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Evaluation of the Quality and Suitability of Roof-Harvested Rainwater for Domestic Use in Benin City, Nigeria

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Abstract: Rainwater harvesting (RWH) is increasingly adopted in certain parts of Nigeria as a supplementary domestic water source due to declining access to safe groundwater and surface water. However, the safety of harvested rainwater is strongly influenced by roofing materials, which may leach contaminants or alter water chemistry. Rainwater was harvested between the months of May-July 2025, from three roof types (asbestos, zinc, and aluminum) and roofless (control) in Benin City, Nigeria. Samples were analysed for physicochemical parameters, including pH, acidity, alkalinity, bicarbonate, sulfate, calcium, magnesium, potassium, sodium, iron, lead, chromium, total dissolved solids (TDS), and electrical conductivity (EC) using standard methods. Heavy metals were analysed using Flame Atomic Absorption Spectrophotometry. Data were compared against WHO drinking-water standards, since there is no standard for rainwater quality. Iron was the most abundant metal, with the highest concentration observed in zinc roofs (0.065 mg/L), followed by asbestos roofs (0.048 mg/L). Lead was detected only in zinc and asbestos roofs (0.005 mg/L), below the WHO's permissible limit (0.01 mg/L). Chromium was present in zinc (0.02 mg/L) and aluminum (0.0165) roof types. Other findings were pH (5.7-7.55), EC (8-90 µS/cm), and TDS (4-45 mg/L). The mineral contents were very low with sulfate (0.06-0.151), calcium (0.32-5.932), magnesium (0.389-1.264), potassium (0.2905-0.7085), and sodium (0.465-0.9725). All samples showed low mineral contents, which can increase water corrosivity and increase the leaching of heavy metals from the roof. The type of Roof can influence the quality of rainwater, although most parameters fell within WHO limits, detectable lead levels, and extremely soft water present potential health risks.

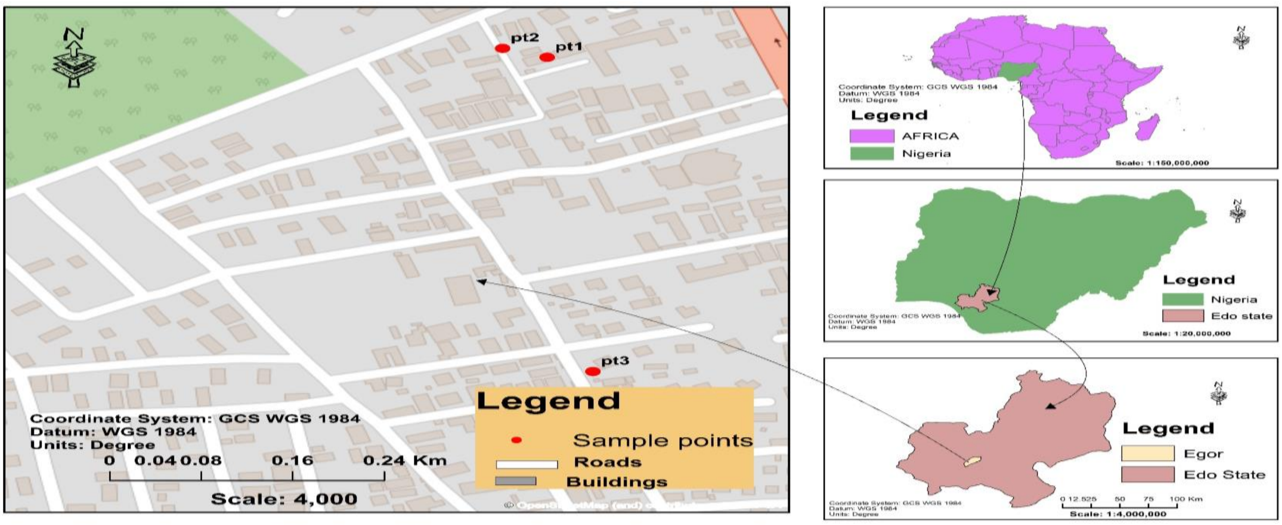
1. Introduction

The importance of the essential natural resource, water, cannot be overemphasized. It is necessary for the sustenance of existence. It is vital to humans, animals, and plants directly or indirectly (Tobin *et al*., 2013). It is found in rivers, oceans, glaciers, and groundwater. It can also come as precipitation (rainwater). A means through which it is renewed is the hydrological cycle. Its readiness for human use is increasingly threatened by drivers such as climate change, rapid urbanization, industrialization, and poor resource management (UN, 2023). Globally, water scarcity is projected to intensify with climate shifts. An estimated 5 - 20% of the global population will live in areas affected by severe water shortages if global temperatures continue to rise (Koop Van Leeuwen, 2016). This can have a significant impact on agriculture, health, and socioeconomic stability, particularly in low- and middle-income countries with inadequate infrastructure, such as Nigeria (USGCRP, 2012). As of 2023–2024, approximately 80% of Nigerians have access to water services, yet only 29% have access to safely managed water, highlighting a stark contrast between quantity and quality (UNICEF, 2021). Benin City is the capital of Edo State in Nigeria, with a rapidly urbanizing, densely populated city, facing high levels of urban poverty. Residents source water from private boreholes and harvested rainwater, with the latter being the most economical and easiest technically (Livhuwani *et al*., 2025). Rainwater harvesting (RWH) involves the collection and storage of rainwater for immediate and future use, including domestic, agricultural, and industrial purposes (Tobin *et al*., 2013; Lepcha *et al*., 2024). This technology has three stages: catchment areas (rooftops and land surfaces), conveyance systems (plastic or corrugated iron gutters), and collection devices (storage tanks) (Tobin *et al*., 2013). The most common technique in Benin City, Nigeria, is small-scale rooftop rainwater harvesting. The quality of rainwater is directly connected to the cleanliness of the atmosphere and the materials of the rooftop from which the water was harvested (Tobin *et al*., 2013). Modern rooftops, especially those constructed with heavy metals or synthetic materials, can leach harmful constituents into the water (Ojo, 2019), particularly during initial runoff, a phenomenon known as the "first-flush effect" (Maykot *et al*., 2025). The presence of heavy metals such as lead (Pb), iron (Fe), chromium (Cr), and zinc (Zn) has been previously detected in harvested rainwater, particularly in samples collected from galvanized metal and asbestos roofs (Malassa *et al*., 2014; Anabtawi *et al*, 2022). One route by which heavy metals enter the human body is ingestion of contaminated water and food. Contaminated harvested rainwater used for domestic and agricultural purposes can introduce metal contaminants to the human body. Heavy metals such as lead and chromium can cause neurological, hematological, renal, and reproductive problems (Wani *et al*., 2015; Hossini *et al*., 2022; Errich *et al*., 2024). Additionally, iron and zinc, although needed by the body in small quantities, can cause health challenges. With this understanding, there is an urgent need to assess rainwater quality on a localized, case-by-case basis, especially in urban centers such as Benin City, where a variety of roofing materials that can leach heavy metals are in use. In this study, the physicochemical quality and metal concentrations of roof-harvested rainwater in Benin City were evaluated, and its suitability for use was determined.

2. Methodology

2.1 Study Area

The study was conducted in an urban location in the Egor Local Government Area, Benin City, Nigeria (06° 24' 18.86" N, 05° 36' 20.808" E), at an elevation of 122 meters above sea level.



2.2 Sample Collection

Rainwater was collected from aluminum, zinc, and asbestos roofs and directly from the sky (roofless/control). Aluminum, zinc, and asbestos were chosen because they are the common roofing types in Benin City and because they are the sample locations. The samples were harvested for three months, May–July 2025, using precleaned polyethylene containers placed 2 m above the ground to avoid splash contamination. After collection, the samples were stored at 4°C before analysis.

2.3 Analytical Procedures

The parameters analysed included pH, acidity, alkalinity, bicarbonate, sulfate, calcium, magnesium, potassium, sodium, iron, lead, chromium, TDS, and EC, following standard procedures. Heavy metals were measured using atomic absorption spectrometry (AAS) (El Hammari *et al.*, 2022).

2.4 Statistical Analysis

Parameter data were analysed using descriptive (mean, standard deviation) and inferential tests (one-way ANOVA) to compare differences across roof types. Significant differences were defined as those for which p was <0.05. When a significant difference was detected, Tukey's honestly significant difference (HSD) post hoc test was conducted. These were achieved using Microsoft Excel 10.0 software.

3. Results and Discussion

3.1 Physicochemical Properties

The pH levels of the harvested rainwater (RWH) collected from three different roof types (aluminum roof, asbestos roof, and zinc roof) and the control (roofless) are shown in **Figure 1**. The roofless rainwater (control) had the lowest pH, at 5.7. The acidity increases as the pH decreases. Aerodynamic pollutants such as oxides of carbon, sulfur, and nitrates found in the atmosphere can react with water vapour to form a weak acid, a phenomenon called 'acid rain'. The study location is characterized by commercial and industrial activities largely driven by the presence of a nearby tertiary institution. Institutional minority population influx, small-scale enterprises, transportation services, printing services, and other ancillary operations may contribute to increased aerodynamic pollutants. Similar studies on harvested rainwater conducted in the eastern part of Nigeria recorded acidic pH values of 5.46–5.98 (Chukwuma *et al*., 2013). The slight increase in pH recorded on the aluminum and zinc roofs is attributed to the mild leaching of metal ions that may displace hydrogen from the reaction and, as such, reduce acidity (Mathews *et al*., 2019). The highest pH (7.5) was recorded in the asbestos roof, an alkaline runoff. The asbestos production material contains cement, which can release calcium and hydroxide ions. Calcium, an electropositive alkaline earth metal, displaces hydrogen to form salts and hydroxide ions, changing rainwater to slightly alkaline (Ojo, 2019; WHO, 2017). The ideal pH range for drinking water, according to WHO guidelines, is between 6.5 and 8.5 (**Table 1**). All roof types except the roofless option fall within this range. A study conducted in South–South Nigerian River states reported similar findings for pH values within the WHO guidelines (Nicholas and Ukoha, 2024). Notably, harvested rainwater with an acidic pH value needs treatment before it can be used for domestic purposes (Maykot *et al*., 2025). Acidic rainwater can corrode pipes and cause damage to plants (Joseph *et al*., 2021; Prakach *et al*., 2023; Ikumapayi *et al.*, 2025).

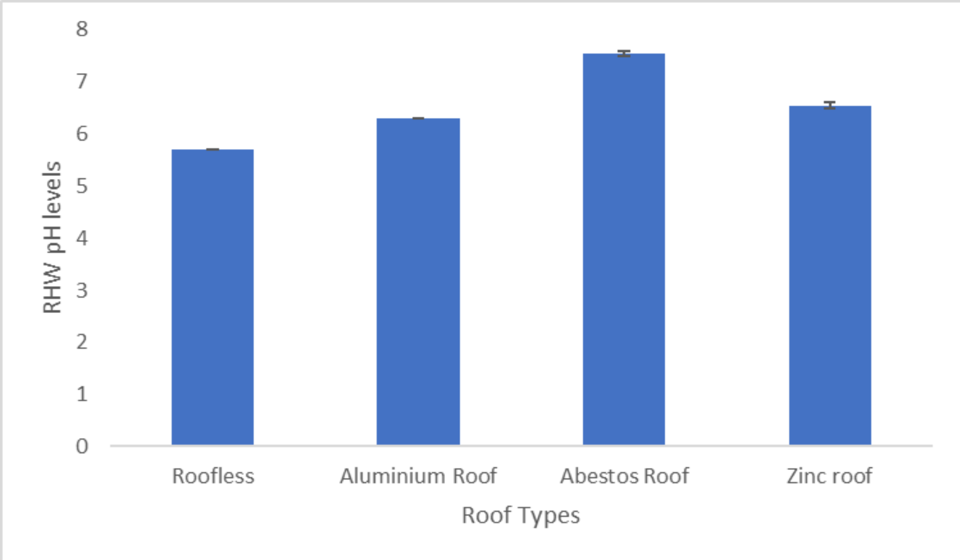


Figure 1. pH of rain-harvested water from different roof types

Table 1. Comparison of the sampled parameters of the different roof types with those of the WHO guidelines

Parameters	Roofless	Aluminum	Asbestos Roof	Zinc roof	WHO Guidelines
Acidity	3±0.01	3±0.11	4.5±1.01	4.5±0.91	6.5-8.5
Alkalinity	5.34±0.11	5.34±0.91	19.825±1.27	9.15±1.84	100
Bicarbonate	4.375±1.24	4.375±1.22	16.25±2.04	7.5±1.99	50-300
Sulfate	0.0905±0.48	0.06±0.31	0.121±0.24	0.151±0.11	250
Calcium	0.32±0.87	0.64±0.27	5.932±0.01	1.283±1.01	-
Magnesium	0.389±1.44	0.389±0.87	1.264±0.31	0.389±0.02	50
Potassium	0.2905±0.87	0.3805±1.07	0.7085±0.15	0.456±0.02	1-2
Sodium	0.465±1.04	0.4975±1.49	0.9725±1.27	0.611±1.49	200
Ph	5.7±0.30	6.3±0.28	7.55±1.02	6.55±0.31	6.5-8.5
TDS (mg/l)	8±1.02	4±0.02	45±2.98	14±0.09	250
EC (µS/cm)	16±3.61	8±2.32	90±4.12	28±3.22	1200
Iron(mg/l)	0.0235±0.04	0.031±0.01	0.045±0.02	0.0595±0.30	0.3
Lead(mg/l)	0	0	0.005±0.00	0.005±0.00	0.01
Chromium(mg/l)	0	0.0165±0.00	0	0.02±0.00	0.05

The acidity, alkalinity, and bicarbonate concentrations across the different roof types and the control are shown in **Figure 2**. Alkalinity was substantially higher in water harvested from asbestos roofs (20 mg/L), followed closely by that in water harvested from bicarbonate roofs (17 mg/L), suggesting a strong buffering capacity. This aligns with the elevated calcium levels and supports the notion that carbonate and hydroxide ions are released from asbestos materials (Macher, 2025). The control and aluminium roofs presented lower but more balanced levels of acidity and alkalinity, indicating a more neutral rainwater profile. Zinc roofs showed moderate alkalinity and bicarbonate values, potentially because of mild buffering effects from zinc oxide or related compounds. The results indicate that asbestos roofs significantly modify the chemical composition of rainwater, introducing both beneficial (alkalinity and calcium) and concerning (mineral load and possible contaminants) attributes. Moreover, roofless rainwater, despite being low in minerals and alkalinity, may exhibit greater acidity, as indicated by the pH level. Although there are typically no regulated guidelines on toxicological grounds by the World Health Organization (WHO) on alkalinity, acidity, and bicarbonate. However, the evaluation of these parameters is essential for determining the chemical stability, corrosion potential, and general suitability for domestic use.

The electrical conductivity (EC) and total dissolved solids (TDS) levels of rainwater harvested from the different roof types were directly proportional (**Figure 3**). The highest values for both the EC (90 µS/cm) and TDS (45 ppb) were recorded for the asbestos roof, indicating significant mineral leaching and ion dissolution from the roofing material. Asbestos has been reported to increase dissolved solids by releasing calcium, magnesium, and other ions from production materials (Abdulkareem *et al*., 2015). The zinc roof, on the other hand, demonstrated moderate EC and TDS levels, reflecting interactions between zinc oxide or other metallic compounds and rainwater. The control and aluminum roofs had the lowest EC and TDS values, consistent with minimal contact with leachable materials and lower contamination. Since EC is a proxy for ion concentration and TDS represents the total concentration of dissolved substances, the high values in asbestos and zinc roofs suggest lower suitability for direct domestic use without treatment, especially when coupled with the presence of heavy metals.

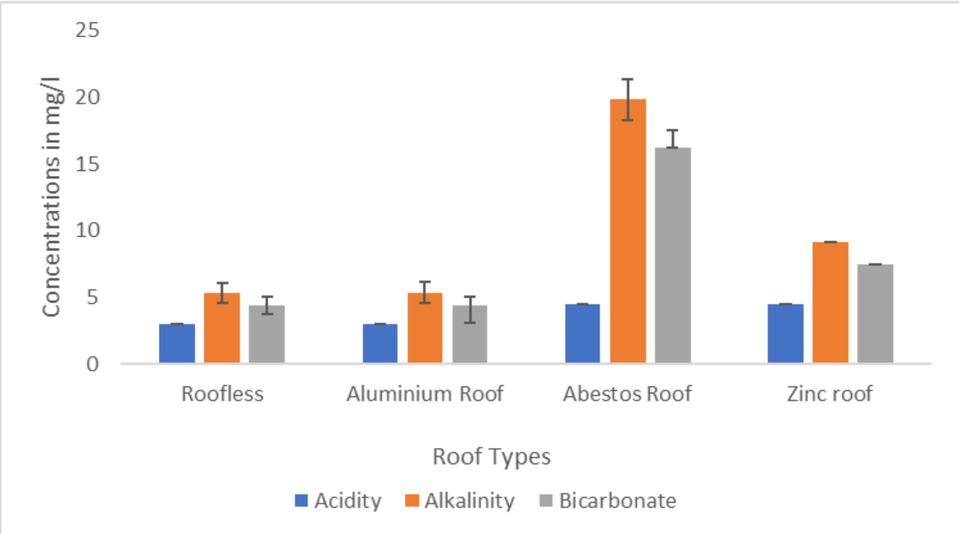


Figure 2. Concentration levels of the physicochemical properties of the rainwater.

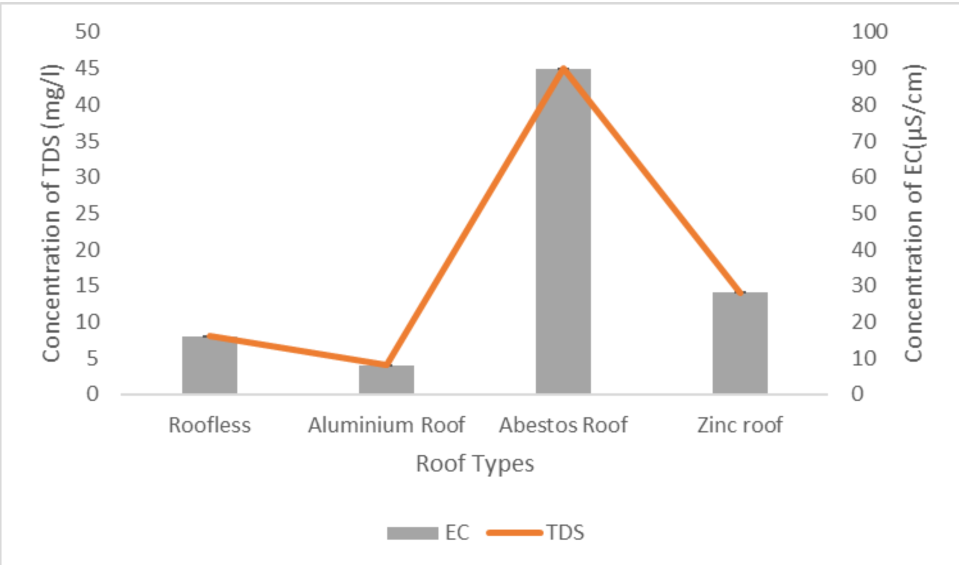


Figure 3. Concentration of TDS and EC of the rain-harvested water.

3.2 Mineral Content

Zinc roofs yielded high concentrations of sulfate (0.15 mg/L), iron (0.059 mg/L), and chromium (0.02 mg/L). Asbestos roofs presented elevated levels of calcium (5.932 mg/L), magnesium (1.264 mg/L), potassium (0.709 mg/L), and sodium (0.973 mg/L). The control had the lowest mineral concentrations. The concentrations of mineral ions (sulfate, calcium, magnesium, potassium, and sodium) in the collected rainwater are shown in Figure 4. The abundant calcium in the asbestos roof rainwater results from the leaching of the cementitious matrix of asbestos roofing, which has been noted in previous studies (Macher, 2025). Magnesium (1.264) and sodium (0.9725) levels were also highest under asbestos roofs, albeit to a lesser extent, suggesting broader mineral leaching. Zinc and aluminium roofs exhibited moderate levels of mineral content, with relatively balanced concentrations of sulfate, calcium, and sodium. The roofless collection yielded the lowest mineral concentrations across all the parameters, reflecting the chemical profile of direct rainwater, which is minimally influenced by surface interactions but may still contain atmospheric inputs (Mekonnen and Hoekstra, 2016; Omokpariola *et al*., 2024). The findings show that roofing materials significantly influence the chemical quality of harvested rainwater, with potential implications for human consumption, irrigation, and long-term infrastructure use.

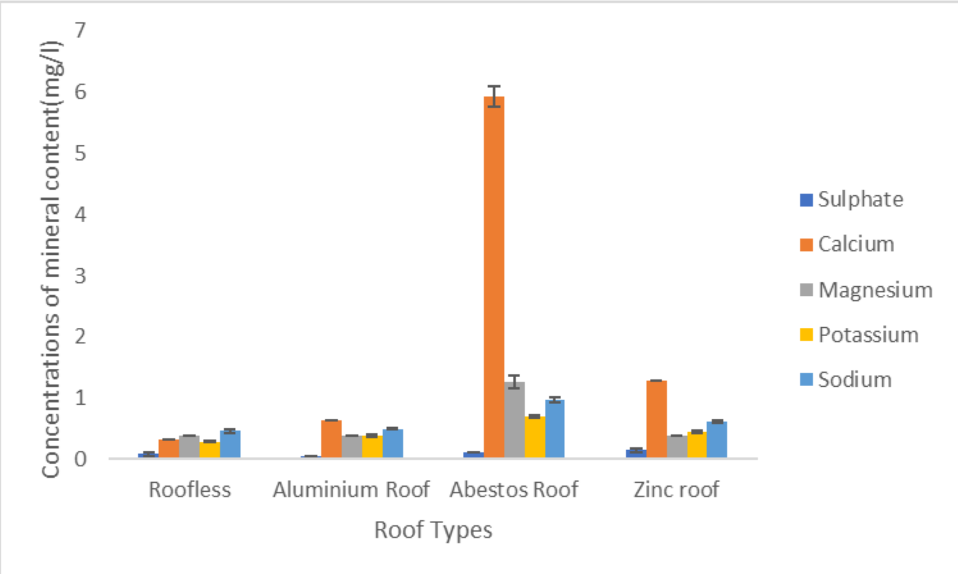


Figure 4. Concentrations of the mineral contents of the harvested rainwater.

3.3 Heavy metals

The concentrations of Fe, Pb, and Cr in the harvested rainwater varied notably with roof type (Figure 5). Iron (Fe) was the most abundant heavy metal detected across all the samples, with concentrations ranging from 0.025 mg/L (control) to 0.065 mg/L (zinc roof). Although Fe is not generally considered toxic at concentrations found in drinking water, elevated concentrations can cause undesirable taste, staining, and promote microbial growth in the water, especially during storage. The World Health Organization (WHO) has set a guideline value of 0.3 mg/L for Fe on the basis primarily of acceptability rather than health concerns (WHO, 2017). The values observed in this study were well below this limit, but the consistently higher Fe concentrations in zinc and asbestos roofs suggest contributions from roofing corrosion and the leaching of Fe-rich substrates, which is in line with the findings of previous studies linking metal roofing to increased Fe contamination in harvested rainwater (Lye, 2009). Lead (Pb) was detected only in the zinc (0.005 mg/L) and asbestos (0.005 mg/L) roofs and was absent in the control and aluminium roof samples. This suggests the leaching of Pb from the manufacturing materials of zinc and asbestos. The presence of Pb, even at low concentrations, is a concern because of its cumulative toxicity potential. The WHO guideline value for Pb in drinking water is 0.01 mg/L, a threshold derived from evidence linking chronic exposure to neurological impairment, particularly in children (WHO, 2017). Possible sources include Pb-based roofing paints, degradation of coatings, or atmospheric deposition from industrial and vehicular emissions, which is consistent with findings in urban rainwater studies (Nnaji, 2013). Chromium (Cr) was detected in all roof types, with the highest level observed for zinc (0.02 mg/L). The WHO guideline value for total Cr is 0.05 mg/L (WHO, 2017), meaning that the concentrations measured in this study were below the permissible limit. However, it is important to note that the guidelines are based on total Cr, without distinguishing between Cr(III), which is an essential micronutrient, and the more toxic and carcinogenic form of Cr(VI) (WHO, 2017). The detection of Cr across roof types suggests possible leaching from paints, coatings, or deposition of industrial atmospheric particles, in agreement with prior studies (Nnaji, 2013).

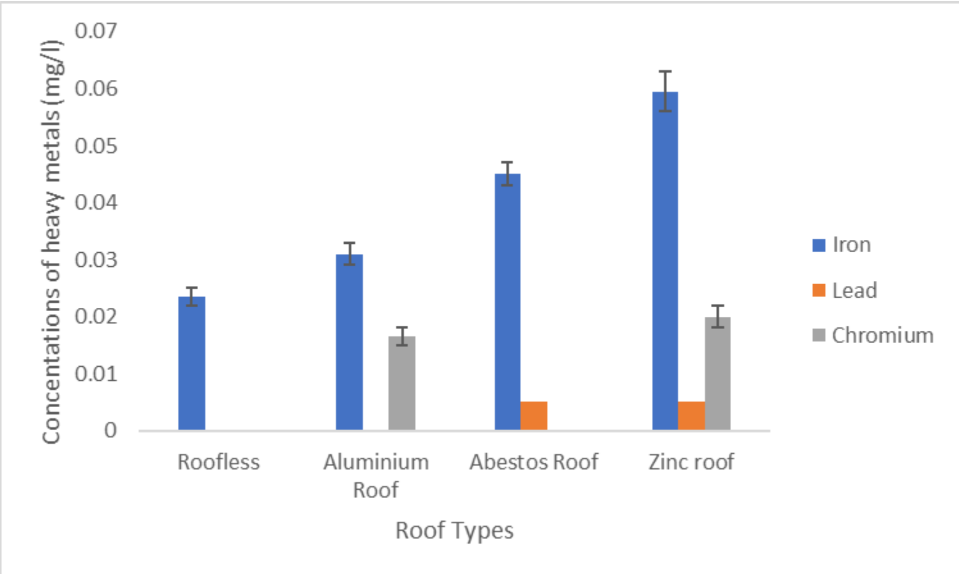


Figure 5. Concentrations of heavy metals in the rainwater harvested

The amounts of dissolved solids and contaminants in the rainwater samples harvested from all roof types were extremely low, and the samples generally met the WHO drinking-water criteria (Table 1). The total dissolved solids (TDS) concentration ranged from only 4–45 mg/L, far below the WHO palatability threshold of 250 mg/L. Similarly, the calcium and magnesium concentrations were near zero, while the alkalinity ranged from 5.34–19.825 mg/L. Bicarbonate concentrations, on the other hand, ranged between 4.375 and 16.25 mg/L. This is typical of rainwater: the WHO notes that collected rainwater is "soft and usually slightly acidic**.**" Soft water has low scaling potential but can be aggressive to pipes, requiring stabilization (e.g., adding calcium carbonate). pH (acid–base): The values ranged between 5.7 and 7.55. The WHO recommends 6.5–8.5% for drinking water. The control sample's pH was 5.7, and the aluminium roof's pH was 6.3, which was slightly less than 6.5, whereas the asbestos and zinc roofs gave 7.55 and 6.55 (within range), respectively. This pattern reflects natural rain acidity. Pure rain is slightly acidic (pH =5.6–5.7) because of dissolved CO_2, so the control collection is exactly as expected. In contrast, cementitious surfaces (as in asbestos-cement roofing) can buffer the rain and increase the soil pH, which explains the higher alkalinity (20 mg/L) and pH under the asbestos roof. In general, pH alone is not a direct health hazard, but low-pH water can corrode plastic, mobilize heavy metals, and affect taste. The WHO explicitly notes that water with a pH below 6.5 can increase corrosivity; thus, slight adjustments (e.g., neutralizing filters or concrete tanks) are often used in rainwater systems to stabilize the pH. All measured ions (Na, K, Ca, Mg, and SO_4) were trace (<1–6 mg/L) and well within the WHO limits. The sulfate concentration ranged from 0.06–0.15 mg/L (guideline 250), the sodium concentration ranged from 0.46–0.97 mg/L (<200), the potassium concentration ranged from 0.29–0.71 mg/L (<1-2), and the magnesium concentration ranged from 0.389–1.26 mg/L (<50). The calcium concentration ranged from 0.32–5.93 mg/L (no WHO limit). The notably higher concentrations of Ca (6 mg/L) and Mg (1.26 mg/L) under the asbestos roof again reflect the alkaline cement matrix of that roof type. Overall, hardness (as Ca/Mg) is negligible; the WHO treats hardness as a non-health parameter. Such a low mineral content means that the water supplies little dietary calcium/magnesium, but it also means no scaling (which is consistent with the WHO's description of rainwater as soft). EC followed TDS, with the highest (90 µS/cm) under the asbestos roof and the lowest (4–8) under the control/aluminum roof. All are extremely low. The WHO confirms that water with a TDS concentration <1000 mg/L is usually acceptable. Such a low TDS means that the water is essentially "ultrapure" (and can taste flat), but it also has high aggressiveness unless it is stabilized. Iron, lead, and chromium were detected only at trace levels. Iron concentrations ranged from 0.023–0.059 mg/L (0.3 mg/L), lead concentrations ranged from 0–0.005 mg/L (0.01), and chromium concentrations ranged from 0–0.02 mg/L (0.05 mg/L). All are well below the WHO limits. Even the highest values (0.059 Fe and 0.02 Cr) are an order of magnitude below their limits, and lead (0.005) is one-tenth of 0.05. Such low levels are typical of properly maintained rainwater systems. For example, Anabtawi *et al.* (2022) reported that rainwater samples with occasional guideline exceedances still yielded health risk indices *with HRIs* < 1 (no significant risk). (Zhu *et al*., 2024). The minor differences in metal concentrations reflect the use of roof material: compared with roofs with no roof, zinc and asbestos roofs yield slightly higher Fe/Cr (and trace Pb) ratios. This aligns with known sources of contaminants: degraded roofing can leach heavy metals into runoff (Macher, 2025; Mishra, 2023). For instance, galvanized zinc sheets can impart Zn (and associated Cr/Fe from coatings), and asbestos roofs contain metal additives or particles. Studies report that aging roofs can release Pb, Cr, Ni, and Cd into rainwater (Macher *et al*., 2025). In any case, all measured heavy metals are so low that domestic use poses negligible direct health risk. Nonetheless, any detectable lead or chromium can lead to long-term accumulation (Anabtawi *et al*., 2022; Nnaji, 2013). From a human-health perspective, harvested rainwater is generally chemically safe. All the ion concentrations and heavy metal concentrations were far below the WHO limits; thus, routine consumption would not directly cause toxicity. The only potential concern is the slightly low pH in some samples, which itself is not a health hazard (e.g., many foods/drinks have lower pH values than rainwater) but can lead to indirect effects (WHO, 2007; TWDB, 2025). The very low mineral content also has health ramifications. While soft water is good for reducing scale, its low calcium and magnesium mean that it contributes little to the dietary intake of these nutrients. In communities that rely solely on rainwater, dietary supplementation or remineralization (e.g., adding calcium carbonate) may be needed to ensure adequate nutrition and to stabilize the water. Although our results from the asbestos roof show that its rainwater is chemically acceptable, asbestos roofs pose unique long-term risks. Asbestos fibres themselves can erode into water; the health effects of ingesting asbestos are less studied than those of inhalation, but any form of exposure is of concern (Macher *et al*., 2025). However, including microbial contamination is beyond the scope of this study. Future research should consider microbial contamination in harvested rainwater since hard and soft water can promote microbial survival and proliferation. Roof runoff is a pathway through which roof-bound pollutants (dust, bird droppings, and vehicle exhaust) reach soil and groundwater. Although our samples contain low amounts of contaminants, the long-term use of heavy metal-coated roofs can gradually increase local metal loads. For example, zinc and lead from roofs can accumulate in soil, potentially harming soil microbes and plants (Zhu *et al*., 2004).

Conclusion

The roof-harvested rainwater was generally within the WHO limits for domestic water quality but showed variation in chemical composition based on roofing material. Asbestos roofs, while they are beneficial for buffering pH and having the highest mineral content, appear to significantly increase TDS, EC, and heavy metal levels, which can compromise water quality. Zinc Roofs similarly show elevated iron, chromium, and lead levels, suggesting metal leaching concerns. The aluminum roof and control yielded lower contaminant loads. While beyond the scope of this study, microorganisms can also decrease the quality of harvested rainwater. Harvested rainwater is environmentally beneficial because it reduces the demand for surface or groundwater resources. However, regular monitoring is essential for determining the safety of water for domestic purposes.

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Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

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