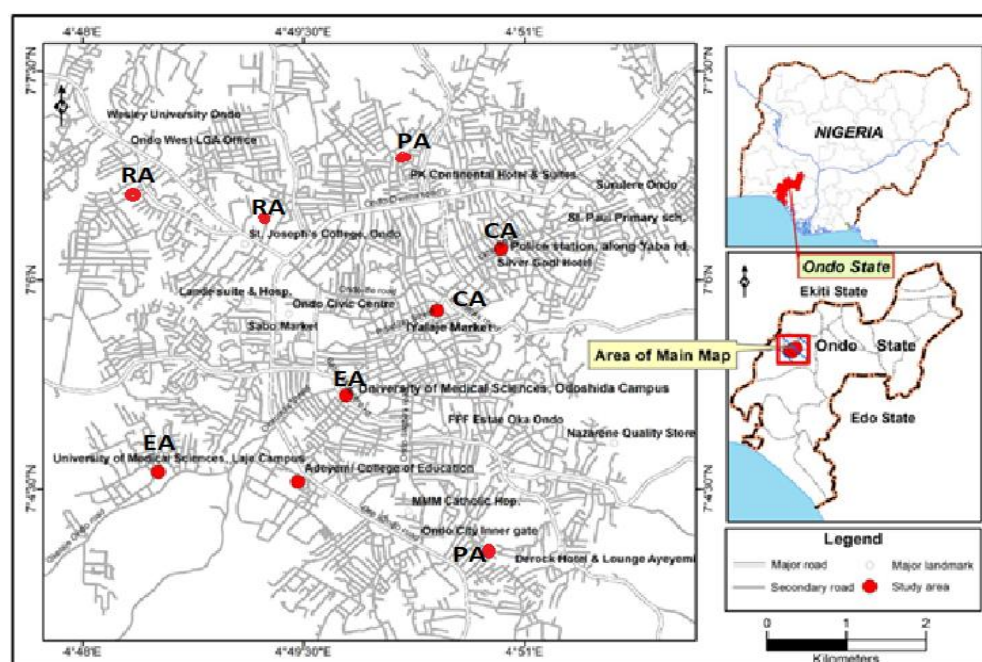


Figure 1
Map of Ondo city showing the sampling locations

KEY
RA – Residential areas
CA – Commercial areas
PA – Park areas
EA – Educational areas
MA – Market areas

sity, Adeyemi Federal University of Education, two campuses of the University of Medical Sciences, and her two Teaching Hospital are all located within Ondo City. There are over fifty (private and government) secondary schools within the city. The residential environments consist of well-planned areas and several ancient parts of the city. The road networks in Ondo city are mixed with paved and unpaved roads. The city was home to a number of artisan, electrical, and vehicle repair shops as well as small-scale and cottage industries (Ogundele et al., 2020). Settled surface outdoor dusts samples were collected at five major functional areas within Ondo city. The locations consist of motor park area (PA), educational areas (EA), commercial areas (CA), residential areas (RA), and market areas (MA). Figure 1 showed the map of the sampling points. The sampling sites were carefully chosen to reflect the areas with high anthropogenic activities. For each sampling, four sub-samples of settled dusts were gathered randomly within a radius of 1 m and pooled to obtain a representative sample of about 150 g using plastic brush and pan. The dust samples were kept in a polythene sample bag and well labelled to prevent cross contamination. The samples were collected once a month for the period of four months starting from December 2023 to March 2024. This period accounted for high rate of dust remobilization and suspension with less humid soil. The numbers of samples for EA, PA, CA, RA and MA are 13, 10, 12, 15 and 10, respectively summing up to 60 samples.

Sample preparation and chemical analysis. The samples were screened by removing biological materials, stone fragments, and coarse debris. The samples were sieved using 47 mm Teflon filters to limit the analysis to the fine inhalable fraction of the dust. To eliminate the moisture, the Teflon filters were vacuum-dried for six hours at 150 °C. Before being digested, the fine dust samples were then stored in the desiccator for 48 hours. Using a Foss Tecator digestion vessel, 2.0 g of each fine dust sample was accurately weighed and digested in a 15 mL solution of Nitric (HNO₃) and Perchloric acid (HClO₄) (1:3). The entire mixture was heated to 350 °C on an electric plate, until the mixture became transparent, and then it was cooled. Following cooling, the solution was diluted with distilled-deionized water to 50 mL and filtered into a 100 mL volumetric flask (Ogundele et al., 2019). Prior to chemical analysis, the digest was stored in the sample vial and the process was repeated for each sample. The

concentration of Cu, Pb, Cd, Ni, Mn, Cr, As, and Zn concentrations were measured with Inductive Couple Plasma Mass Spectrometry (ICP-MS). For quality control and assurance, great care was taken to ensure all tools and containers were completely washed in deionized water after being immersed in 10% HNO₃ for a full day before used during the digesting and analysis processes.

Statistical analysis. Descriptive analysis was used to summarize the measured trace metal concentrations. A one-way analysis of variance (ANOVA) was used to determine whether the concentrations of trace metals varied significantly between the locations, and post hoc tests were performed using the Duncan multiple range test at $p < 0.05$. The Statistical Package for Social Sciences (SPSS) version 21.0 software was used for all statistical analyses.

Contamination and ecological risk assessment. The contamination and ecological risks were assessed using a combination of the ecological risk index (ERI), the pollution load index (PLI), and the index of geo-accumulation (I_{geo}) by utilizing the trace metal concentration data. Each index has its unique formulae, classification categories, and interpretations. One of the quantitative indices used to evaluate a pollutant's level of contamination in different environmental matrices is the I_{geo} (Olujimi et al. 2014; Ogundele et al., 2020). To calculate I_{geo}, the logarithmic function was utilized as follows:

$$I_{geo} = \text{Log}_2 \left(\frac{C_n}{1.5B_n} \right) \quad [1]$$

where C_n is the element's concentration in the sample. The element geochemical background concentration in the sample is denoted by B_n . To reduce the impact of potential changes in the background values, a factor of 1.5 was added. According to Ogundele et al. (2020) and Zhang et al. (2020), the I_{geo} values fall into the following categories: I_{geo} < 0, 0 < I_{geo} < 1, 1 < I_{geo} < 2, 2 < I_{geo} < 3, 4 < I_{geo} < 5, and I_{geo} > 5 and are interpreted as unpolluted, unpolluted to moderately polluted, moderately polluted, moderately to strongly polluted, strongly polluted, strongly to extremely polluted, and extremely polluted, respectively. The Pollution Load Index (PLI), which is calculated as the n th root of the product of contamination factors (CFs) for each measured heavy metal, is a technique used to evaluate the level of pollution caused by trace metals in soils, sediments, and other environmental matrices (Ogundele et al., 2017). The predicted PLI resulting from the detected trace metals was:

$$PLI = \sqrt[n]{(CF_1 \times CF_2 \times CF_3 \times \dots \times CF_n)} \quad [2]$$

where $CF_{n=1, 2, 3, \dots}$ is the computed contamination factor, and n is the number of measured trace elements. The following PLI values indicate the presence of unpolluted, moderately polluted, strongly polluted, and extremely polluted circumstances as < 1 , $1 < 2$, $2 < 10$, and $PLI > 10$, respectively (Ogundele et al., 2017; 2018; Chonokhuu 2019). Swedish scientist Hakanson created the Ecological Risk Index (ERI) as a way to evaluate the ecological concerns associated with heavy metal contamination in terrestrial and aquatic environmental matrices, considering both concentrations of trace metals, their toxic response factors and contamination status. The ecological risk index was estimated as follow using:

$$Eri = Ti \times \frac{Cn}{C_{ref}} \quad [3]$$

The concentration of the outdoor dust sample is C_n . T_i represents the toxic response factor of trace metals, while C_{ref} represents the background metal level in an uncontaminated environment. The following are the ecological risk index classifications. Low ecological risk, moderate ecological risk, significant ecological risk, and extremely high ecological risk are denoted by $RI < 150$, $150 < RI < 300$, $300 < RI < 600$, and $RI > 600$, respectively (Hakanson, 1980; Soliman et al. 2015; Ogundele et al., 2020).

Health risk assessment. Information on the likelihood of harmful effects on humans from excessive exposure to trace metals by ingestion, inhalation, and dermal contact is provided by the human health risk assessment of trace metals (Jiang et al., 2017). Using risk-based formulas created by the United State Environmental Protection Agency, the carcinogenic

and non-carcinogenic impacts of trace metals were quantitatively described. The following formulas can be used to calculate the average daily dose from ingestion, inhalation, and dermal contact (Zhou et al., 2019):

$$ADD_{ing} = \frac{c \times Ring \times EF \times CD}{BW \times AT} \quad [4]$$

$$ADD_{inh} = \frac{c \times Rinh \times ED \times EF}{PEF \times BW \times AT} \quad [5]$$

$$ADD_{derm} = \frac{c \times SA \times CF \times SL \times ABS \times ED}{AT \times BW} \quad [6]$$

The exposure doses by ingestion, inhalation, and dermal intake are denoted by the symbols ADD_{ing} , ADD_{inh} , and ADD_{derm} (mg/kg/day) respectively. Table 1 displays the exposure parameters used in the health risk assessment. C is the trace metal concentration ($\mu\text{g/g}$) in outdoor dust. ED stands for exposure time (year). A conversion factor is CF . The exposure frequency (days/year) is denoted by EF . The corresponding absorption and dermal adherence variables are ABS and AF , respectively. PEF is the particle emission factor (m^3/kg), AT is the average exposure period (days), and BW is the average body weight of persons (kg) (USEPA, 2001). As, Pb, Cr, Ni, Cd, Mn, Cu, and Zn were among the elements that were analyzed in order to determine the health risk. Because of their low quantities in the surface dust samples, other trace elements including Co and Hg were not included.

Non-carcinogenic risks. By dividing the estimated average daily dose (ADD) by a specific reference dose (RfD) of each metal while taking into account the three exposure pathways, the hazard quotient (HQ) based on the non-carcinogenic toxic risk was determi-

Table 1. Health impact assessment calculations summary.

Parameter	Unit	Adult	Child	References
Dermal absorption factor (ABS)	none	0.03 (As)	0.001(others)	Ferreira-Baptista & De Miguel, (2005)
Exposure duration (ED)	years	24	6	USEPA, (2001)
Ingestion rate (R_{ing})	mg/day	100	200	USEPA, (2001)
Inhalation rate (R_{inh})	m^3/day	20	10	USEPA, (1991)
Soil adherence factor (SL)	$\text{mg}/\text{cm}^2 \cdot \text{day}$	0.07	0.2	USEPA, (2001)
Exposure frequency (EF)	days/year	180	180	USEPA, (2001)
Body weight (BW)	Kg	70	15	USEPA, (1989)
Particle emission factor (PEF)	m^3/kg	1.36×10^9	1.36×10^9	USEPA, (2001)
Conversion factor (CF)	kg/mg	1×10^{-6}	1×10^{-6}	USEPA, (2004)
Average time (AT) for	carcinogens	365×70	365×70	USEPA, (2001)
	non-carcinogens	$365 \times ED$	$365 \times ED$	USEPA, (1989)
Skin surface area (SA)	cm^2	5700	2800	USEPA, (2001)

ned as follows:

$$HQ = \frac{ADD}{RfD} \quad [7]$$

The state of non-carcinogenic risks resulting from measured trace metals was assessed to see whether there are now any detrimental health impacts on humans using the RfD values as a threshold. There would be no negative health effects if the RfD number exceeded the ADD. There are no negative health impacts if the HQ value is less than 1. However, an HQ value greater than 1 indicates that the tested trace metals are probably having a negative impact on health (USEPA, 1993, 2001). The hazard index (HI), which is determined by adding the hazard quotients for a number of elements having comparable toxic effects, is a tool used to evaluate the overall health hazards associated with exposure to several elements (USEPA, 2001).

$$HI = \sum(HQ_{inh} + HQ_{ing} + HQ_{der}) \quad [8]$$

The values of $HI \leq 1$ indicate that no significant risk of non-carcinogenic effects exists. However, > 1 implies that there is a probability of non-carcinogenic effects occurring which increases as HI value increases (USEPA, 2001).

Carcinogenic risks. According to the categorization list created by the International Agency for Research on Cancer (IARC, 2004), the carcinogenic risks resulting from Cr, As, and Pb were regarded as carcinogenic elements and were utilized to calculate the carcinogenic risk in the manner described below.

$$\text{Cancer risk (CR)} = ADD \times SF \quad [9]$$

where ADD is the average daily dose and SF is the cancer risk analysis reference slope factor (SF) in mg/kg day values are as follows: As 1.5 (ingestion), 1.51 (inhalation), 3.66 (dermal); Pb 0.0085 (ingestion), 0.042 (inhalation); Cr 0.05 (ingestion), 4.2 (inhalation), 2.0 (dermal); Ni 1.7 (ingestion), 0.9 (inhalation), 4.25 (dermal) and Cd 6.3 (ingestion), 6.1 (inhalation). The range of acceptable cancer risk numbers is 10^{-4} to 10^{-6} . A carcinogenic risk value that is greater than 10^{-4} is considered harmful for human health (USEPA, 2011).

Carcinogenic risk estimation using Monte Carlo simulation. Given the complex environmental behaviour and human health implications of trace metal exposure, particularly via dust inhalation, ingestion and dermal contact, deterministic risk models, may fail to fully capture the uncertainties and variabilities inherent

in such assessments. To address this limitation, the present study employed a Monte Carlo Simulation (MCS) to derive probabilistic estimates of carcinogenic risk associated with exposure to trace metals in outdoor dust. Monte Carlo simulation is a powerful statistical tool that utilises stochastic sampling to simulate a wide range of possible outcomes under conditions of uncertainty (Orosun et al., 2022). This method accounts for inherent variations in exposure parameters (e.g. carcinogenic slope factors, ingestion rate, body weight and exposure duration) by assigning probability distributions to each variable, thereby enabling a more realistic and robust estimation of cancer risk (Orosun, 2021; Changsheng et al., 2012; Orosun et al., 2023). MCS has been widely endorsed by international regulatory agencies including the National Research Council (NRC, 1994) and the United State Environmental Protection Agency (USEPA, 1997) and as a scientifically reliable approach for quantifying uncertainty and variability in environmental health risk assessments. In this study, the probabilistic cancer risk was modelled using Oracle Crystal Ball (version 11.1.2.4.850), a widely used simulation software that automatically fits appropriate distributions to input parameters based on goodness-of-fit statistics and performs iterative sampling. Each simulation comprised 10,000 iterations, where values were randomly drawn from the defined probability distributions for each exposure parameter. This process generated a distribution of incremental lifetime cancer risk (CR) values for each metal across the different exposure routes. MCS provided insight not only into the mean and 95th percentile cancer risks but also into the variability and likelihood of exceeding critical health benchmarks. By capturing the full range of uncertainty and variability in exposure and toxicological parameters, Monte Carlo Simulation not only complements deterministic approaches but also provides a more realistic representation of health risks, ultimately informing evidence-based decision-making.

Results and Discussion

Trace metals concentration. The average ($\pm$ standard deviation) of the concentrations of Cu, Pb, Ni, Cd, Mn, Cr, As, and Zn in the outdoor dust samples collected from different functional locations (park areas, residential area, commercial areas, market areas, and educational areas) in Ondo city were presented in Table 2. The measured trace metals showed similar compositions and varied concentrations across the sampling

areas. The highest average concentrations of Pb and Cr were $0.43 \pm 0.03 \mu\text{g/g}$ and $0.46 \pm 0.05 \mu\text{g/g}$, respectively at the PA. Mn has the highest average concentrations of $3.22 \pm 0.02 \mu\text{g/g}$ at the RA. The average concentrations of Zn vary from $1.08 \pm 0.01 \mu\text{g/g}$ (PA) to $1.46 \pm 0.03 \mu\text{g/g}$ (MA). The mean range of trace metals concentrations of Cu, Pb, Cd, Ni, Mn, Cr, As, and

Zn in the sample dust were; 0.95 - 1.77, 0.17 - 0.43, 0.02 - 0.03, 0.06 - 0.35, 0.87 - 3.22, 0.20 - 0.46, 0.01 - 0.03, and 1.04 - 1.46 $\mu\text{g/g}$, respectively. Comparison of the measured values with the global background values (BV) of concentrations of the measured trace metals indicated that they were several orders of magnitude less than the global background values.

Table 2. Mean Trace Metals Concentration ($\mu\text{g/g}$) of outdoor dust across the sampling locations.

	PA	RA	CA	MA	EA	Mean	BV
Cu	1.08 ± 0.05^a	1.03 ± 0.04^a	1.17 ± 0.05^b	1.77 ± 0.08^c	0.95 ± 0.07^a	$1.2.0 \pm 0.32$	188
Pb	0.43 ± 0.03^b	0.28 ± 0.02^a	0.179 ± 0.03^a	0.36 ± 0.05^b	0.27 ± 0.05^a	0.30 ± 0.09	16.59
Cd	0.03 ± 0.02^a	0.02 ± 0.01^b	0.05 ± 0.02^a	0.04 ± 0.03^a	0.02 ± 0.02^a	0.008 ± 0.01	0.15
Ni	0.20 ± 0.04^b	0.11 ± 0.01^a	0.35 ± 0.05^c	0.17 ± 0.12^b	0.06 ± 0.12^a	0.18 ± 0.11	18.37
Mn	2.02 ± 1.66^c	3.22 ± 0.02^c	0.87 ± 0.05^a	1.52 ± 0.16^b	2.33 ± 0.21^c	1.99 ± 0.88	589
Cr	0.46 ± 0.08^c	0.33 ± 0.03^b	0.20 ± 0.01^a	0.43 ± 0.01^c	0.22 ± 0.01^a	0.332 ± 0.12	116
As	0.04 ± 0.02^a	0.02 ± 0.01^a	0.03 ± 0.02^b	0.01 ± 0.02^b	0.04 ± 0.02^a	0.006 ± 0.04	4.36
Zn	1.08 ± 0.01^a	1.04 ± 0.05^a	1.44 ± 0.07^b	1.46 ± 0.03^b	1.16 ± 0.02^a	1.24 ± 0.02	236

Note: Superscript of the same alphabet along the same rows are not significantly different from each other ($p \leq 0.05$). Residential areas (RA); Educational areas (EA); Park areas (PA); Market areas (MA) and Commercial areas (CA).

The moderate concentrations of the measured trace metals in all the sites might be attributed to both natural sources such as disintegration of the parent material and composition of local geological materials. The major anthropogenic sources that could contribute to the trace metals content in the studied areas are debris from construction materials such as plaster, concrete, broken brick and cement. Also, they could also be released and settled in the surface dust from vehicular emissions from automobiles and combustion of diesel engines during transportation activities within Ondo city. Several other anthropogenic activities, sewage sludge, uncontrolled disposal of spent fuel from the auto and motorcycle workshop, small-scale waste burning activities, and disposal of metallic waste from artisanal workshops, could also add to the concentrations of the measured trace elements in this study. Across the sites, the mean values of all the trace metals in residential areas (RA) and educational Areas (EA) differ significantly from park areas (PA), Market areas (MA), and commercial Areas (CA). Some of the activities that contribute to Cu and Zn are lubricants, tyre abrasion, corrosion of the automotive metallic parts, and emissions from industries and incinerators (Jiries et al., 2001; Al-khashman, 2004). Cu and Zn have high average concentrations from the commercial districts, which is characterized with high traffic volu-

mes and vehicular congestion. At the residential and educational sites, the concentrations of trace metals were low. This might be related to human activities, such as exhaust from diesel engine that release them into the environment. Highest concentration of Cr were recorded in the Park areas, whereas industrial centers had the lowest concentration. Generally, trace metals are more likely to be emitted into the environment from commercial and industrial locations. Trace metals Pollution load index (PLI) values analyzed in this study were less than 1 ($PI < 1$), indicating minimal trace metals pollution (Fig. 2). The results of the I_{geo} are presented in Figure 3. The I_{geo} values of As in all the locations were less than 1, which implies unpolluted condition with respect to As. Cu and Ni I_{geo} values were found to range between 1-2, indicating moderately contaminated condition. Mn and Cr range between 0-1 which signify unpolluted to moderately polluted status. Trace metals like Cb and Pb had the I_{geo} range of 5 and 8, classifying the locations highly polluted. This could be attributed to atmospheric deposition of dust by gravitational settling, remobilization of previously settled dust and chemical absorption of metal constituents by the road particles. Largely, the increasing order of I_{geo} values of the measured elements are: $\text{Pb} < \text{Cd} < \text{Ni} < \text{Cu} < \text{Zn} < \text{Mn} < \text{As}$.

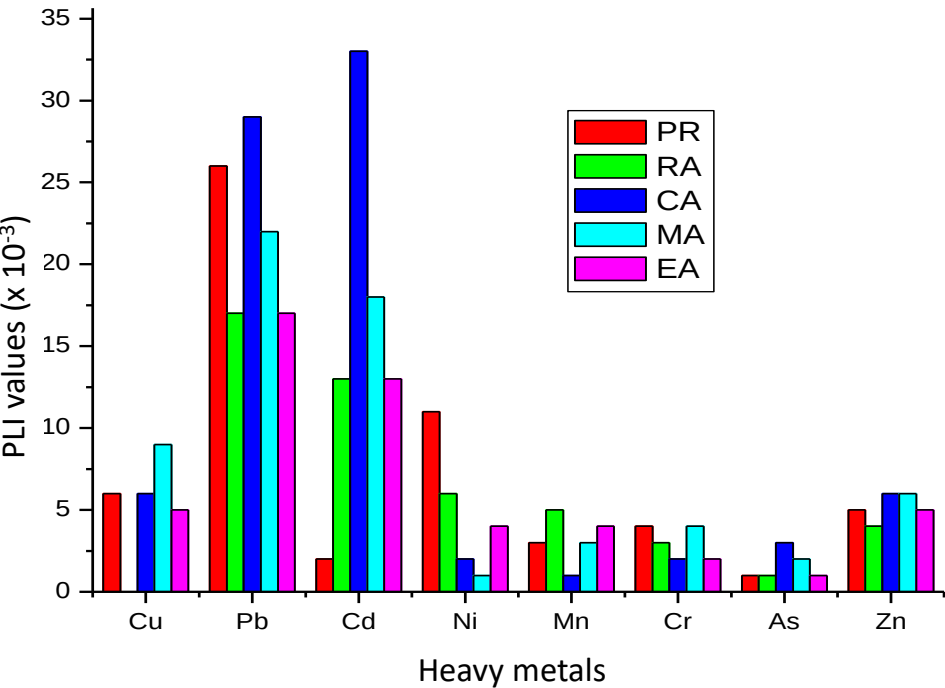


Figure 2
Pollution load index results

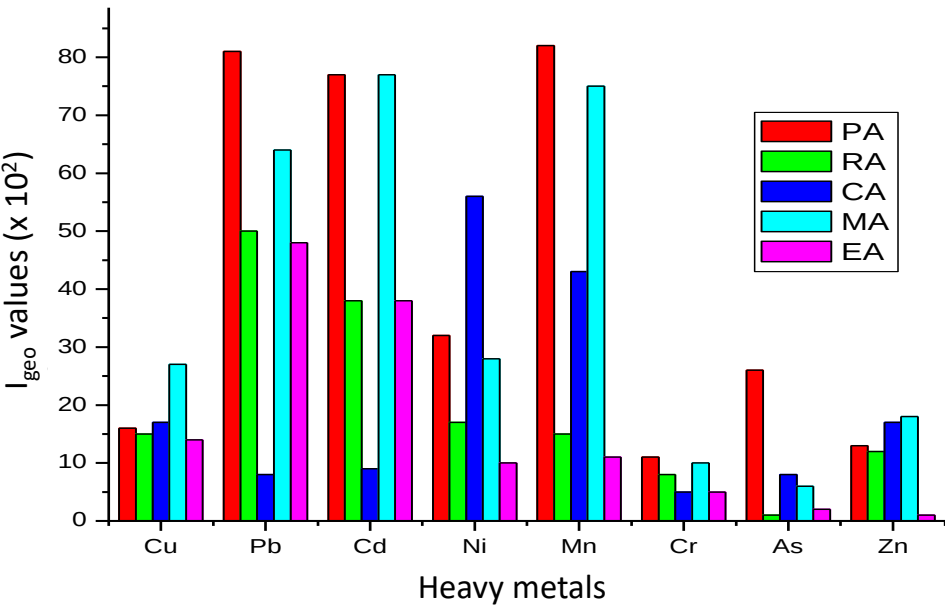


Figure 3
Index of geoaccumulation results

Ecological risk factor of Cu, Pb, Cd, Ni, Mn, Cr, Zn and As (Table 3) were below 40, indicating low ecological risk factor. The risk index across the sampling locations were in decreasing orders as follows; Commercial area (CA) > Park area (PA) > Market Areas (MA) > Residential area (RA) > Educational Area (EA). Among the measured trace metals, Cd had the highest ecological risk index and its concentration in the settled outdoor dust requires greater attention. According to Gope *et al.* (2017), Cd are released from motor oil combustion, batteries, plastics, engine wear, lubricating oil, and brake wear. Additionally, it was di-

Table 3. The ecological risk factor results

	PA	RA	CA	MA	EA
Cu	0.03	0.025	0.03	0.045	0.025
Pb	0.13	0.085	0.145	0.11	0.085
Cd	0.6	0.39	0.99	0.54	0.39
Ni	0.055	0.03	0.1	0.05	0.02
Mn	0.003	0.005	0.001	0.003	0.004
Cr	0.008	0.006	0.004	0.008	0.004
As	0.01	0.01	0.03	0.02	0.01
Zn	0.005	0.004	0.006	0.006	0.005
RI	0.841	0.636	1.306	0.782	0.543

scovered that the ecological risk potential of the investigated trace metals was far lower than 150, with the ecological risk index (ERI) potential of all the trace metals falling between 0.001 and 0.99, classified to be low-risk.

Health Risk Assessment Results. Table 4 (a–c) shows the average daily dose resulting from exposure to trace metals (Cu, Ni, Pb, Cd, Mn, Cr, Zn, and As) through the dermal exposure, inhalation and ingestion. The quantities of trace metals in dust samples taken from various operational locations of Ondo city were used to estimate the daily exposure dosage for adults and children. Interestingly, the contributions of the observed trace elements to the overall exposure levels vary. The results also suggested that the exposure burden of the measured trace metals is relatively influen-

ced by the various anthropogenic activities, taking place in the vicinity of the sampling areas. For ingestion, average daily exposure dose of various measured metals were low for adults in all the areas. The sequence of the average daily dose of exposure among the studied locations are RA < MA < EA < PA < CA for the adults and the children. Among the measured metals, Pb and Cr showed relatively high burden compared to other trace metals among the children in the educational centers. The ingestion of dust particle containing trace metals may occur unintentional among the adults by negligence of washing hand after daily activities, most especially among the people in the marketer areas and commercial centers. Most children are prone to ingestion of soil dust, more frequently by contact with the dust. This occurs by frequent hand-to-mouth acti-

Table 4. Results of the average daily dose

HM	Park Areas		Residential Areas		Commercial Areas		Market Areas		Educational Areas		HI
	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children	
a) via dermal exposure route											
Cu	1.69E-11	1.10E-10	1.61E-11	1.05E-10	1.83E-11	1.20E-10	2.76E-11	1.81E-10	1.48E-11	9.72E-11	1.18E-08
Pb	2.30E-12	3.77E-12	1.50E-12	2.45E-12	9.58E-13	1.57E-12	1.93E-12	3.16E-12	1.45E-12	2.37E-12	7.15E-09
Cd	1.61E-13	2.63E-13	1.07E-13	1.75E-13	2.68E-13	4.38E-13	2.14E-13	3.51E-13	1.07E-13	1.75E-13	2.26E-09
Ni	4.54E-12	7.45E-12	2.50E-12	4.10E-12	7.95E-12	1.30E-11	3.86E-12	6.33E-12	1.36E-12	2.24E-12	2.67E-09
Mn	3.15E-11	2.07E-10	5.03E-11	3.29E-10	1.36E-11	8.90E-11	2.37E-11	1.55E-10	3.64E-11	2.38E-10	5.87E-09
Cr	4.93E-12	8.07E-12	3.53E-12	5.79E-12	2.14E-12	3.51E-12	4.60E-12	7.54E-12	2.36E-12	3.86E-12	1.54E-08
As	2.35E-11	3.85E-11	3.92E-13	1.93E-11	5.88E-13	2.89E-11	1.96E-13	9.63E-12	7.84E-13	3.85E-11	8.01E-08
Zn	1.69E-11	1.10E-10	1.62E-11	1.06E-10	2.25E-11	1.47E-10	2.28E-11	1.49E-10	1.81E-11	1.19E-10	2.43E-09
b) via inhalation exposure route											
Cu	1.09E-09	6.39E-11	1.04E-10	6.09E-11	1.19E-10	6.92E-11	3.01E-11	1.05E-10	9.63E-11	5.62E-11	3.00E-08
Pb	7.85E-12	4.27E-12	4.77E-12	2.78E-12	3.05E-12	1.78E-12	8.90E-10	3.58E-12	4.60E-12	2.68E-12	3.09E-07
Cd	7.42E-11	4.33E-11	4.95E-11	2.89E-11	1.24E-10	7.21E-11	1.46E-10	5.77E-11	4.95E-11	2.89E-11	6.74E-07
Ni	7.30E-10	4.26E-11	4.01E-10	2.34E-11	1.28E-09	7.45E-11	1.72E-11	3.62E-11	2.19E-10	1.28E-11	1.42E-07
Mn	2.05E-09	1.19E-10	3.27E-10	1.9E-10	8.82E-11	5.14E-11	2.59E-09	8.99E-11	2.36E-10	1.38E-10	2.94E-08
Cr	7.83E-10	4.57E-10	5.62E-10	3.28E-10	3.41E-10	1.99E-10	2.61E-10	4.27E-10	3.75E-10	2.19E-10	1.32E-06
As	2.43E-11	1.42E-11	1.22E-11	7.10E-12	1.82E-11	1.06E-11	1.01E-12	3.55E-12	2.43E-11	1.42E-11	6.49E-08
Zn	1.09E-09	6.39E-11	1.05E-10	6.15E-11	1.46E-10	8.51E-11	1.48E-10	8.63E-11	1.18E-10	6.86E-11	6.59E-09
c) via ingestion exposure route											
Cu	7.61E-06	1.52E-05	7.26E-06	1.45E-05	8.24E-06	1.65E-05	1.25E-05	2.50E-05	6.69E-06	1.34E-05	0.002115
Pb	6.02E-09	1.41E-08	3.92E-09	9.16E-09	2.51E-09	5.85E-09	5.04E-09	1.18E-08	3.78E-09	8.83E-09	2.36E-05
Cd	4.56E-07	1.07E-06	3.04E-07	7.11E-07	7.61E-07	1.78E-06	6.09E-07	1.42E-06	3.04E-07	7.11E-07	0.008119
Ni	8.21E-07	1.92E-06	4.52E-07	1.05E-06	1.44E-06	3.36E-06	6.98E-07	1.63E-06	2.46E-07	5.75E-07	0.000609
Mn	1.42E-05	2.85E-05	2.27E-05	4.54E-05	6.13E-06	1.23E-05	1.07E-05	2.14E-05	1.64E-05	3.29E-05	0.001053
Cr	5.55E-08	1.3E-07	3.98E-08	9.31E-08	2.42E-08	5.64E-08	5.19E-08	1.21E-07	2.66E-08	6.2E-08	0.00022
As	1.45E-07	3.38E-07	7.25E-08	1.69E-07	1.09E-07	2.54E-07	3.62E-08	8.46E-08	1.45E-07	3.38E-07	0.000846
Zn	7.61E-06	1.52E-05	6.29E-06	1.47E-05	1.01E-05	2.03E-05	1.03E-05	2.06E-05	8.17E-06	1.64E-05	0.000432

vities of the children. The toddlers and infant in the preschool environments could also ingest dust though small in quantity. For inhalation exposure route, the sequences of the average daily dose of exposure in all the studied locations are PA < MA < CA < RA < EA and PA < MA < RA < CA < EA for the adults and the children, respectively. Breathing of dust laden with polluted air that contained trace metals could increase daily dose of trace metals among the exposed population. The dust remobilization and resuspension of previously settled dust most especially along the traffic corridors and the exhaust from internal combustion of fossil fuel in the vehicles could also increase the exposure level. Among the measured metals, Pb and Cr showed relatively high burden compared to other trace metals. Park, commercial and market areas of the city appeared to be more susceptible to high exposure to Pb and Cr. Additionally in educational areas, children are more exposed to trace metals measured in this study through inhalation routes. The primary route for Pb is the inhalation of Pb-containing particles that are emitted from burning of Pb-containing materials like gasoline and particles of paints from the wall of the classroom. The inhalation of the dust laden particle may increase as the children engaged in all sort of playing activities within the school environment. The sequences of the average daily dose of exposure through dermal pathway in all the studied locations are RA < CA < EA < MA < PA and RA < MA < EA < CA < RA for the adults and the children, respectively. Also, the dermal contact exposure route occurs through direct contact of the skin with the contaminated dust. Dermal absorption of the particle into human body depends mostly on the nature of the occupational and the length of time spend in the outdoor environment. For most artisans, the dermal contact with the polluted dust is very high and they also spend most of their time on outdoor environment which increases their daily dose. This can occur in most studied areas. The rate of remobilized and resuspended dust increased during the dry season when the soil is less humid and the deposition on the skin can be more than in the wet season. At school (educational areas) and at home (residential areas), the majority of kids played outside on the ground and crawled, which increased their exposure to trace metals through skin contact. Exposure through dermal contact can also take place through improper handling of the materials that release the trace metals into the soil. The dermal exposure pathway is quite similar for all the measured metals in all the sampling locations. Since lead (Pb) in-

hibits the development of the brain system and other organs, it is harmful to human health even at low concentrations (Mohmand et al., 2015). Elevated blood Pb levels can potentially cause bone abnormalities, especially in children (Shil and Singh, 2019). Additionally, they might negatively impact the kidneys, brain tissues, and neurological system (Duan et al., 2014; Mohmand et al., 2015). The HI distribution trend of each trace metal is the same for adults and children, particularly kids who are in contaminated commercial and market environments. Children have a higher HI for some specific trace metals at a given concentration (Mohmand et al., 2015). It should be noted that settled dust is the fractional matrix through which exposure to trace metals occurs to humans. Other sources such as food consumption and drinking of water can also contribute to the total burden of the trace metals in the human body. Each metal might have its own specific implications. The combined potential health effects could also occur depending on the available trace metals and level of their concentration. Prolonged exposure to As, which is mostly absorbed through food and water consumption, has been linked to chronic arsenic poisoning.

Carcinogenic risks results. The carcinogenic risks of Pb, Cr, Ni, and Cd, in this study are 1.96×10^{-7} , 5.1×10^{-8} , 9.03×10^{-9} , 8.52×10^{-8} , and 3.71×10^{-4} , respectively (Table 5). These values fall below the lower range of threshold values 10^{-6} to 10^{-4} and are therefore being judged acceptable. The results demonstrated that the risk of cancer for the metals under consideration were negligible. However, the high concentration of Cd sparked worries because it could have some negative consequences, including serious impairment as pulmonary edema, testicular damage, osteomalacia, hepatic and renal failure, and harm to the adrenal glands and hematological system (Tinkov et al., 2018). The population's cancer risk for children ($Cd = 3.71 \times 10^{-4}$) may have been quite near to the 10^{-4} upper limit value. Five functional groups were used to group carcinogenic compounds based on the values of their hazard index. Arsenic exposure everywhere and cadmium exposure in commercial zones are associated with the highest hazards to children's health from cancer, with identical HI values for both. Moreover, arsenic is often used in herbicides and insecticides due to its germicidal qualities. Sodium arsenite, one of the inorganic arsenic compounds, is a common weed killer and non-selective soil sterilant (Tinkov et al., 2018). Thus, the risk of cancer associated with human exposure to arsenic ne-

Table 5. *Carcinogenic health index results*

Heavy metals	Park area		Residential area		Commercial area		Market area		Educational area	
	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children
As	1.12E-07	4.09E-07	5.61E-08	1.73E-07	3.38E-09	1.23E-08	2.83E-09	8.48E-07	1.13E-09	3.397E-07
Pbs	6.87E-08	2.1E-07	4.55E-10	9.86E-10	7.62E-10	2.29E-07	5.78E-10	1.15E-09	4.39E-10	1.33E-09
Cr	4.43E-09	1.46E-08	3.18E-09	3.44E-08	1.55E-09	6.31E-09	4.11E-09	1.37E-08	9.72E-10	7.14E-09
Ni	6.63E-08	2.13E-08	3.54E-08	1.07E-07	1.14E-07	3.45E-07	5.70E-08	1.84E-08	2.16E-08	6.577E-08
Cd	3.53E-08	1.1E-08	2.36E-09	7.12E-09	5.89E-09	1.78E-08	4.71E-09	1.42E-08	2.39E-09	3.712E-04

eds to be carefully considered, particularly in commercial settings. A comprehensive evaluation of a city's pollution concerns should consider not only the risks posed by other pollutants but also the health risks connected to particular toxins, such as polycyclic aromatic hydrocarbons, undiscovered Trace metals, or areas with relatively high pollution levels.

Monte Carlo simulation of cancer risk results.

Table 6 and Figures 4 (a- k) provide the results of the MCS conducted in this study. The MCS provides a robust probabilistic assessment of carcinogenic risks from exposure to the trace metals in outdoor dust across various functional zones in Ondo City, Nigeria. The results revealed a wide range of risk values across best-case (5th percentile), most likely (50th percentile), and worst-case (95th percentile) scenarios, emphasizing the variability and uncertainty inherent in environmental exposure pathways. Across all exposure conditions,

children consistently exhibited significantly higher cancer risk values than adults, reflecting their increased vulnerability due to higher intake rates relative to body weight and longer expected exposure durations. For instance, under worst-case conditions, cancer risks for children in the educational area peaked at 2.97E-03, exceeding the upper bound of the U.S. EPA's acceptable risk range of E-04. Although under most likely scenarios, most of the areas, recorded values within the acceptable threshold, except for the educational area for children. This high risk in the educational area, which is up to 30 times higher than the safety limit, suggests that children in schools and playgrounds face severe long-term health consequences from chronic exposure to contaminated dust. The worst-case scenario (95th percentile) is particularly concerning, as it indicates that nearly all children in these environments could be at significant risk unless immediate interventions are implemented.

Area	Age subgroup	Best case scenario (5 %)	Most likely scenario (Median)	Worst case scenario (95 %)
Park	Adults	4.25E-06	9.49E-06	1.59E-05
	Children	6.84E-06	2.12E-05	4.17E-05
Residential	Adults	9.85E-07	3.13E-06	6.12E-06
	Children	3.75E-06	1.05E-05	1.96E-05
Commercial	Adults	3.58E-07	7.90E-07	1.36E-06
	Children	6.32E-06	1.97E-05	3.82E-05
Market	Adults	7.86E-07	2.61E-06	5.32E-06
	Children	4.33E-06	2.67E-05	6.71E-05
Educational	Adults	2.08E-07	8.04E-07	1.85E-06
	Children	3.12E-04	1.27E-03	2.97E-03

Table 6.

Results of Monte Carlo simulation of cancer risk due to trace metals in outdoor dust.

This elevated risk is primarily driven by cadmium (Cd), which accounted for nearly 100% of the carcinogenic risk in the sensitivity analysis for this age group (Fig. 4j). Cadmium, a known human carcinogen, is associated with kidney, lung, and bone toxicity and is particularly hazardous in early life stages due to. This elevated

risk is primarily driven by cadmium (Cd), which accounted for nearly 100% of the carcinogenic risk in the sensitivity analysis for this age group (Fig. 4j). Cadmium, a known human carcinogen, is associated with kidney, lung, and bone toxicity and is particularly hazardous in early life stages due to bioaccumulation

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and long biological half-life. Given that children are more vulnerable due to frequent hand-to-mouth behavior and lower body weight, this finding demands urgent action. Possible sources include industrial emissions, phosphate fertilizers, or improper e-waste disposal near schools, necessitating environmental audits and source apportionment studies. Adults generally showed lower risk estimates, but in areas like parks and residential neighborhoods, median risks still approached E-05, indicating moderate exposure concerns. Sensitivity analysis (Fig. 4 a-j) identified As, Ni and Cd as the predominant risk drivers, with As contributing up to 99.9% of the cancer risk in multiple exposure scenarios, particularly for children. Nickel and

Cadmium were notably influential in adult exposures in market and educational zones, highlighting occupational exposure vulnerabilities. These findings point to the urgent need for targeted public health interventions such as dust control strategies, environmental monitoring, and metal-specific source identification. Particular attention should be paid to school environments, markets, and areas with high foot traffic, where vulnerable populations may face long-term health impacts. The use of MCS enhances the reliability of this risk characterization by incorporating real-world variability and uncertainty, making the findings valuable for evidence-based environmental policy and risk management in urban settings.



Figure 4a
Sensitivity plots for
the cancer risk for
children in Park
area

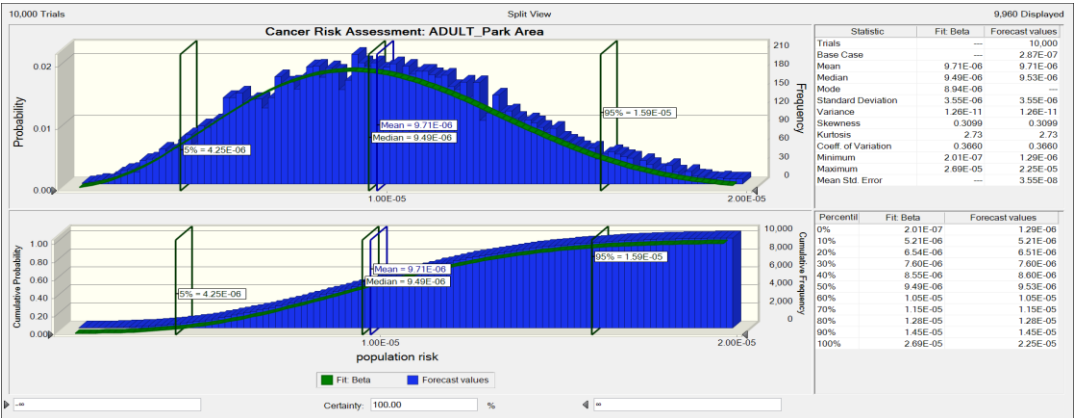


Figure 4b
Sensitivity plots for
the cancer risk for
adults in Park area

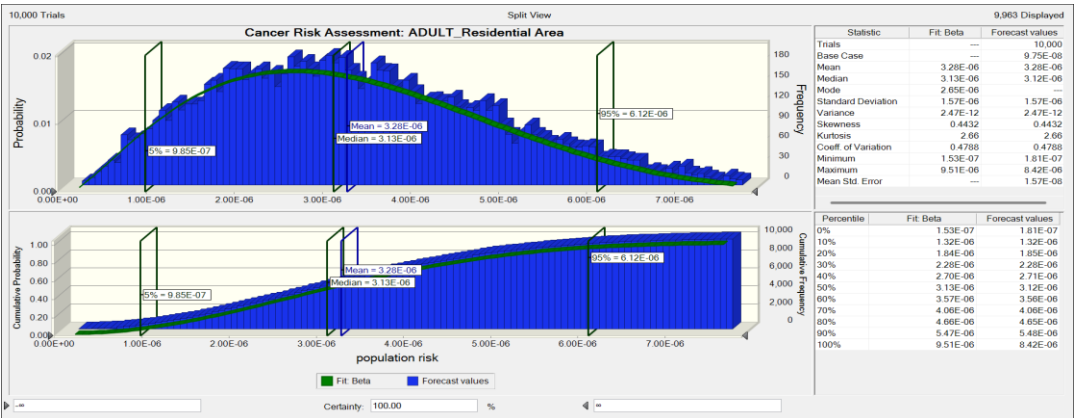


Figure 4c
Sensitivity plots for
the cancer risk for
adults in Residential
area.

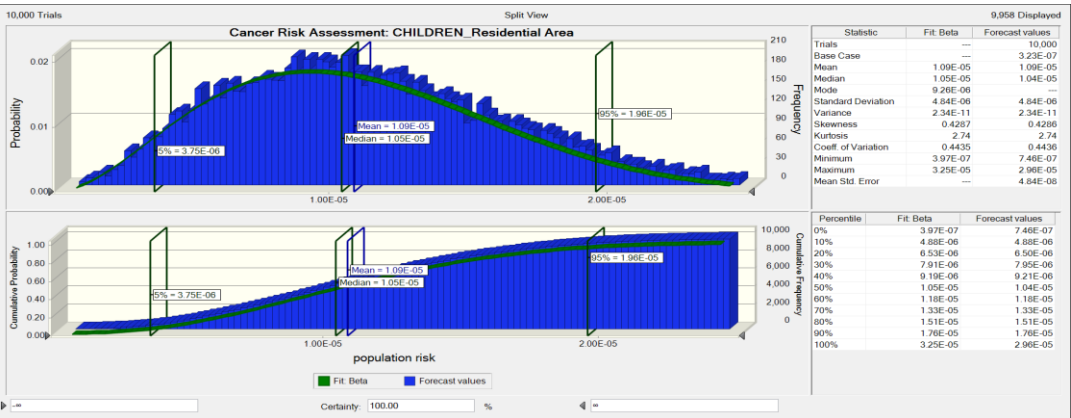


Figure 4d
Sensitivity plots for the cancer risk for children in Residential area

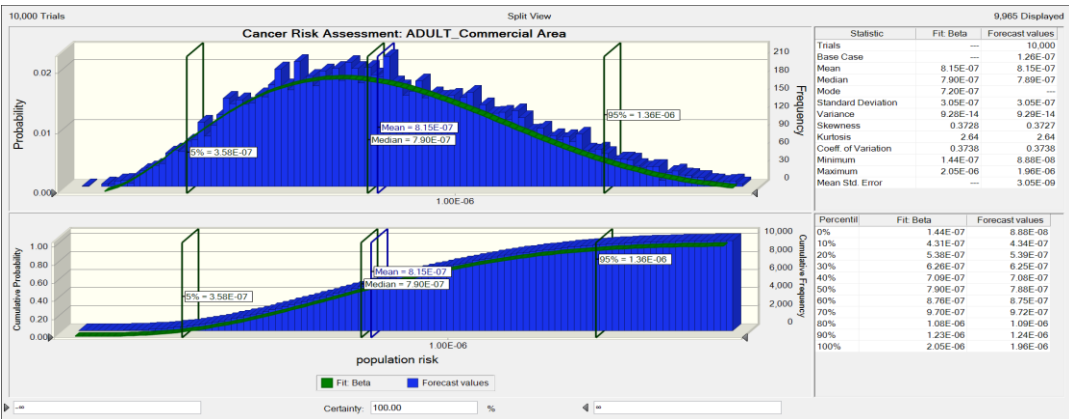


Figure 4e
Sensitivity plots for the cancer risk for adults in Commercial area

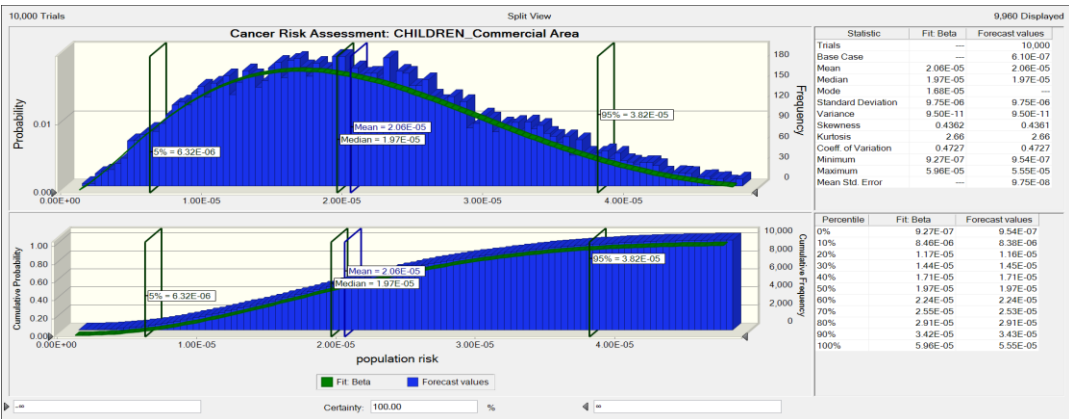


Figure 4f
Sensitivity plots for the cancer risk for children in Commercial area

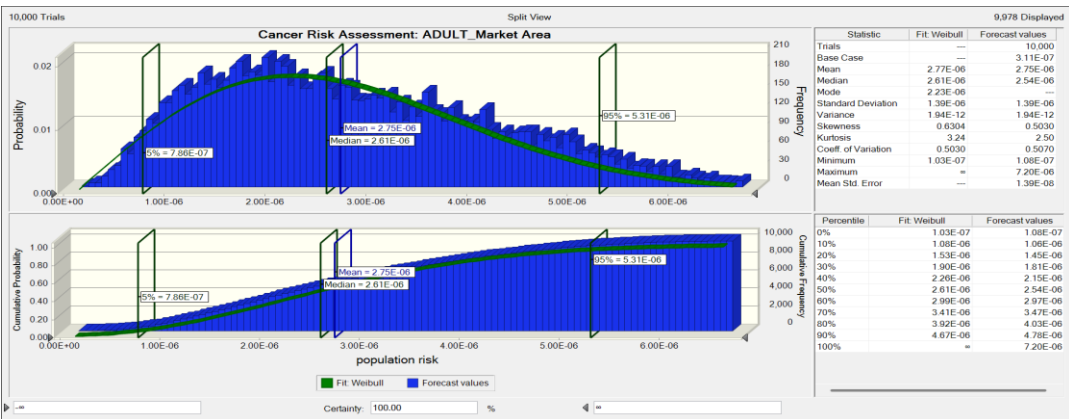


Figure 4g
Sensitivity plots for the cancer risk for adult in Market area

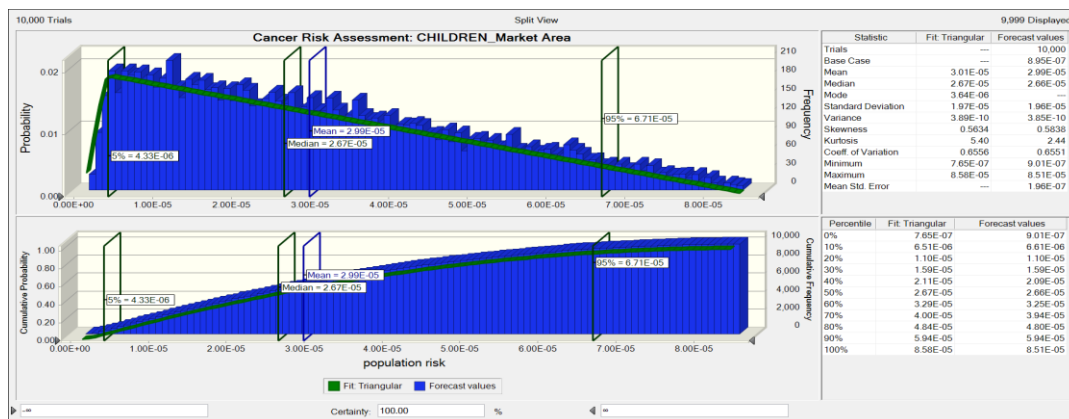


Figure 4h
Sensitivity plots for
the cancer risk for
children in Market
area

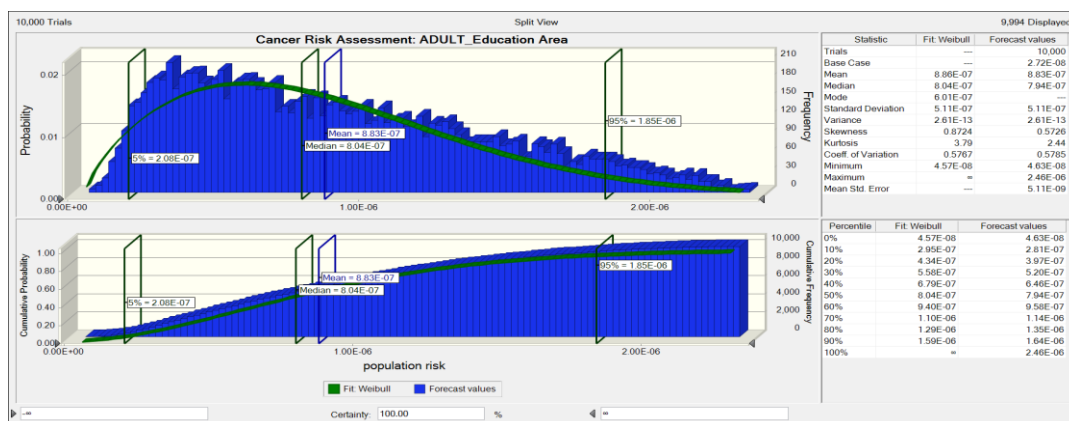


Figure 4i
Sensitivity plots for
the cancer risk for
adult in
Educational area

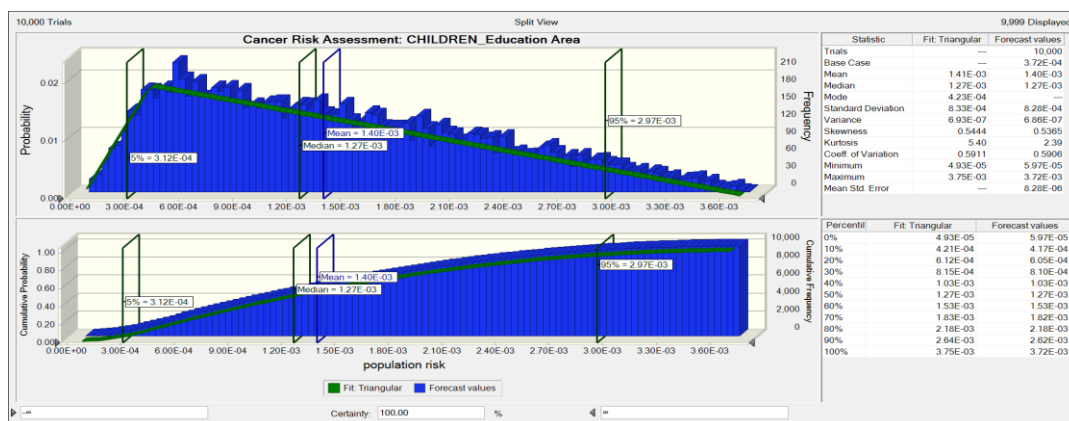


Figure 4j
Sensitivity plots for
the cancer risk for
children in
Educational area

Figures 4 (a-i) Sensitivity plots for the cancer risk for park area (a and b) for adult and children, residential area (c and d) for adult and children, commercial area (e and f) for adult and children, market area (g and h) for adult and children and educational area (j and k) adult and children.

Conclusions

This study assessed the contamination levels and potential health risks associated with trace metals in outdoor dust from various functional zones in Ondo City, Southwestern Nigeria. Although the measured concentrations of Trace metals were generally below global background values, pollution indices such as the geo-accumulation index (I_{geo}) revealed localized contamination patterns-ranging from unpolluted conditions

for Mn, As, Zn, and Cr, to high and extreme contamination for Cu, Ni, Cd, and Pb. The order of contamination based on I_{geo} values was $Pb > Cd > Ni > Cu > Zn > Mn > As$. Despite all Pollution Load Index (PLI) values being below 1, indicating low overall contamination, specific zones, particularly market areas, exhibited elevated concentrations of trace metals. Ecological risk index (ERI) assessments further confirmed that the metals posed a generally low eco-

logical threat, with risk index values ranging from 0.001 to 0.99, all well below the threshold of concern (150). Crucially, the carcinogenic risk assessment, enhanced using Monte Carlo Simulation (MCS), provided a deeper insight into health risks by accounting for variability and uncertainty in exposure conditions. The MCS revealed that most metals and exposure scenarios fell within the U.S. EPA's acceptable risk range of E-06 to E-04. However, Cd stood out as a significant carcinogenic risk, particularly in the educational area, where children's worst-case cancer risk exceeded 2.90E-03, far above the upper safety threshold. Sensitivity analysis showed that As, Ni and Cd were the major drivers of risk across most zones, especially affecting vulnerable populations such as children in schools and individuals in high-traffic commercial areas. These findings highlight the need for targeted mitigation strategies and policy interventions, especially in educational and market environments, to reduce exposure to high-risk contaminants. Measures such as dust control, environmental remediation, and routine monitoring of metal concentrations in public areas are recommended. This research offers critical evidence to support urban environmental health planning, helping city administrators and public health authorities implement science-based actions to reduce health risks and improve air and environmental quality in urban Nigeria.

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