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Concentration and Pollution Characteristics of Heavy Metals in Rooftop Dust Deposition on Buildings of Varying Heights in Kathmandu Metropolitan Area

Bhushan Shakya[1], Supriya Kandel[2], Bindra Devi Shakya[3], Deepak Chhetry Karki[4], Pawan Raj Shakya[5*]
[1]Department of Chemistry, Amrit Campus, Tribhuvan University, Kathmandu, Nepal
[2]Department of Environmental Science, Padmakanya Multiple Campus, Tribhuvan University, Kathmandu, Nepal
[3]Department of Mathematics and Statistics, Padmakanya Multiple Campus, Tribhuvan University, Kathmandu, Nepal
[4]Department of Environmental Science, Tri-Chandra Multiple Campus, Tribhuvan University, Kathmandu, Nepal
[5]Department of Chemistry, Padmakanya Multiple Campus, Tribhuvan University, Kathmandu, Nepal
[*]Correspondence: pawansh2003@yahoo.com

Abstract

Heavy metals (HMs) in dust act as potential indicators of air pollution and pose significant risks to both human health and the environment. This study investigates the concentrations and pollution characteristics of six heavy metals (Cd, Cr, Cu, Ni, Pb, and Zn) in rooftop dust collected from three types of concrete buildings of varying heights: low-rise buildings (LRB), medium-rise buildings (MRB), and high-rise buildings (HRB) in the Kathmandu metropolitan area. A total of 36 dust samples were collected from the buildings during the dry season (March–April 2024) and analyzed for HMs content using flame atomic absorption spectrophotometry (FAAS). Pollution assessment was conducted using four indices: contamination factor (C_f), degree of contamination (C_{deg}), pollution load index (*PLI*), and geo-accumulation index (I_{geo}). Results indicated that the mean HM concentrations were highest in dust from low-rise buildings, with all measured values exceeding background levels. The overall abundance of metals (mg/kg) in rooftop dust followed the order: Zn (372.0) > Cu (85.9) > Cr (69.3) > Ni (65.8) > Pb (56.2) > Cd (0.65). Pollution assessment using the contamination factor (C_f) and degree of contamination (C_{deg}) revealed values ranging from 0.42 to 5.06 and 7.83 to 15.72, respectively, indicating low to considerable and considerable levels of contamination across all building types, with zinc (Zn) identified as the predominant pollutant. Pollution load index (*PLI*) values greater than 1.0 in this study confirmed that rooftop dust was polluted in all cases. Meanwhile, geo-accumulation index (I_{geo}) values ranging from 0.11 to 1.03 indicated a contamination level from unpolluted to moderately polluted. These findings suggest that vehicular emissions, industrial activities, construction and demolition, and other anthropogenic sources are the primary contributors to rooftop dust contamination in the metropolitan area.

Keywords: *Ecological risk assessment, Heavy metal pollution, Kathmandu metropolitan city, Pollution index, Rooftop dust*

Introduction

Heavy metals are naturally occurring elements with high atomic weights and densities exceeding 5 g/cm³. Common environmental heavy metals include lead (Pb), cadmium (Cd), chromium (Cr), zinc (Zn), copper (Cu), and nickel (Ni), which are toxic even at low concentrations. Many originate from anthropogenic activities such as industrial emissions, vehicular exhaust, construction, and waste disposal (Charlesworth et al., 2003; Zhang et al., 2016). Due to their non-biodegradable nature and ability to accumulate in the environment and living organisms, heavy metals pose significant threats to human health and ecosystems. They can enter the human body through various pathways, including inhalation, ingestion, and dermal absorption (Napit et al., 2020; Bhandari et al., 2021).

Dust particles, comprising soil, airborne particles, building materials, soot from industrial and vehicle emissions, and heavy metals, significantly contribute to urban pollution (Niroula et al., 2022). These particles can be resuspended into the atmosphere, further dispersing heavy metals and exacerbating pollution levels. Consequently, these metals may pose health risks to urban dwellers, particularly in areas with high levels of anthropogenic activity

(Vegter, 2007). Studies on the chemical composition of roadside dust have shown that it contains potentially toxic metals such as Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Zn, Ti, and Zr, along with organic contaminants (Banerjee, 2003). Numerous studies have demonstrated that both soil and dust particles possess a higher capacity to bind and transport heavy metals (Shakya et al., 2019; Niraula et al., 2022). Prolonged exposure to elevated levels of heavy metals can lead to both acute and chronic toxicity, causing damage to the central and peripheral nervous systems, blood composition, lungs, kidneys, and liver, and potentially resulting in death (Georgaki & Charalambous, 2022; Sudharshan Reddy & Sunitha, 2023). Additionally, the neurological, gastrointestinal, hormonal, cardiovascular, and reproductive systems are also directly affected (Ismanto et al., 2022; Jamali et al., 2023). Young children are particularly at risk for heavy metal poisoning, as this stage is critical for optimal brain development and growth (Lin et al., 2020).

Kathmandu is one of the most densely populated cities in Nepal, with an approximate density of 28,418 people per km² according to the 2021 Census of Nepal. It has not developed a substantial transport infrastructure that includes a metro, light rail, or trams, and instead relies predominantly on public transport options like buses, microvans, taxis, private vehicles, and motorbikes. Consequently, these vehicles contribute to heavy road traffic, which is considered the primary cause of air pollution in the city center. The contamination of soil and road dust systems in Kathmandu with heavy metals can be attributed to rapid population growth, industrial development, increasing urbanization, and various other anthropogenic activities (Bhandari et al., 2021; Niraula et al., 2022). Additionally, Kathmandu is experiencing rapid and chaotic demolition and construction activities, often in violation of building regulations and bylaws. According to the "Nepal National Building Code NBC 206: 2024" (NBC, 2024), there are four types of building construction classified by their stories and heights: low-rise or general, medium-rise, high-rise buildings, and skyscrapers. Low-rise or general buildings (1 to 5 stories or below 16 m) are those whose heights are within reach of firefighters' ladders and hose streams. These buildings are typically accessible without elevators, making them the most common type of structure overall in Nepal, including Kathmandu metropolitan city. Medium-rise buildings (6 to 8 stories or 16 to 24 m) have heights that are accessible to fire hose streams. In emergencies, firefighters can use stairways for rescue in these structures. High-rise buildings (9 or more up to 39 stories, ≥ 25 to below 100 m) exceed the reach of standard firefighting equipment on the ground. Rescue operations in emergencies require fire lifts on the upper floors of these buildings. Skyscrapers (40 stories and above, and ≥ 100 m) necessitate new approaches to safety, design, and technology, and have yet to be experimented with in Nepal; therefore, they are not covered by the code. All these construction types in Kathmandu not only obstruct air movement but also cause their upper surfaces to accumulate dust, serving as a significant secondary source of dust. In dusty environments, adults may inhale as much as 100 mg of dust each day (Rout et al., 2012). Local communities in these areas suffer from exposure to heavy metals in dust, resulting in harmful health effects.

In recent decades, there has been growing interest in the potentially toxic heavy metals found in soils and road dust because of their harmful effects on the environment and human health. Niraula et al. (2022) assessed the ecological risks of heavy metals in various land-use urban soils of Kathmandu. Similar studies by Shakya et al. (2019) and Napit et al. (2020) focused on assessing contamination and pollution characteristics associated with heavy metal exposure in street dust within Kathmandu. Bhandari et al. (2021) evaluated the health risks posed by heavy metals in indoor dust in Kathmandu. The study by Pradhananga et al. (2017) concentrated on heavy metal accumulation in dust from indoor ceiling fans in residential areas of the Kathmandu metropolitan city, while Shakya et al. (2017) analyzed heavy metals in fine particle size fractions from roadside dust in the same city. Moreover, the studies conducted by Bourliva et al. (2017), Roy et al. (2019), Castillo-Nava et al. (2020), and Sadeghduost et al. (2020) primarily focused on the ecological risk assessment of heavy metals in road dust across various countries. Similarly, Javid et al. (2021) and Song et al. (2022) assessed the ecological risks of heavy metals in air dust fall particles in Iran and rooftop dust at various building heights in China, respectively. An in-depth analysis of existing literature reveals that only limited research has concentrated on the pollution characteristics of heavy metals in dust deposits on rooftops of different building types worldwide, with Kathmandu being no exception. The Kathmandu metropolitan area has become densely populated, resulting in significant socio-economic and land-use changes. The city contains many vulnerable areas with metal contaminants arising from rampant construction and demolition, traffic emissions, waste disposal, and industrial activities. Consequently, this study aims to quantify the concentrations of six heavy metals (Cd, Cr, Cu, Ni, Pb, and Zn) in rooftop dust collected from buildings of varying heights in the Kathmandu Metropolitan Area. Additionally, the study evaluates the pollution characteristics of these heavy metals using multiple pollution assessment indices to enhance understanding of their environmental implications. While previous research has primarily focused on ground-level or ambient air pollution (Shakya et al., 2019; Napit et al., 2020; Bhandari et al., 2021; Niraula et al., 2022), this study is unique and presents a novel investigation into the vertical stratification of heavy metal accumulation on rooftops, providing new insights into how buildings of differing heights influence pollutant deposition patterns in densely populated and topographically complex urban areas like Kathmandu. This approach is particularly innovative concerning Kathmandu, a rapidly urbanizing city with limited green infrastructure and poor air quality. The findings are expected to provide baseline information for urban planning and public health strategies by highlighting height-related disparities in pollutant exposure in densely populated urban settings.

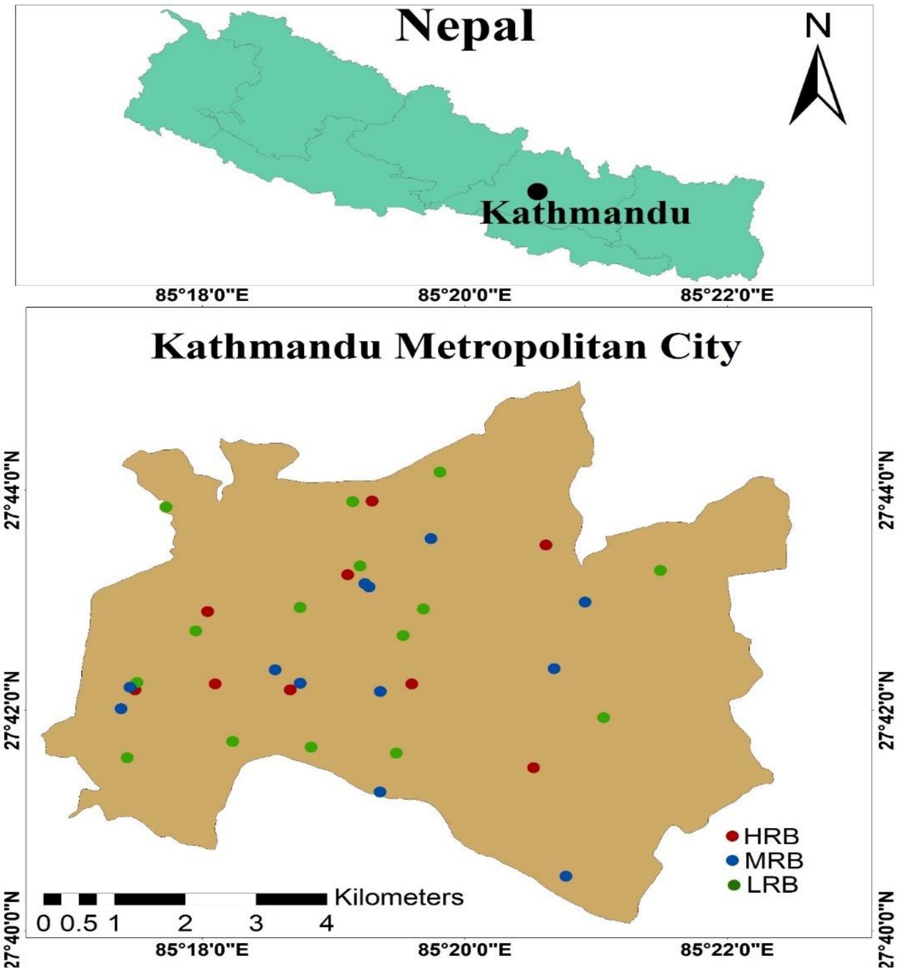

Figure 1: Map of the study area and sampling sites indicating building types across Kathmandu metropolitan.

Materials and Methods

Study area and selection of sampling sites

Kathmandu Metropolitan City (KMC), also known as Kathmandu Municipality (Fig. 1), is the capital and largest city of Nepal. It serves as the political, cultural, and economic center of the country. The city is located in the Kathmandu Valley, a basin-like area in central Nepal, surrounded by the Shivapuri, Phulchoki, and Nagarjun hills. Covering an area of 50.67 sq. km, it is positioned at a latitude of 27.7° N and a longitude of 85.3° E, with an elevation of approximately 1,400 meters above sea level. The city's average annual precipitation is about 1,400 mm, primarily occurring during the monsoon season from June to September.

The city's landscape is diverse, featuring certain flat areas and others that gently slope to the south. According to the 2021 Census of Nepal, the population of KMC is approximately 1.4 million, with an estimated growth rate of about 2.22% per year. The city experiences a moderate climate influenced by its altitude, boasting an average annual temperature of around 16°C. This metropolitan area is divided into 32 wards, each responsible for local administration, public services, and infrastructure development.

For this study, preliminary information was gathered from the office of Kathmandu Metropolitan City (KMC) and relevant government agencies regarding the classifications of building types by law in Nepal. Among the four building categories identified according to the "Nepal National Building Code NBC 206: 2024" (NBC, 2024), only the first three types, *viz.*, low-rise or general, medium-rise, and high-rise buildings located in the metropolitan area, were selected for sampling in this study. To achieve this, a field survey was conducted to identify several potential sampling sites, including the desired building types and areas encompassing commercial, heavy-traffic, and residential zones in the Kathmandu metropolitan city. Regarding the sampling technique, we adopted a purposive sampling approach. Buildings were chosen based on their height category (low-, medium-, and high-rise) from commercial, heavy-traffic, and residential areas across the Kathmandu metropolitan area, as well as rooftop accessibility and safety considerations. This non-probability sampling method allowed us to target locations most relevant to the study's objectives while ensuring representation of different building heights. Only concrete structures from all three building types were selected within each land use category to maintain uniformity in sampling. For sampling purposes, the number of selected low-rise, medium-rise, and high-rise buildings was 15, 12, and 9, respectively. The sample size was considered based on the availability and accessibility of suitable buildings within the study area and land-use types (table 1), taking into account logistical and safety considerations, particularly for high-rise structures. Despite the variation in sample numbers, we ensured sufficient representation across all height categories to allow for reliable comparison and spatial assessment. The location map (Fig. 1) illustrates the sampling points for rooftop dust collection from the three building types across the Kathmandu metropolitan area using GIS mapping methods, while table 1 provides a brief overview of the building types, number of samples, locations, and land use types for sampling.

Table 1: Description of building types and sampling sites across Kathmandu metropolitan city.

Sample code	Building type	Height/ stories (floors)	No. of samples (n)	Location of sampling sites	Land-use type for sampling
LRB	Low-rise or general	<16m / 1 to 5	15	Sinamangal, Maharajganj, Thamel, Naxal, Ranibari, Teku, Bauddha, Balaju, Dallu, Bafal, Tripureshwor, Babarmahal, Kalanki, Lazimpat, Kamalpokhari	Commercial, heavy traffic, and residential areas
MRB	Medium-rise	16 – 24m / 6 to 8	12	Tahachal, Baluwatar, Lazimpat, Indrachowk, Koteshwor, Chabahil, Gonbabu, Kalimati, Putalisadak, Thapathali, Battishputali, Bafal	Commercial, heavy traffic, and residential areas
HRB	High-rise	≥ 25 to below 100m / 9 or more	9	Tahachal, Bafal, Kalikasthan, Sobha bhagawati, Lazimpat, Dhumbarahi, New Baneshwor, Gongabu, Newroad	Commercial, heavy traffic, and residential areas

Sample collection and analytical procedure

During the dry season (March-April 2024), a total of 36 dust samples falling on the rooftops of all three building types were collected. Sample collection from each building type involved sweeping an area of approximately 1 m² with a brush and a plastic dustpan. Two corners and the center of the rooftop area were gently swept and mixed. Care was taken to avoid contamination from rooftop flower vases or kitchen gardens, if present. Dust samples from each structure were collected three times at regular intervals and mixed homogeneously within each category to account for potential variations in elemental concentrations. The dust collected from each building type and sampling site weighed between 250 and 500 g. The sweeping was done carefully, and the dust was collected directly into labeled plastic bags to prevent the resuspension of fine particles during sample collection. Consequently, each dust sample consisted of a composite mixture of three sub-samples collected simultaneously during three successive collections from each structure and sampling site. In the laboratory, the collected dust samples were air-dried at room temperature for two weeks and sifted to remove pebbles, leaves, and other debris. The samples were stored as stock in properly labeled plastic bags with zip locks and kept in a dry location for further processing and analytical purposes.

The concentration of six heavy metals (Cd, Cr, Cu, Ni, Pb, and Zn) in dust samples was determined using a Perkin Elmer AAnalyst 800 Atomic Absorption Spectrophotometer equipped with an AS-800 autosampler and cooling system, utilizing an air-acetylene flame atomizer. These heavy metals were selected due to their well-documented toxicity, strong association with urban anthropogenic sources (e.g., traffic, industrial emissions), and significance to human health. Furthermore, these metals are frequently used as indicators of environmental pollution in urban studies. A microwave-assisted acid digestion method was employed to extract the total quantities of the analyzed heavy metals from rooftop dust samples (USEPA, 1994). Accordingly, a pre-weighed quantity (1.0 g) of an air-dried dust sample was processed for chemical extraction with 10 mL of concentrated HNO_3 and then heated in a microwave using a CEM, Mars HP 500 microwave extraction system. After complete digestion, the solution was filtered through medium-textured Whatman filter paper, diluted to 25 mL with double-distilled water, and stored in plastic bottles. A similar method was used for all dust sample solutions. All certified standard solutions (1000 ppm) for Cd, Cr, Cu, Ni, Pb, and Zn were obtained from FLUKA AG, Switzerland, for calibration. These solutions were carefully diluted to the required concentrations using double-distilled water. All glass and plastic containers were treated with a diluted (1:1) nitric acid solution for 24 hours and washed with double-distilled water before use. The nitric acid (E. Merck, Germany) was of analytical grade and used without additional purification. The instrumental settings followed the manufacturer's recommendations. The precision and accuracy of the analytical method were verified by analyzing standard reference materials NIST SRM 1648. The recovery percentages for metal concentrations from the reference materials were 98.5 (Cd), 97.8 (Cr), 97.3 (Cu), 99.0 (Ni), 98.5 (Pb), and 98.0 (Zn). To assess the accuracy of the analytical procedure, several samples from the sampling locations were examined three times. The calculated standard deviations for the pretested samples were 3.1, 2.1, 2.5, 2.9, 2.2, and 3.0% for Cd, Cr, Cu, Ni, Pb, and Zn, respectively, which are considered acceptable for the analysis of dust samples. The detection limits for Cd, Cr, Cu, Ni, Pb, and Zn in dust samples using FAAS were 0.5, 2.0, 1.0, 2.0, 0.5, and 2.0 μg^{-1}, respectively.

Pollution characteristics of heavy metals in rooftop dust

Estimation of pollution indicators

In this study, the Contamination Factor (C_f), Degree of Contamination (C_{deg}), Pollution Load Index (*PLI*), and Geoaccumulation Index (I_{geo}) were determined to evaluate the pollution characteristics of rooftop dust samples in urban areas. The C_f was used to assess the degree of metal contamination and the probable contribution of anthropogenic sources (Yuen et al., 2012).

This factor was first proposed by Håkanson (1980) and was computed using the following equation.

$$Cf = Cn/Bn \quad (1)$$

where C_n represents the measured concentration of the target heavy metal (HM) in dust and B_n denotes the geochemical background concentration of the corresponding heavy metal. Due to insufficient data on the background concentrations of HMs in Nepal's soils, we adopted the background values of HMs from Turekian and Wedepohl (1961). Accordingly, the background concentrations for Cd, Cr, Cu, Ni, Pb, and Zn are 0.3, 90, 45, 68, 20, and 95 mg/kg, respectively.

The C_{deg} represents the sum of contamination factors for all the HMs and indicates the integrated pollution index. This contamination index, derived from the six measured HMs in rooftop dust, was determined as follows (Håkanson, 1980).

$$Cdeg = \sum Cf \quad (2)$$

Hakanson (1980) suggested four C_f and C_{deg} classes to evaluate the heavy metal (HM) contamination levels (table 2).

The PLI aids in quantifying and evaluating pollution levels in a given area, including air, water, or soil. It represents an integrated approach to pollution that simplifies the understanding of pollution intensity. Additionally, the index is particularly useful for identifying areas with higher pollution loads. The index is defined as the geometric mean of the contamination factor (C_f) for the nth metals (Madrid et al., 2002) and was calculated using Eq. (3):

$$PLI = \sqrt[n]{Cf1 \ x \ Cf2 \ x \ Cf3 \ x \ \ldots\ldots\ldots\ldots..Cfn} \quad (3)$$

where C_f is the contamination factor and n is the number of elements. A PLI value >1 indicates polluted soil, whereas <1 indicates no pollution (Tomlinson et al., 1980).

The I_{geo} has recently been utilized as a quantitative measure to assess the extent of heavy metal contamination in airborne dust deposition (Xinming et al., 2022) and soils (Xiong et al., 2017). It reflects the effects of both anthropogenic activity and natural geological processes. The index, first introduced by Muller (1969), was calculated using Eq. (4).

$$Igeo = log2 \left[\frac{Cn}{1.5\ Bn}\right] \quad (4)$$

where C_n represents the measured concentration of the target heavy metal, and B_n denotes the geochemical background concentration. The constant 1.5 serves as the background matrix correlation factor, accounting for lithological variability. According to Muller (1969), the I_{geo} values are classified into seven categories of heavy metal pollution levels (table 3).

Table 3: Classification of pollution levels based on geo-accumulation index (I_{geo}) values.

Degree of pollution	I_{geo} value	Classification of heavy metal pollution levels
0	$I_{geo} \leq 0$	Unpolluted
1	$0 < I_{geo} \leq 1$	Unpolluted to moderately polluted
2	$1 < I_{geo} \leq 2$	Moderately polluted
3	$2 < I_{geo} \leq 3$	Moderately to heavily polluted
4	$3 < I_{geo} \leq 4$	Heavily polluted
5	$4 < I_{geo} \leq 5$	Heavily to extremely polluted
6	$I_{geo} \geq 5$	Extremely polluted

Statistical analysis

Data processing and statistical evaluation were performed on an IBM-PC computer using Excel spreadsheets. Descriptive statistics (such as frequency, mean, range, standard deviation, etc.) were conducted following the elemental analysis. A Box and Whisker plot was utilized to summarize the distribution of a dataset of heavy metals in rooftop dust falls. Pearson's correlation coefficient was used to assess the correlation between the metals, along with a significance test ($p<0.05$).

Table 2: Classifications of contamination levels based on the contamination factor (C_f) and degree of contamination (C_{deg}) values.

Class	C_f value	Level of HM contamination	C_{deg} value	Degree of HM contamination
I	$C_f < 1$	Low	$C_{deg} < 5$	Low
II	$1 \leq C_f < 3$	Moderate	$5 \leq C_{deg} < 10$	Moderate
III	$3 \leq C_f < 6$	Considerable	$10 \leq C_{deg} < 20$	Considerable
IV	$6 \leq C_f$	Very high	$20 \leq C_{deg}$	Very high

Results and Discussion

Heavy metal (HM) concentrations in rooftop dust

Table 4 displays the concentrations of analyzed heavy metals (Cd, Cr, Cu, Ni, Pb, and Zn) found in the dust accumulation on the rooftops of three types of buildings.

Results revealed that these buildings exhibited varying concentrations of heavy metals (HMs) in their rooftop dust. The order of HMs in the rooftop dust of low-rise buildings (LRB) was Zn > Cu > Cr > Ni > Pb > Cd. Similarly, medium-rise buildings (MRB) demonstrated HM contents as Zn > Cu > Ni > Cr > Pb > Cd, while high-rise buildings (HRB) displayed them in the order of Zn > Cu > Cr > Pb > Ni > Cd. The concentrations of heavy metals differed slightly across building heights. These variations may be attributed to differences in sources, particle sizes, and the vertical transport dynamics of atmospheric particles. Zn and Cu, which were dominant across all building types, are linked to fine particles and sources such as vehicular emissions, brake and tire wear, and industrial activities, which can be transported vertically. Cr, Ni, and Pb, often associated with coarser particles or ground-based activities (e.g., construction, residual fuel combustion), show more variability in vertical deposition patterns due to gravitational settling and local turbulence. Similar vertical variations in metal composition have been observed in studies of urban particulate matter deposition (Chen et al., 2010; Zhang et al., 2018; Li et al., 2020). The results of this study are consistent with the findings of Song et al. (2022), which similarly noted elevated levels of Zn and the lowest levels of Cd among the analyzed heavy metals in rooftop dust from structures of different heights in China. Castillo-Nava et al. (2020) also reported the lowest level of Cd among the HMs tested in dust from Monterrey, Mexico. In this study, the overall mean concentrations of heavy metals (mg/kg) were ranked as follows: Zn (372.0) > Cu (85.9) > Cr (69.3) > Ni (65.8) > Pb (56.2) > Cd (0.65). Among the HMs examined, only Cr and Ni had overall mean concentrations lower than their background levels (Turekian & Wedepohl, 1961). Moreover, the percent accumulation of the six heavy metals ($\sum_6$HM) in rooftop dust in this study, shown in Fig. 2, was found in the order of LRB (44%) > HRB (29%) > MRB (27%). The HMs in dust falling on the rooftops of building structures could be attributed to several factors, many of which relate to local environmental conditions and human activities (Song et al., 2022). These may include local industrial activities, automobile exhaust, historical contamination, atmospheric

Table 4: Statistical parameters of heavy metal concentration (mg/kg) in dust deposition on the rooftops of different building types.

Heavy metal	Statistical parameters	LRB (n=15)	MRB (n=12)	HRB (n=9)	Overall mean	Background value
Cd	Mean	0.84	0.63	0.47	0.65	
	Range	0.47 – 1.32	0.40 – 0.81	0.30 - 0.75		0.3
	SD	0.27	0.11	0.14		
Cr	Mean	98.1	50.8	60.0	69.3	
	Range	67.8 – 127.8	36.7 – 62.4	39.0 – 79.8		90
	SD	17.7	8.1	13.0		
Cu	Mean	117.5	79.0	61.2	85.9	
	Range	85.0 – 148.3	50.5 – 108.7	40.0 – 81.2		45
	SD	17.1	17.5	13.4		
Ni	Mean	95.0	57.8	44.5	65.8	
	Range	62.5 – 128.0	35.4 – 81.7	30.0 – 60.7		68
	SD	21.0	14.9	10.7		
Pb	Mean	66.8	46.7	55.1	56.2	
	Range	41.0 – 92.5	32.9 – 65.0	39.6 – 72.0		20
	SD	14.8	10.7	10.6		
Zn	Mean	489.6	288.8	337.6	372.0	
	Range	315.7 – 632.7	195.0 – 393.6	234.9 – 481.3		95
	SD	96.2	62.9	84.2		
$\sum_6$HM		867.8	523.7	558.9		

deposition, geological sources, and urban practices. Environmental conditions such as wind patterns, rainfall, and waste disposal practices can exacerbate these issues (Biswas, 2015). In this study, higher concentrations of HMs in the rooftop dust of low-rise buildings might be due to proximity to local sources such as traffic, transport of HMs through varying sizes of windborne particles, or industrial activities (Song et al., 2022).

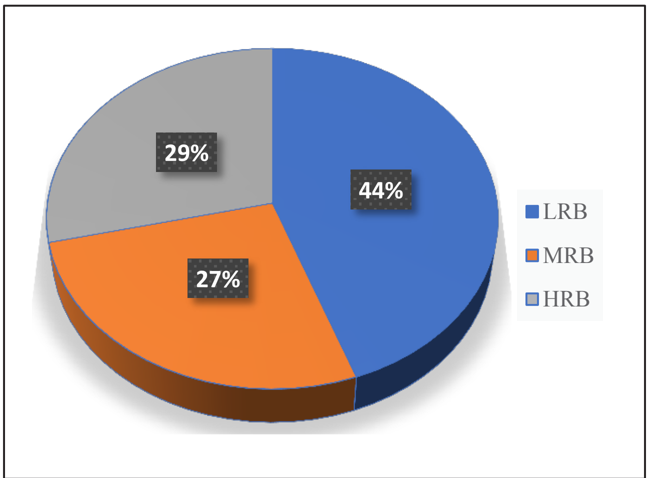

Figure 2: Percent accumulation of $\sum_6$HM in dust deposition on rooftops of different building types in Kathmandu metropolitan city.

The Box and Whisker plots (Fig. 3) for various building types showed differing interquartile ranges, suggesting that building height may influence the distribution of HM concentrations in dust fall on rooftops. The plots highlight key statistical features (median, range, interquartile range, and outliers), aiding in the recognition of trends, variations, and potential risks in the urban environment. This visualization method is particularly useful and advantageous over others when comparing multiple groups, such as metal concentrations across buildings of varying heights, as it allows for clear, compact comparisons of variability and skewness in the data (McGill et al., 1978).

From Table 4, the mean concentration of Cd in dust collected from the rooftops of three building types can be arranged in the order of LRB > MRB > HRB. The LRB recorded the highest concentration of Cd (0.84 mg/kg), while the HRB measured the lowest level at 0.63 mg/kg. Nevertheless, the Cd levels in all the building types exceeded the background level of 0.3 mg/kg. Cadmium is a relatively rare heavy metal that occurs naturally in combination with Zn. Possible sources of Cd in the dust include emissions from vehicles, automobile lubricants, and Zn-reinforced tires (Al-Khashman, 2003). Additionally, wear and tear, as well as the burning of vehicle tires, are reported as human-induced sources of cadmium in the dust (Shakya et al., 2019). Similar to Cd, the Cr content in rooftop dust from LRB was higher than that of MRB and HRB. However, the mean elemental concentration (mg/kg) was found in the order of LRB (98.1) > HRB (60.0) > MRB (50.8). In this case, only the Cr level from the HRB type exceeded the background concentration (90.0 mg/kg). Chromium originates from both geogenic and anthropogenic sources in the environment. Potential sources of Cr contamination in dust include traffic emissions and industrial activities like the chrome plating of vehicle parts and alloys, particularly stainless steel (Johansson et al., 2009; Mollaer et al., 2005). Additionally, Cr is also discharged into the environment through sewage and fertilizers (Ghani & Ghani, 2011).

Similar to the Cd levels, the highest mean concentration of Cu was found in LRB (117.5 mg/kg), followed by MRB (79.0 mg/kg) and HRB (61.2 mg/kg) in that order. The mean concentrations of Cu in rooftop dust across all three building types exceeded the background concentration (45.0 mg/kg). Sources of Cu in dust include sewage sludge, inorganic fertilizer, and atmospheric deposition (Panagos et al., 2018). In addition to Zn and Cd, Cu contamination in soil and dust has been associated with car components, tire abrasion, lubricants, oil product leaks, and emissions from industries and incinerators (Markus & McBratney, 1996). Following the trend of Cu content, Ni also showed its mean concentration in a descending order: LRB > MRB > HRB. LRB had the highest Ni concentration (95.0 mg/kg) in rooftop dust, while the elemental concentrations in MRB and HRB were 57.8 and 44.5 mg/kg, respectively. Only LRB was found to exceed the Ni level above the background level of 68.0 mg/kg. Like chromium, Ni is also a notable component of traffic emissions (Johansson et al., 2009). The corrosion of cars, tire rims, cylinders, and pistons in motor engines is a potential source of Ni contamination in dust (Fergusson & Kim, 1991).

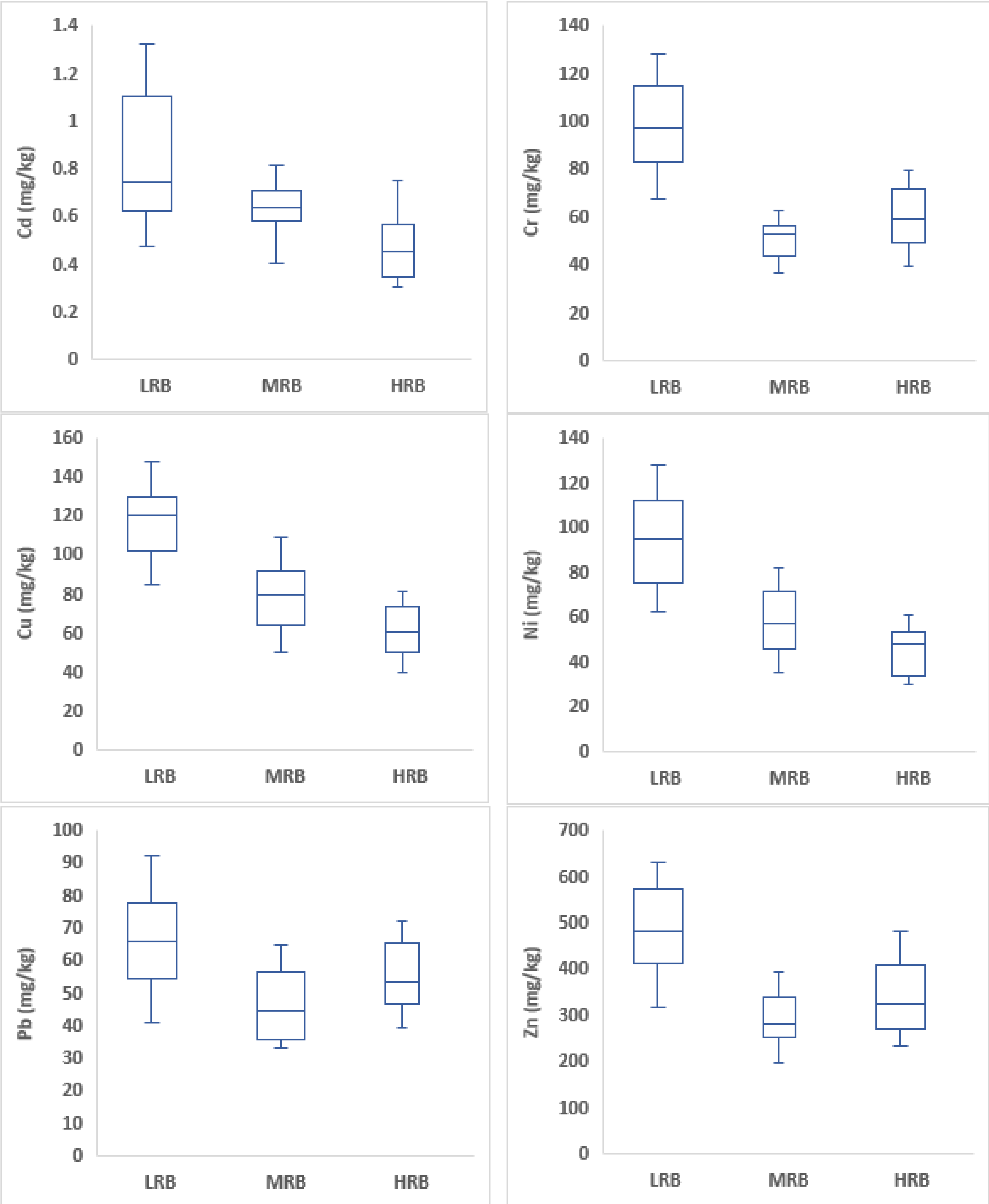

Figure 3: Box and whisker plots of heavy metal concentration showing minimum and maximum values along with median, 25th, and 75th percentile (central box) in rooftop dust of three building types.

The results indicated that the mean concentration of Pb in LRB was measured at 66.8 mg/kg. The MRB and HRB exhibited Pb concentrations of 46.7 and 55.1 mg/kg, respectively. Therefore, the sequence of mean concentrations of Pb can be arranged as LRB > HRB > MRB. It was observed that the mean Pb levels in the rooftop dust of all building types exceeded the background level of Pb (20.0 mg/kg). A significant contributor to Pb in dust comes from the wear of automobile tires, engine components, and leaks from batteries, as well as gasoline that contains Pb (Rout et al., 2013). Additionally, the low solubility of Pb contributes to its prolonged presence in a dusty environment (Yuen et al., 2012). Zinc levels in dust on rooftops across all building types were notably elevated among the HMs examined in this study. The LRB had the highest Zn level (489.6 mg/kg), followed by HRB (337.6 mg/kg) and MRB (288.8 mg/kg) in descending order. The results also revealed that the levels of Zn in the rooftop dust ranged between 315.7 – 632.7 mg/kg, 195.0 – 393.6 mg/kg, and 234.9 – 481.3 mg/kg for LRB, MRB, and HRB, respectively. The mean concentrations of Zn in all three building types surpassed the background concentration of 95.0 mg/kg. The elevated levels of Zn may have resulted from emissions from motor vehicles, the deterioration of brake systems, and galvanized zinc coatings. Faiz et al. (2009) stated that higher road temperatures in summer may cause significant tire wear in vehicles, leading to elevated Zn levels in road dust. Zinc in the form of zinc oxide is retained in the rubber matrix.

Based on table 4, it can be noted that low-rise structures exhibited higher concentrations of all heavy metals (HMs) tested in their rooftop dust compared to medium and high-rise buildings in the Kathmandu metropolitan area. The elevated HM levels in low-rise buildings are primarily due to their proximity to ground-level sources, such as traffic, dust resuspension, and industrial activities, which release coarser particles that settle quickly. In contrast, higher levels in high-rise buildings are often attributed to finer particles (e.g., Zn, Cu) that remain airborne longer and are transported upward by wind and atmospheric turbulence. This vertical distribution pattern has also been reported in other urban environments (Buccolieri et al., 2010; Li et al., 2020). Song et al. (2022) also observed elevated levels of HMs in the rooftop dust of low-rise buildings in China, noting the highest levels of Zn in building structures of varying heights, consistent with the present study. Shakya et al. (2019) showed increased levels of Zn in dust samples from various land use types in Kathmandu. Similarly, elevated levels of Zn in the street dust of Delhi, India, were reported by Roy et al. (2019), in Monterrey, Mexico, by Castillo-Nava et al. (2020), and in Dezful, Iran, by Sadeghdoust et al. (2020). In all cases, Zn was found to be more mobile than other heavy metals due to its smaller ionic size and greater binding affinity for dust particles. However, the extent of their mobility and binding affinities depends on the redox potential and pH of the surrounding dust environment (Hermann & Neumann-Mahlkau, 1985). The findings of this study suggest that the elevated levels of HMs in dust accumulating on rooftops across all types of buildings in the Kathmandu metropolitan region may be attributed to Earth's crust sources (such as road dust, construction dust, and distant dust transmission) as well as emissions from fossil fuel combustion (including vehicle emissions, coal burning, biomass burning, and industrial activities).

Correlation of heavy metals

Pearson correlation coefficients were calculated to establish the relationships among elements in the rooftop dust samples. Understanding these relationships can help identify the source of the elements and their distribution in the environment (Rodriguez et al., 2008). Table 5 illustrates the relationships between various heavy metals in a correlation matrix.

Table 5: Correlation matrix of heavy metals.

	Cd	Cr	Cu	Ni	Pb	Zn
Cd	1.000					
Cr	**0.519***	1.000				
Cu	**0.506***	**0.761***	1.000			
Ni	0.359	**0.832***	**0.765***	1.000		
Pb	0.369	0.438	**0.585***	0.257	1.000	
Zn	0.372	0.306	**0.602***	0.300	**0.634***	1.000

*Correlation is significant at $p<0.05$

It is evident from this matrix that Cr exhibited the strongest positive and significant correlation at $p < 0.05$ with Ni (0.832). The element also positively and significantly correlated with Cu (0.761) and Cd (0.519). This strong positive correlation suggests that these elements share common sources of contamination. Similarly, Cu showed a positive and significant correlation at $p < 0.05$ with Cd (0.506), Ni (0.765), Pb (0.585), and Zn (0.602). Additionally, Pb also had a positive and significant correlation with Zn (0.634) at $p < 0.05$. The sources of these heavy metals likely stem from anthropogenic activities (for Cr, Cd, and Ni metals), such as traffic and the wear and tear of vehicle rims and tires (Varrica et al., 2003). Likewise, the use of leaded gasoline, lubricating oil and grease, waste burning, industrial gases, vehicle emissions, engine part corrosion, and brake emissions may be potential sources of Cu, Pb, and Zn contaminants in dust (Lu et al., 2009; Kong et al., 2012). Moreover, a moderate correlation coefficient among Cd-Pb (0.519), Cd-Cu (0.506), Cu-Pb (0.585), Cu-Zn (0.602), and Zn-Pb (0.634) may imply that these elements share similar sources to some extent or at least one common source (Faiz et. al., 2009). A weak correlation matrix among the other elements suggests various or distinct sources.

Pollution characteristics of heavy metals (HMs)

The pollution characteristics of heavy metals (HMs) in rooftop dust deposition on buildings of varying heights in the Kathmandu metropolitan area were evaluated using both single and integrated pollution indices. The contamination factor (C_f) and geo-accumulation index (I_{geo}) are single pollution indices (Håkanson 1980), while the degree of contamination (C_{deg}) (Müller, 1969) and pollution load index (*PLI*) (Madrid et al., 2002) are integrated pollution indices.

Contamination factor (C_f) and degree of contamination (C_{deg})

The C_f indicates the amount of metal released into dust by human activities compared to that metal's natural or background level. At the same time, C_{deg} measures the total accumulation of metals in dust due to human influences. The C_f and C_{deg} values calculated for each building category, along with the level and degree of HM contamination, are summarized in table 6.

Among the building categories, LRB exhibited comparatively higher C_f values for all analyzed heavy metals (HMs) in rooftop dust, ranked in the decreasing order of Zn > Pb > Cd > Cu > Ni > Cr. The MRB and HRB also demonstrated a similar sequence regarding their C_f values. However, LRB showed various levels of contamination, ranging from moderate ($1 \leq C_f < 3$) to considerable ($3 \leq C_f < 6$) based on the C_f values, while the MRB and HRB categories indicated contamination levels from low ($C_f < 1$) to considerable ($3 \leq C_f < 6$). Thus, LRB presented a moderate level of contamination (1 d" C_f< 3) for Cd, Cr, Cu, and Ni, and a considerable level ($3 \leq C_f < 6$) for Pb and Zn. The MRB and HRB revealed low levels of contamination ($C_f < 1$) for Cr and Ni, moderate levels ($1 \leq C_f < 3$) for Cd, Cu, and Pb, and considerable levels ($3 \leq C_f < 6$) for Zn. Still, every building category showed a considerable level ($3 \leq C_f < 6$) of Zn contamination, ranked as LRM (5.15) > HRB (3.55) > MRB (3.04). Moreover, moderate levels ($1 \leq C_f < 3$) of contamination by

Table 6: Classification of contamination level based on contamination factor (C_f) and degree of contamination (C_{deg}) for heavy metals in rooftop dust on different building types.

Contamination factor (C_f)				
Heavy metal	**C_f index**	**Low-rise building (LRB)**	**Medium-rise building (MRB)**	**High-rise building (HRB)**
Cd	C_f value	2.80	2.10	1.57
	Contamination level	Moderate	Moderate	Moderate
Cr	C_f value	1.09	0.56	0.67
	Contamination level	Moderate	Low	Low
Cu	C_f value	2.61	1.76	1.36
	Contamination level	Moderate	Moderate	Moderate
Ni	C_f value	1.40	0.85	0.65
	Contamination level	Moderate	Low	Low
Pb	C_f value	3.34	2.34	2.76
	Contamination level	Considerable	Moderate	Moderate
Zn	C_f value	5.15	3.04	3.55
	Contamination level	Considerable	Considerable	Considerable
Degree of contamination (C_{deg})				
C_{deg} index		**Low-rise building (LRB)**	**Medium-rise building (MRB)**	**High-rise building (HRB)**
C_{deg} value		16.39	10.65	10.56
Contamination degree		Considerable	Considerable	Considerable

Cd and Cu were also prevalent across all building categories in this study.

Table 6 also presents the C_{deg} calculated for each building category. The results indicated that the C_{deg} was significantly higher in LRB (16.39), followed by MRB (10.65) and HRB (10.56). These C_{deg} values demonstrated a significant level of contamination ($10 \leq C_{deg} < 20$) in rooftop dust fall across all the building types examined in this study. The findings of this study align with previous reports on surface soils (Niraula et al., 2022) and dust samples from various land uses in the Kathmandu district (Shakya et al., 2019). Liu et al. (2011) identified Cr, Ni, Cd, Pb, As, and Cu as anthropogenic and geogenic elements in surface soils, emphasizing that their distribution patterns were generally invariant. Prolonged exposure to the dusty environment in the community may result in negative health impacts, particularly for children, pregnant women, and vulnerable elderly individuals (Du et al., 2013).

Pollution load index (PLI)

The pollution load index (*PLI*) represents the combined pollution effect on soil from various heavy metals. Figure 4 illustrates the estimated *PLI* values for rooftop dust deposition across three categories of buildings in this study.

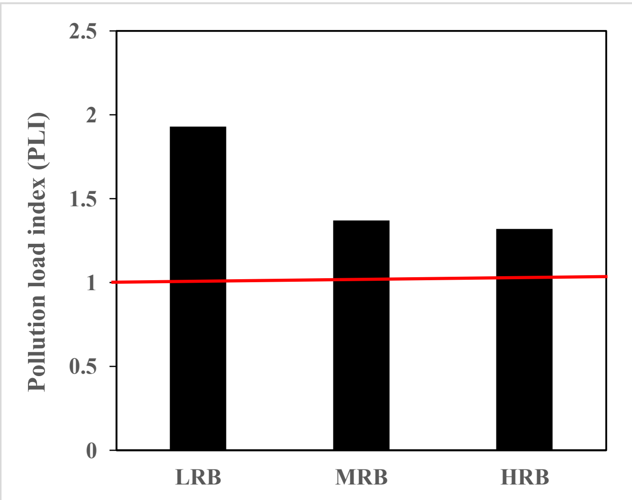

Figure 4: Pollution load index (*PLI*) for heavy metals in rooftop dust deposition on different building types.

Results revealed that the *PLI* values for the buildings were in the order of LRB (1.93) > MRB (1.37) > HRB (1.32). Since the *PLI* values exceeded the suggested threshold of 1.0, rooftop dust from all studied building categories was found to be polluted. The elevated *PLI* value could be attributed to the cumulative accumulation of heavy metals in rooftop dust, indicating an alarming condition in the study area with increased pollution levels. The higher *PLI* value in low-rise buildings (LRB) is mainly due to their proximity to direct emission sources such as traffic, road dust, and ground-level industrial activities, which contribute to greater deposition of heavy metals. In contrast, MRB and HRB are more affected by atmospheric transport of fine particles that are more widely dispersed and uniformly deposited at higher elevations. As a result, MRB and HRB show comparable *PLI* values, but generally lower than LRB due to their distance from ground-level sources. This pattern reflects typical heavy metal deposition mechanisms, where coarse particles settle rapidly near sources and fine particles are carried upward by wind and urban turbulence (Li et al., 2020; Wei & Yang, 2010). The results of this study are consistent with those of Roy et al. (2019), which similarly showed a high pollution load in the road dust of Delhi, India, as indicated by elevated *PLI* values. Additionally, the results of this study also align with Niraula et al. (2022), who reported elevated *PLI* values across various land uses in urban soils of Kathmandu, indicating the progressive soil deterioration from metal contamination.

Geo-accumulation index (I_{geo})

The geo-accumulation index (I_{geo}) serves as a pollution indicator to assess the level and extent of anthropogenic contaminant deposition in surface soil (Barbieri, 2016). This index is calculated by normalizing a metal's concentration in the topsoil against the background concentration of the same element. The results indicated that the I_{geo} values varied among the selected HMs and building types (table 7).

The I_{geo} helps quantify and compare pollution levels of heavy metals on the rooftops of different building types in Kathmandu. Higher I_{geo} values on low-rise buildings, for instance, indicate a stronger influence from nearby ground-level pollution sources, while similar or lower I_{geo} values on high-rise buildings

Table 7: Geo-accumulation index (I-geo) for heavy metals in rooftop dust deposition on different building types.

Heavy metal	I_{geo} index	Low-rise building (LRB)	Medium-rise building (MRB)	High-rise building (HRB)
Cd	I_{geo} value	0.56	0.42	0.31
	Pollution degree	1	1	1
	Pollution level	Unpolluted to moderately polluted	Unpolluted to moderately polluted	Unpolluted to moderately polluted
Cr	I_{geo} value	0.22	0.11	0.13
	Pollution degree	1	1	1
	Pollution level	Unpolluted to moderately polluted	Unpolluted to moderately polluted	Unpolluted to moderately polluted
Cu	I_{geo} value	0.52	0.35	0.27
	Pollution degree	1	1	1
	Pollution level	Unpolluted to moderately polluted	Unpolluted to moderately polluted	Unpolluted to moderately polluted
Ni	I_{geo} value	0.28	0.17	0.13
	Pollution degree	1	1	1
	Pollution level	Unpolluted to moderately polluted	Unpolluted to moderately polluted	Unpolluted to moderately polluted
Pb	I_{geo} value	0.67	0.47	0.55
	Pollution degree	1	1	1
	Pollution level	Unpolluted to moderately polluted	Unpolluted to moderately polluted	Unpolluted to moderately polluted
Zn	I_{geo} value	1.03	0.61	0.71
	Pollution degree	2	1	1
	Pollution level	Moderately polluted	Unpolluted to moderately polluted	Unpolluted to moderately polluted

may suggest reduced deposition or finer particle transport (Turekian & Wedepohl, 1961; Wei & Yang, 2010). In this study, the sum of all six I_{geo} values indicated that the levels of metal pollution in the dust falling on the buildings were in the descending order of LRB (3.28) > MRB (2.13) > HRB (2.10). Among the three building types, the LRB demonstrated comparatively higher I_{geo} values for all the examined heavy metals, in the order of Zn > Pb > Cd > Cu > Ni > Cr. The MRB and HRB exhibited the same sequence of heavy metals according to their I_{geo} values. Nevertheless, the I_{geo} values showed that all three building types, except for the LRB regarding Zn, remained within the unpolluted to moderately polluted range, indicating a first degree of pollution. The LRB was moderately polluted with Zn, showing a second degree of pollution. In this study, Zn demonstrated higher I_{geo} values across all building types, consistent with the findings of Song et al. (2022), which indicated elevated I_{geo} values for Zn in rooftop dust on buildings of various heights in China. Hence, the present study suggests that Zn is the primary contaminant in rooftop dust in the Kathmandu metropolitan area. Conversely, the I_{geo} index showed that Cd pollution was highest in atmospheric deposition in central urban areas of Chongqing, Southwestern China, as demonstrated in the study conducted by Zhang et al. (2020).

Conclusion

This study investigated the concentration and ecological risks of six heavy metals (Cd, Cr, Cu, Ni, Pb, and Zn) in rooftop dust collected from low, medium, and high-rise concrete buildings in the Kathmandu metropolitan area. The findings indicate that building height significantly influences the deposition of heavy metals, with low-rise buildings showing substantially higher metal concentrations and pollution indices compared to medium and high-rise structures. This trend likely results from their closer proximity to ground-level emission sources, such as traffic, resuspended road dust, and local industrial activities, leading to greater contamination of rooftop dust in low-rise buildings. Among all the metals analyzed, Zn and Cu were consistently dominant, suggesting a strong association with anthropogenic activities like vehicle wear (brake and tire dust), construction, and metal processing. The Pollution Load Index (*PLI*), Contamination Factor (C_f), and Degree of Contamination (C_{deg}) confirmed that rooftop dust, particularly on low-rise buildings, is moderately to considerably polluted, posing potential environmental and public health concerns. Furthermore, the Geo-accumulation Index (I_{geo}) revealed unpolluted to moderately polluted conditions for most metals while highlighting moderately polluted levels of Zn in low-rise buildings, reflecting elevated urban metal loads. The strong correlation between Cr and Ni also indicates a common source, likely related to combustion or industrial emissions.

Overall, this research highlights the importance of urban form and building typology in influencing the distribution of heavy metals in atmospheric dust deposition. Given the potential for human exposure to toxic metals through inhalation, ingestion, or dermal contact with rooftop dust, particularly fine particles, regular monitoring and pollution source identification are essential. The findings provide a valuable baseline for policymakers and urban environmental planners aiming to manage air quality and reduce heavy metal pollution in urban areas. Future research should concentrate on assessing the non-carcinogenic and carcinogenic health risks associated with metal-contaminated rooftop dust, as well as identifying specific point and non-point sources that contribute to heavy metal enrichment in the Kathmandu Valley.

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