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**Physicochemical quality and metal contamination of boiled water consumed in the
panda neighborhood of Likasi (Haut-Katanga), DRC**

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ABSTRACT

Introduction: In mining regions, chemical contamination of water resources poses a significant public health issue. This study aimed to characterize the physicochemical quality and metal contamination of boiled water consumed in the Panda neighborhood of Likasi, Democratic Republic of the Congo.

Methods: An observational, descriptive, cross-sectional, and analytical study was conducted on 40 boiled water samples, distributed equally among four supply sources: three wells and the REGIDESO municipal network. Physicochemical parameters and concentrations of Cu, Co, Fe, Mn, Cd, Zn, Ni, and Pb were determined. Distributions were assessed using the Shapiro–Wilk test. Differences between sources were analyzed using the Kruskal–Wallis test, supplemented where necessary by Dunn’s post hoc test with Bonferroni correction.

Results: The mean pH was 7.48 ± 0.43 . Significant differences between sources were observed for Co ($p = 0.013$), Fe ($p < 0.001$), Mn ($p = 0.030$), Ca ($p = 0.031$), Mg ($p = 0.004$), Zn ($p = 0.010$), SO_4^{2-} ($p = 0.027$), and Cl^- ($p = 0.001$). Mean concentrations for Pb and Cd were 0.014 ± 0.007 mg/L and 0.014 ± 0.018 mg/L, respectively. Guideline values were exceeded in 57.5% of samples for Pb and 90.0% for Cd.

Conclusion: Despite generally satisfactory quality regarding several parameters, the high frequency of guideline exceedances for Pb and Cd is a major cause for concern. Enhanced monitoring and investigations into contamination sources are required.

Keywords: Boiled water; Boiling; Physicochemical quality, Heavy metals; Lead; Cadmium; Drinking water; Likasi; Democratic Republic of the Congo.

1. Introduction

Water is an essential resource for life, health, and socio-economic development. It is used for human consumption, food preparation, hygiene, and numerous domestic activities. However, access to a water source does not necessarily guarantee its potability. Water quality depends on microbiological, physicochemical, and organoleptic characteristics, the variations of which can compromise consumer health (Van Leeuwen, 2000 ; Khan et al., 2016). According to the World Health Organization (WHO) and UNICEF, water intended for human consumption must, among other things, be free from fecal contamination and contain chemical substances at concentrations that do not exceed recommended limits (Delahoy et al., 2022).

Water resource quality is influenced by both natural and anthropogenic factors. Geochemical processes, rock weathering, and mineral dissolution can facilitate the mobilization of certain chemical elements, while agricultural, industrial, mining, and urban activities can introduce various contaminants into aquatic environments.

Groundwater, widely used for public water supply, is particularly vulnerable to contamination from the soil, human activities, and recharge zones. Distribution networks and household plumbing systems can also contribute to water quality degradation, notably through corrosion or the leaching of substances from materials in contact with the water (Fahes et al., 2025).

Chemical contaminants of concern include trace metal elements such as lead, cadmium, arsenic, mercury, copper, and cobalt. Their presence in water can result from natural processes or anthropogenic activities, particularly in regions characterized by intensive mining. Repeated or prolonged exposure to some of these elements can lead to adverse effects on various biological systems, including the neurological, renal, and cardiovascular systems (Hossain et al., 2025; Admasu et al., 2026). Monitoring their concentrations in drinking water is therefore a crucial measure for preventing health risks.

In sub-Saharan Africa, water quality remains a major concern due to rapid urbanization, inadequate drinking water supply infrastructure, and frequent reliance on alternative sources such as wells and boreholes. Mining and agricultural activities can also exacerbate the contamination of water resources. In Burkina Faso, seasonal variations in certain metal contaminants, particularly arsenic, have been reported (Sawadogo et al., 2026). Recent studies in Côte d’Ivoire and Ghana have also highlighted the presence of toxic elements in certain water sources and emphasized the importance of appropriate treatment and monitoring prior to consumption (Kamagate et al., 2025; Danso-Boateng et al., 2026; Asare et al., 2026; Sawadogo et al., 2026).

In the Democratic Republic of the Congo (DRC), this issue is of particular importance in provinces with high levels of mining activity, such as Haut-Katanga. Mining and metallurgical operations, industrial and artisanal discharges, ore processing tailings, and runoff can all contribute to the contamination of water resources with various trace metals specifically lead, cadmium, copper, and zinc (Mwanamoki et al., 2015; Atibu et al., 2018). Furthermore, aging or inadequate distribution infrastructure can lead to further deterioration in water quality, notably through pipe corrosion

and the leaching of substances from network materials (Edwards & Dudi, 2004).

Faced with uncertain water quality, households employ various domestic treatment methods, with boiling being a widely accessible practice. It primarily serves to reduce microbial load and limit risks associated with numerous pathogens (Ma et al., 2024). However, unlike microbiological contaminants, dissolved chemical substances are not necessarily removed by heating. Depending on their nature and the treatment conditions, boiling can alter certain physicochemical water parameters and through the evaporation of some of the water lead to increased concentrations of certain non-volatile constituents in the remaining water (Li et al., 2023; Zha et al., 2025). Consequently, boiled water cannot be deemed chemically safe based solely on heat treatment.

In Likasi, a city characterized by significant mining activity, households rely on various water sources, including wells, boreholes, and the public Régideso network. In the Panda neighborhood, some of this water is boiled before consumption. Given the potential influence of mining activities and the diversity of supply sources, this practice raises questions regarding the chemical quality of the water actually consumed by households. Indeed, the potential presence of chemical contaminants in the water prior to treatment and their behavior during boiling remain insufficiently documented in this local context.

2. Methodology

2.1. Research Setting

This study was conducted in the Panda neighborhood of Likasi, in the Haut-Katanga province of the Democratic Republic of the Congo a region characterized by significant mining and metallurgical activities. A total of 40 samples of boiled water were collected from households, comprising 10 samples from each of the four source categories: Well 1, Well 2, Well 3, and REGIDESO. Following collection, identification, and packaging, the samples were transported to the Gécamines/Panda Central Laboratory in Likasi for physicochemical characterization and the determination of metal concentrations.

2.2. Study Subject

The study subjects consisted of households in the Panda neighborhood of Likasi that routinely used boiled water for human consumption. Information was collected from these households regarding, in particular, their water source, boiling methods, and water storage conditions prior to consumption.

2.3. Study Type

We conducted an observational, descriptive, cross-sectional, and analytical study on the quality of boiled water consumed in the Panda neighborhood of Likasi. The descriptive approach enabled the characterization of physicochemical parameters and metal concentrations. The cross-sectional approach assessed water quality during the study period, while the analytical approach compared these parameters across the different water supply sources studied.

2.4. Inclusion and Exclusion Criteria

2.4.1. Inclusion criteria

Households and water samples meeting the following criteria were included in the study:

- Any household residing in the Panda neighborhood of Likasi at the time of data collection;
- Any household that habitually uses boiled water for consumption;
- Voluntary agreement to participate in the study and provision of the required consent;
- Ability to provide reliable information regarding the water supply source, boiling methods, and water storage conditions within the household;
- Availability, at the time of sampling, of water that had actually been boiled within the household and was intended for consumption by household members;

The selected samples were then collected, packaged, labeled, stored, and transported in accordance with the established protocol to preserve their integrity and ensure the reliability of the analytical results.

2.4.2. Exclusion criteria

The following were excluded from the study:

- Households not residing in the Panda neighborhood at the time of data collection;
- Households that do not habitually consume boiled water;
- Households that refused to participate in the study or to provide consent;

- Households for which information regarding the supply source, boiling methods, or water storage conditions was insufficient or unreliable;
- Water samples that had not undergone prior boiling within the household;
- Water samples for which the supply source or origin could not be clearly established.

2.5. Data Collection

Data collection will rely on surveys, direct observation, sample collection, and laboratory analysis. A structured survey questionnaire will be administered in each selected household to gather information regarding the water source, transport and storage methods, boiling duration, type of container used, and storage time after treatment.

In each household, a sample of the boiled water actually intended for consumption will be collected in a suitable, properly labeled container and transported to the laboratory under conditions that preserve its characteristics. Physicochemical parameters prone to rapid change will be measured on-site or immediately after collection whenever possible. Other parameters will be determined in the laboratory using standardized analytical methods.

Metal contamination will be assessed by determining levels of lead, cadmium, copper, cobalt, iron, manganese, zinc, and nickel, specifically using atomic absorption spectrometry. The results obtained will be expressed in mg/L and compared against guideline values applicable to water intended for human consumption.

2.6. Sampling plan and sample size

• Sampling technique

A multi-stage sampling method was employed. First, the primary water sources used by households in the Panda neighborhood were identified and purposively selected; these consisted of three wells and the REGIDESO distribution network. Second, households using these various sources and boiling their water prior to consumption were identified. Households meeting the inclusion criteria were selected until the target sample size per source was reached. To ensure balanced representation across the different sources, ten households were selected for each of the four supply categories.

• Sample size determination

The sample size was determined a priori based on the study's primary analytical objective. The calculation was performed using a statistical power approach applicable to a one-way analysis of variance (ANOVA) involving four independent groups. Assuming a significance level (α) of 5%, a statistical power of 80% ($1-\beta = 0.80$), four groups, and a large Cohen's effect size ($f = 0.50$), the minimum required sample size was estimated at 48 samples.

To ensure balanced allocation across the different supply sources, 10 independent samples of boiled water were collected from each of the four sources, resulting in a total of 40 samples from 40 distinct households.

Households were selected using stratified sampling, with the water supply source serving as the stratification criterion. Within each stratum, eligible households were randomly selected once the sampling frame became available. This strategy ensured representation of the four main supply sources and enabled statistical comparisons between them.

2.7. Laboratory analysis



Figure 1: PinAAcle500 Atomic Absorption Spectrometer N°3180018 /Serial N°: PSPS24031401.

2.7.1. Atomic absorption spectrometry (AAS)

Operating principle:

PinAAcle 500 Atomic Absorption Spectrometer No. 3180018 / Serial No.: PSPS24031401.

Atomic absorption spectrometry relies on photon absorption by atoms in the ground state and is based on the theory of atomic energy quantization. The liquid sample is aspirated through a capillary tube and injected into the nebulizer (nebulization chamber), where it is transformed into an

aerosol (fine droplets). The resulting aerosol enters the burner and then the flame, where it is heated to a temperature of 2000 to 3000 K, breaking down the chemical compounds containing the elements. After traveling a short distance into the flame, the solvent evaporates from the droplet, leaving behind salts or solid particles that are subsequently melted, vaporized, and atomized (Rouessac F. & Rouessac A., 1998).

Since the absorbed photons are characteristic of the absorbing elements, and their quantity is proportional to the number of atoms of the absorbing element according to the Boltzmann distribution law, absorption measurements allow for the determination of element concentrations.

Atomic absorption analysis utilizes the Beer-Lambert law. When multiple elements are to be determined, the procedure is performed for each element in the sample at a specific, fixed wavelength.

- **Characteristics related to atomic absorption**

Instrumentation and analytical parameters:

Analyses were performed using a PinAAcle 500 atomic absorption spectrophotometer (PerkinElmer, USA) equipped with an air/acetylene flame atomizer.

Summary of analytical validation parameters:

Parameter	Lead (Pb)	Cadmium (Cd)
Spectrometer model	Pinaacle AA 500 (PerkinElmer)	
Wavelength (nm)	283.3	228.8
Atomization method	Air/acetylene flame	Air/acetylene flame
Calibration range (mg/L)	0 – 10	0 – 10
Curve R²	0.997	0.996
LOD (mg/L)	0.002	0.001
LOQ (mg/L)	0.006	0.003
Analytical blanks	< LOD	< LOD

Duplicates (%)	10%	10%
Intra-assay CV (%)	3.2	4.1
Recovery rate (%)	98	95
Certified reference material	ERM®-CA011a	ERM®-CA011a

2.7.2. Caution in interpreting lead and cadmium results

- **Quality control of chemical analyses**

To ensure the reliability of analytical results particularly for trace elements present at concentrations close to guideline values (lead and cadmium) a rigorous quality control protocol was implemented, in accordance with the recommendations of the French Standardization Association (AFNOR) and the World Health Organization (WHO).

- **Limits of detection and quantification**

Limits of detection (LOD) and quantification (LOQ) were determined for each element based on the mean of the blanks plus 3 and 10 times the standard deviation, respectively (IUPAC method). The values obtained are as follows:

Limits of detection and quantification and wavelengths:

Element	Wavelength (nm)	Limit of Detection (LOD) (mg/L)	Limit of Quantification (LOQ) (mg/L)
Lead (Pb)	283.3	0.002	0.006
Cadmium (Cd)	228.8	0.001	0.003
Copper (Cu)	324.7	0.003	0.010
Cobalt (Co)	240.7	0.002	0.007
Iron (Fe)	248.3	0.005	0.015
Manganese (Mn)	279.5	0.002	0.005

Zinc (Zn)	213.9	0.001	0.004
Nickel (Ni)	232.0	0.003	0.008

2.7.3. Blank results

Reagent blanks (ultrapure water subjected to the same treatment as the samples) were analyzed alongside each batch of samples (n = 10). Concentrations measured in the blanks were consistently below the limit of detection for all analyzed elements, confirming the absence of significant contamination during the preparation and analysis stages.

2.7.4. Recovery rates and analytical precision

Measurement precision and accuracy were evaluated through recovery tests on samples spiked with known quantities of certified standards (CertiPUR).

Recovery rates and analytical precision for the analyzed elements:

Element	Average recovery rate (%)	Standard deviation (%)	Coefficient of variation (CV, %)	Number of replicates
Pb	98.7	3.2	3.2	6
Cd	97.9	4.1	4.2	6
Cu	101.2	2.8	2.8	6
Co	96.8	3.9	4.0	6
Fe	99.5	3.5	3.5	6
Mn	100.3	2.5	2.5	6
Zn	98.1	3.7	3.8	6
Ni	97.5	4.3	4.4	6

Recovery rates, ranging from 96.8% to 101.2%, fall within generally accepted criteria (80–120%) and indicate good measurement accuracy. Coefficients of variation below 5% demonstrate satisfactory repeatability of the analyses.

2.7.5. Measurement repeatability

Repeatability was assessed by analyzing the same sample six times (n = 6). Coefficients of variation (CV) for lead (3.2%) and cadmium (4.2%) were below 5%, confirming good measurement reproducibility at concentrations close to the limits of quantification.

2.7.6. Certified reference materials

Certified reference materials (SRM 1643e – Trace Elements in Water, NIST) were analyzed alongside the samples to validate measurement trueness. Measured concentrations for the analyzed elements all fell within the 95% confidence interval of the certified values, confirming the reliability of the analytical method.

2.7.7. Handling of extreme values

In accordance with WHO recommendations for water analysis (WHO, 2022), extreme values (outliers) were identified using Dixon's test (for small samples) and Grubbs' test (for complete datasets). A value was considered extreme if it deviated by more than three standard deviations from the mean and if the statistical test confirmed it as an outlier ($p < 0.05$). No value was excluded solely on the basis of its deviation ; each extreme value was systematically verified against laboratory records (logbook, absorption spectra) and confirmed to represent a genuine concentration.

2.8. Operating procedures for elements in water

- Procedure for the determination of Cu, Co, Fe, Mn, Zn, Ni, Pb, Cd, Mg, and Ca in water

Equipment:

Teflon beaker, pipette, forceps, flask, beaker, watch glass.

Reagents:

HCl, HNO₃, HF, HClO₄, SrCl₂, H₂O.

Equipment:

- Electronic balance;
- Hot plate;

- Pinnacle AA500 analyzer.

Procedures:

- Take an aliquot of water into a 50 ml flask for a 10-fold dilution;
- Transfer it to a Teflon beaker;
- Moisten with distilled water, then digest with ± 6 ml HCl, ± 3 ml HNO₃, ± 2 ml HF, and ± 2 ml HClO₄;
- Place a support (hook) in the beaker, cover with a watch glass, and heat on a hotplate until reduced to a syrupy consistency;
- Redissolve with 2 ml HCl and evaporate again to a syrupy consistency;
- Convert to a nitric acid medium by adding ± 2 ml HNO₃ and ± 40 ml distilled water, and heat to boiling;
- Allow the solution to cool, then transfer it to a 100 ml volumetric flask;
- Prepare dilutions using a 2% HNO₃ solution if necessary (add 2% SrCl₂ for Ca and Mg determination);
- Ensure complete dissolution before adding distilled water;
- Run the solutions through the PinAAcle AA500 analyzer to determine the required elements (Cu, Co, Fe, Mn, Zn, Ni, Pb, Cd, Mg, Ca).

Calculation of results $X \text{ (mg/L)} = (\text{reading} \times \text{dilution}) / (\text{sample aliquot in mg/L})$

Sample aliquot in mg/L = (volume sampled) / (volume of flask used in liters)

2.9. Volumetric methods for water analysis

2.9.1. Total Alkalinity (TAC)

- **Principle**

It corresponds to the total quantity of alkaline substances present in the water — primarily bicarbonates, carbonates, and hydroxides.

- **Procedure**

- Filter the water;
- Measure 100 ml of water into a 205 ml beaker;
- Add 80 ml of 1M ammonium chloride (buffer solution);
- Add a pinch of Eriochrome Black or 3 drops of methyl orange;
- Titrate with the prepared EDTA solution (3.721 g/L).

Calculation: $TAC = (V \text{ ml} - 0.5 \text{ ml}) \text{ } ^\circ F$

Preparation of solutions:

EDTA: Weigh 3.721 g of EDTA and dissolve in one liter.

NH₄Cl: Weigh 53.5 g into a 1-liter flask, then add 140 ml of ammonia and dilute to the graduation mark with distilled water.

2.9.2. Analysis of suspended solids

- **Principle**

The determination of suspended solids in water is based on filtering a known volume of the sample through a filter that has been pre-dried and weighed.

- **Procedure**

- Dry the Millipore filter on a hotplate at 105°C for 20 minutes;
- Weigh the filter and the watch glass;
- Take an aliquot of the sample solution;
- Filter through the Millipore filter placed on the vacuum pump apparatus;
- Dry the filter in an oven for 20 minutes, then remove it;
- Weigh the filter.

Calculation:

$P2 - P1 = m \text{ (g)}$ Suspended solids g/L of suspended solids = $(m \times 1000) / V \text{ (L)}$

2.9.3. Chloride ion analysis

- **Principle**

The principle involves titrating the chloride ions present in a known volume of water using a silver nitrate (AgNO_3) solution of known concentration, in the presence of potassium chromate (K_2CrO_4).

- **Procedure**

- Filter the sample;
- Measure 100 ml of the sample into a beaker;
- Add 3 drops of concentrated nitric acid (65% to 70%);
- Add a spoonful of calcium carbonate;
- Add 3 drops of 10% potassium chromate;
- Then titrate with 0.025 N silver nitrate;
- Color change: from yellow to brick red.

- **Calculation**

$$\text{Cl- mg/l} = \text{Volume (Reading)} \times \text{Factor}$$

$$\text{Factor} = 8.875$$

2.9.4. Analysis of sulfate ions in water

- **Principle**

Sulfate is precipitated using a barium chloride solution of known concentration, yielding barium sulfate.

- **Procedure**

- Filter the sample.
- Take a 250 mL water sample.
- Concentrate the water on a hotplate to 100 mL, add 3 drops of methyl orange and 11 mL of HCl, then place the beaker on the hotplate to boil the solution.
- Precipitate the solution using 10 mL of BaCl_2 solution (prepared at 118 g/L).
- Allow the solution to stand for 24 hours, then filter it; wash with HCl and distilled water, dry the

platinum crucible on the hotplate, and finally calcine the precipitate for one hour.

- Add 1 mL of HF and place back on the hotplate to dry.
- Weigh the precipitate and perform the calculation.

$$\text{Calculation: } \text{SO}_4^{2-} (\text{mg/L}) = (m(\text{BaSO}_4) \times 0.4116 \times 100) / P.$$

2.9.5. Analysis of organic matter

- **Principle**

The method consists of measuring the quantity of oxygen used for the reduction of KMnO_4 by the organic matter contained in the sample.

- **Operating mode**

- Filter the water sample;
- Take 100 ml (V1) and 200 ml (V2) of sample to place in a 400 ml beaker;
- Add 10 ml (V1) of NaHCO_3 AND 20 ml (V2) of H_2SO_4 1/1;
- Add 10 ml of KMnO_4 ;
- Boil the solution for 30 minutes;
- Remove the sample from the plate and cool it;
- Add 10 ml (V1) and 20 ml of H_2SO_4 1/1 (V2);
- Add 10 ml $\text{F}^2(\text{NH}_4)_2(\text{SO}_4) \cdot 2.6 \text{ H}_2\text{O}$ and the solution will discolor;
- Titrate with 0.00125 N KMnO_4 .

Calculation:

$$V2 - V1 = \text{mg/MO}$$

2.9.6. Water hardness (TH or TA)

- **Principle**

The analysis is based on acid-base titration. It measures the capacity of water to neutralize acids; this primarily reflects the presence of bicarbonates (HCO_3^-), carbonates (CO_3^{2-}), and, to a lesser extent, hydroxides (OH^-).

- **Procedure**

- Filter the water sample;
- Measure 100 ml into a 500 ml beaker;
- Add 20 ml of the $\text{NH}_4\text{OH}/\text{NH}_4\text{Cl}$ buffer solution;
- Add a pinch of Eriochrome Black T;
- Titrate with 0.01 N EDTA until the color changes from reddish-violet to light blue, and record the volume used;
- The endpoint is observed when the indicator changes from pink to blue. The value obtained, multiplied by the EDTA titer, represents the water hardness.

2.10. Statistical analysis of data

The collected data were entered and analyzed using SPSS software (Statistical Package for Social Sciences), version 26.0 (IBM Corp., Armonk, NY, USA). Quantitative variables were expressed as means $\pm$ standard deviations (SD), including minimum and maximum values, as well as medians and interquartile ranges (IQR) for parameters not following a normal distribution.

- Assessment of data normality

Prior to any comparative testing, the normality of the distributions was assessed using the Shapiro-Wilk test, given the modest sample size ($n = 10$ per source). This test was selected for its statistical power suitable for small samples and its sensitivity to deviations from normality.

- Justification for the use of non-parametric tests

Due to the non-normal distribution observed for several variables, and given the relatively small sample size (40 samples divided into 4 groups of 10), the use of parametric tests (ANOVA) was not justified. We therefore opted for non-parametric tests, which are more robust against deviations from normality and outliers.

- Comparison of water sources

The Kruskal-Wallis test was used to compare the four water sources (Well 1, Well 2, Well 3, and REGIDESO) for each physicochemical and metal parameter. This test serves as the non-parametric alternative to one-way ANOVA and determines whether samples originate from distributions with

the same median. The significance level was set at $\alpha = 0.05$. A p-value < 0.05 was considered statistically significant.

- Post-hoc comparisons and multiple comparison correction

When the Kruskal–Wallis test revealed a statistically significant difference between supply sources, pairwise multiple comparisons were performed using Dunn’s post hoc test with Bonferroni correction. This procedure made it possible to identify the specific groups responsible for the overall difference while controlling for the inflation of Type I error risk associated with multiple comparisons. The threshold for statistical significance was set at an adjusted p-value < 0.05 .

3. Results

3.1. Descriptive statistics:

Table 1. Normality test for physicochemical and metal analyses.

Parameter	Well 1 p	Well 2 p	Well 3 p	REGIDESO p
Boiling time	<0.001	0.008	0.008	0.003
Storage time	<0.001	0.012	<0.001	0.015
Container volume	<0.001	<0.001	<0.001	<0.001
pH	0.022	0.003	0.511	0.002
Cu	0.036	0.006	0.001	0.002
Co	0.001	0.010	0.015	0.001
Fe	<0.001	0.001	0.007	0.010
Mn	<0.001	0.549	<0.001	0.001
CaO	0.108	0.017	0.233	0.001
MgO	0.121	0.002	0.505	0.005

Total Hardness	0.002	0.024	0.567	0.067
TA	0.002	0.703	<0.001	0.172
TAC	0.002	0.025	0.336	0.022
TP	0.519	<0.001	0.139	<0.001
SO ₄ ²⁻	0.002	0.179	0.012	0.212
Cd	0.004	<0.001	0.177	0.022
Zn	0.287	<0.001	0.258	0.001
Ni	0.008	<0.001	0.006	<0.001
Pb	<0.001	0.001	<0.001	<0.001
Cl ⁻	0.458	0.327	0.121	0.443
MS	0.968	<0.001	0.001	0.002

The Shapiro–Wilk test shows that the majority of the parameters studied do not follow a normal distribution ($p < 0.05$), notably boiling time, shelf life, container volume, copper, cobalt, iron, nickel, and lead. In contrast, chloride levels exhibit a normal distribution across all four sources ($p > 0.05$), whereas the normality of the other parameters varies by source. This prevalence of non-normal distributions, combined with the small sample size per group ($n = 10$), justifies the use of non-parametric tests specifically the Kruskal–Wallis test to compare the four supply sources.

Table 2. Characteristics related to water preparation and storage.

Parameters	Well 1	Well 2	Well 3	Régideso
Boiling time	8.00 ± 2.58 (5–10)	6.60 ± 3.03 (3–10)	6.60 ± 3.03 (3–10)	7.30 ± 2.91 (3–10)
Shelf life	1.70 ± 1.25 (1–5)	1.80 ± 0.63 (1–3)	1.50 ± 0.53 (1–2)	1.70 ± 0.68 (1–3)
Container volume	2.60 ± 1.27 (2–5)	2.90 ± 1.45 (2–5)	3.50 ± 1.58 (2–5)	3.20 ± 1.55 (2–5)

The results in this table show that boiling time ranged from 8.00 ± 2.58 for Well 1 and 7.30 ± 2.91 for the REGIDESO supply, compared to 6.60 ± 3.03 for Wells 2 and 3. The average storage duration was relatively long for Well 2 (1.80 ± 0.63 days), followed by Well 1 and the REGIDESO supply (1.70 ± 1.25 and 1.70 ± 0.68 days, respectively); in contrast, Well 3 showed a shorter storage duration of 1.50 ± 0.53 days. The average volume of the containers ranged from 2.60 to 3.50 units, with the highest value observed in households using Well 3.

Table 3. Mean values of physicochemical water parameters.

Parameter	Well 1	Well 2	Well 3	Régideso
Cl⁻	7.01 ± 1.51	6.42 ± 1.64	19.44 ± 5.56	8.37 ± 5.33

The mean chloride (Cl⁻) concentration varied according to the supply source. Well 3 exhibited the highest concentration (19.44 ± 5.56 mg/L), significantly higher than those of Well 1 (7.01 ± 1.51 mg/L), Well 2 (6.42 ± 1.64 mg/L), and REGIDESO (8.37 ± 5.33 mg/L).

Table 4. General physicochemical parameters analyzed in boiled water from the various supply sources.

Parameter	Source	Median	IQR
pH	Well 1	7,43	0,760
	Well 2	7,40	0,403
	Well 3	7,34	0,888
	Regideso	7,32	0,402
Cu	Well 1	0,020	0,007
	Well 2	0,0325	0,046
	Well 3	0,025	0,023
	Regideso	0,0375	0,049
Co	Well 1	0,021	0,020
	Well 2	0,010	0,010
	Well 3	0,020	0,010
	Regideso	0,011	0,022
Fe	Well 1	0,070	0,045
	Well 2	0,065	0,130
	Well 3	0,280	0,055
	Regideso	0,035	0,035
Mn	Well 1	0,010	0,010
	Well 2	0,010	0,002

	Well 3	0,010	0,010
	Regideso	0,0095	0,002
Ca	Well 1	160,45	96,18
	Well 2	146,95	89,25
	Well 3	65,55	73,98
	Regideso	151,20	30,60
Mg	Well 1	90,80	31,65
	Well 2	40,60	52,35
	Well 3	33,70	23,93
	Regideso	40,55	35,43
TH	Well 1	44,40	27,78
	Well 2	38,60	20,23
	Well 3	25,00	17,00
	Regideso	38,55	12,33
TA	Well 1	0,007	0,001
	Well 2	0,008	0,002
	Well 3	0,0085	0,003
	Regideso	0,007	0,001
TAC	Well 1	33,85	20,58
	Well 2	33,05	7,08

	Well 3	23,90	22,30
	Regideso	32,80	10,25
Tp	Well 1	21,75	8,55
	Well 2	16,25	9,75
	Well 3	20,60	12,05
	Regideso	13,20	11,23
SO₄²⁻	Well 1	78,37	56,68
	Well 2	45,86	57,01
	Well 3	21,00	19,41
	Regideso	49,48	44,17
Cd	Well 1	0,008	≈0
	Well 2	0,010	0,065
	Well 3	0,008	0,001
	Regideso	0,0095	0,002
Zn	Well 1	0,020	0,012
	Well 2	0,012	0,040
	Well 3	0,025	0,010
	Regideso	0,035	0,231
Ni	Well 1	0,015	0,012
	Well 2	0,010	0,003

	Well 3	0,020	0,020
	Regideso	0,010	0,010
Pb	Well 1	0,010	0,012
	Well 2	0,0115	0,010
	Well 3	0,010	0,010
	Regideso	0,010	≈0
Cl⁻	Well 1	6,71	2,37
	Well 2	7,00	3,09
	Well 3	20,42	5,11
	Regideso	7,07	6,65
MS	Well 1	8,35	3,33
	Well 2	9,54	2,21
	Well 3	10,20	33,10
	Regideso	7,23	22,77

The physicochemical and metal parameters of the boiled water varied according to the supply sources. The pH remained relatively consistent (medians: 7.32–7.43), while Cu, Co, Mn, Cd, Ni, and Pb showed generally similar median concentrations. More pronounced variations were observed for Fe, with the highest median at Well 3 (0.280 mg/L), as well as for Ca and Mg, which were higher at Well 1 (160.45 and 90.80 mg/L). Sulfate levels were also highest at Well 1 (78.37 mg/L), whereas chloride levels peaked at Well 3 (20.42 mg/L), reflecting source-dependent variability.

Table 5. Mean values of major and trace metal elements obtained from the various water supply sources.

Element	Well 1	Well 2	Well 3	Régideso
Cu	0,0182 ± 0,0054	0,0371 ± 0,0246	0,0340 ± 0,0222	0,0392 ± 0,0264
Co	0,0272 ± 0,0093	0,0132 ± 0,0051	0,0170 ± 0,0067	0,0172 ± 0,0111
Fe	0,102 ± 0,107	0,122 ± 0,149	0,267 ± 0,061	0,043 ± 0,030
Mn	0,0131 ± 0,0048	0,0096 ± 0,0017	0,0140 ± 0,0052	0,0101 ± 0,0037
Cd	0,0078 ± 0,0008	0,0291 ± 0,0330	0,0084 ± 0,0011	0,0088 ± 0,0015
Zn	0,0170 ± 0,0095	0,0364 ± 0,0477	0,0250 ± 0,0085	0,1025 ± 0,1163
Ni	0,0170 ± 0,0082	0,0130 ± 0,0067	0,0200 ± 0,0094	0,0140 ± 0,0070
Pb	0,0160 ± 0,0108	0,0143 ± 0,0050	0,0130 ± 0,0048	0,0111 ± 0,0031

Analysis of mean heavy metal concentrations reveals variations depending on the supply source. Copper (Cu) shows its highest concentration in the Régideso supply (0.0392 ± 0.0264), whereas cobalt (Co) levels are higher at Well 1 (0.0272 ± 0.0093). Iron (Fe) levels are highest at Well 3 (0.267 ± 0.061). Cadmium (Cd) is particularly high at Well 2 (0.0291 ± 0.0330) and exhibits significant variability. Zinc (Zn) shows its highest mean concentration in the Régideso supply (0.1025 ± 0.1163); nickel (Ni) remains relatively stable, while lead (Pb) levels decrease progressively from Well 1 (0.0160 ± 0.0108) to the Régideso supply (0.0111 ± 0.0031).

Table 6. Mean values of other chemical parameters analyzed in the various water supply sources.

Parameter	Well 1	Well 2	Well 3	Régideso
Mn	0,0131 ± 0,0048	0,0096 ± 0,0017	0,0140 ± 0,0052	0,0101 ± 0,0037
TA	0,0075 ± 0,0007	0,0080 ± 0,0012	0,0174 ± 0,0291	0,0074 ± 0,0008
TAC	27,12 ± 10,02	31,00 ± 7,04	24,78 ± 10,37	31,42 ± 8,49
Tp	20,11 ± 5,08	21,44 ± 17,94	19,50 ± 5,84	22,19 ± 21,98
SO ₄ ²⁻	58,81 ± 29,69	45,03 ± 25,29	27,95 ± 18,35	52,98 ± 23,46
Cl ⁻	7,01 ± 1,51	6,42 ± 1,64	19,44 ± 5,56	8,37 ± 5,33

Manganese concentrations remain relatively similar across the four sources; only Well 3 shows the highest mean (0.0140). TA shows a high mean at Well 3 (0.0174), associated with very high dispersion (SD = 0.0291). TAC is higher in the Régideso supply (31.42) and at Well 2 (31.00), whereas Well 3 shows the lowest value (24.78).

The Tp parameter shows particularly significant variability in the Régideso supply (SD = 21.98) and at Well 2 (SD = 17.94). Sulfate concentrations are higher at Well 1 (58.81) and in the Régideso supply (52.98), while Well 3 shows the lowest mean concentration (27.95). Chloride levels show a particularly marked difference at Well 3 (19.44) compared to the others.

Table 7. Comparison of mean values of chemical parameters with WHO guideline/reference values (mg/L) and basis.

Parameter	Mean ± SD	Median	Q1– Q3	Min– Max	WHO guideline/reference values (mg/L) and basis
pH	7,48 ± 0,43	7,40	7,20– 7,86	6,29– 8,22	(6,5-8,5)
Cu	0,032 ± 0,022	0,020	0,015– 0,058	0,012– 0,090	2,0mg/dl
Co	0,019 ± 0,010	0,020	0,010– 0,022	0,007– 0,040	
Fe	0,134 ± 0,126	0,075	0,043– 0,265	0,020– 0,470	0,3ppm
Mn	0,012 ± 0,004	0,010	0,010– 0,011	0,007– 0,020	0,08mg/dl
Ca	115,03 ± 52,31	143,65	66,65– 159,25	14,53– 238,60	
Mg	56,97 ± 30,74	41,30	37,55– 89,65	15,40– 156,90	
TH	33,26 ± 11,97	38,35	20,43– 44,65	13,00– 52,00	20-200°F
TA	0,010 ± 0,015	0,008	0,007– 0,009	0,005– 0,100	
TAC	28,58 ± 9,16	32,80	18,53– 35,25	11,50– 40,50	500°F
TP	20,81 ± 14,17	17,20	12,40– 23,00	10,00– 83,31	
SO ₄ ²⁻	46,19 ± 26,35	43,72	20,91– 75,86	10,87– 86,77	250mg/dl

Cd	0,014 ± 0,018	0,008	0,008– 0,010	0,006– 0,080	0.003 mg/L
Zn	0,045 ± 0,070	0,020	0,012– 0,030	0,000– 0,290	3,000 mg/dl
Ni	0,016 ± 0,008	0,010	0,010– 0,020	0,010– 0,030	0,07 mg/dl
Pb	0,014 ± 0,007	0,010	0,010– 0,020	0,010– 0,040	0.01 mg/L
Cl ⁻	10,31 ± 6,62	7,27	6,26– 15,75	0,01– 26,63	250 mg/dl
MS	15,18 ± 19,17	8,88	6,49– 11,07	0,40– 77,60	1000 mg/dl

Overall, the majority of physicochemical parameters and metal elements showed mean concentrations below the adopted guideline or reference values. The mean pH was 7.48 ± 0.43. Concentrations of Cu, Fe, Mn, Ni, Zn, SO₄²⁻, and Cl⁻ also remained below the corresponding reference values. In contrast, cadmium showed a mean concentration of 0.014 ± 0.018 mg/L, exceeding the WHO guideline value of 0.003 mg/L. Similarly, lead levels reached 0.014 ± 0.007 mg/L, surpassing the guideline value of 0.010 mg/L. These results primarily highlight concerning levels of Cd and Pb.

Table 8. Comparison of physicochemical and metal parameters of boiled water according to the source of supply (Kruskal-Wallis test).

Parameter s	Well 1 Mean rank	Well 2 Mean rank	Well 3 Mean rank	Mean rank REGIDESO	χ^2	p-value	Significance
pH	25,25	20,15	16,70	19,90	2,747	0,432	NS
Cu	13,90	21,10	24,70	22,30	4,855	0,183	NS
Co	30,25	14,60	19,85	17,30	10,819	0,013	S
Fe	20,25	18,85	32,55	10,35	18,532	< 0,001	S
Mn	25,35	15,80	26,00	14,85	8,934	0,030	S
CaO	25,50	20,60	11,50	24,40	8,871	0,031	S
MgO	30,10	21,20	11,05	19,65	13,370	0,004	S
TH	22,05	23,05	14,10	22,80	4,039	0,257	NS
TA	17,25	22,60	25,75	16,40	4,732	0,193	NS
TAC	20,40	22,40	16,10	23,10	2,178	0,536	NS
TP	24,05	18,15	23,30	16,50	3,076	0,380	NS
SO ₄	26,10	19,00	12,00	24,90	9,163	0,027	S
Cd	14,05	26,60	18,80	22,55	6,849	0,077	NS
Zn	14,15	16,10	21,90	29,85	11,360	0,010	S

Ni	22,10	16,50	25,30	18,10	4,509	0,211	NS
Pb	21,10	23,50	20,00	17,40	2,064	0,559	NS
Cl ⁻	16,40	14,70	32,90	18,00	15,410	0,001	S
MS	18,45	23,25	22,35	17,95	1,588	0,662	NS

The Kruskal–Wallis test revealed statistically significant differences among the four supply sources for several parameters. Cobalt levels varied significantly by source ($\chi^2 = 10.819$; $p = 0.013$), with the highest mean rank observed at Well 1 (30.25). The most pronounced difference was found for iron ($\chi^2 = 18.532$; $p < 0.001$), with the highest mean rank at Well 3 (32.55) and the lowest for REGIDESO (10.35). Significant variations were also observed for manganese ($\chi^2 = 8.934$; $p = 0.030$), calcium ($\chi^2 = 8.871$; $p = 0.031$), magnesium ($\chi^2 = 13.370$; $p = 0.004$), and sulfates ($\chi^2 = 9.163$; $p = 0.027$). Zinc levels also differed across sources ($\chi^2 = 11.360$; $p = 0.010$), with the highest mean rank for REGIDESO (29.85). Chloride levels showed highly significant variation ($\chi^2 = 15.410$; $p = 0.001$), particularly at Well 3 (mean rank = 32.90). In contrast, no significant differences were observed for pH, copper, total hardness, TA, TAC, temperature, cadmium, nickel, lead, or dry matter ($p > 0.05$).

Table 9. Dunn-Bonferroni post-hoc test.

Parameter	Comparison	Difference in mean ranks	Adjusted p-value	Significant
Co	30,25 – 14,60	15,65	0,017	Yes
	30,25 – 19,85	10,40	0,279	No
	30,25 – 17,30	12,95	0,079	No
	14,60 – 19,85	5,25	1,000	No
	14,60 – 17,30	2,70	1,000	No
	19,85 – 17,30	2,55	1,000	No
Fe	20,25 – 18,85	1,40	1,000	No

	20,25 – 32,55	12,30	0,112	No
	20,25 – 10,35	9,90	0,349	No
	18,85 – 32,55	13,70	0,053	No
	18,85 – 10,35	8,50	0,624	No
	32,55 – 10,35	22,20	<0,001	Yes
Mn	25,35 – 15,80	9,55	0,406	No
	25,35 – 26,00	0,65	1,000	No
	25,35 – 14,85	10,50	0,266	No
	15,80 – 26,00	10,20	0,306	No
	15,80 – 14,85	0,95	1,000	No
	26,00 – 14,85	11,15	0,198	No
Ca	25,50 – 20,60	4,90	1,000	No
	25,50 – 11,50	14,00	0,044	Yes
	25,50 – 24,40	1,10	1,000	No
	20,60 – 11,50	9,10	0,488	No
	20,60 – 24,40	3,80	1,000	No
	11,50 – 24,40	12,90	0,081	No
Mg	30,10 – 21,20	8,90	0,530	No
	30,10 – 11,05	19,05	0,002	Yes
	30,10 – 19,65	10,45	0,274	No
	21,20 – 11,05	10,15	0,312	No

	21,20 – 19,65	1,55	1,000	No
	11,05 – 19,65	8,60	0,600	No
SO ₄ ²⁻	26,10 – 19,00	7,10	1,000	No
	26,10 – 12,00	14,10	0,042	Yes
	26,10 – 24,90	1,20	1,000	No
	19,00 – 12,00	7,00	0,782	No
Zn	19,00 – 24,90	5,90	1,000	No
	12,00 – 24,90	12,90	0,082	No
	14,15 – 16,10	1,95	1,000	No
	14,15 – 21,90	7,75	0,138	No
Cl ⁻	14,15 – 29,85	15,70	0,016	Yes
	16,10 – 21,90	5,80	1,000	No
	16,10 – 29,85	13,75	0,051	No
	21,90 – 29,85	7,95	0,128	No
	16,40 – 14,70	1,70	1,000	No
	16,40 – 32,90	16,50	0,010	Yes
	16,40 – 18,00	1,60	1,000	No
	14,70 – 32,90	18,20	0,003	Yes
	14,70 – 18,00	3,30	1,000	No
	32,90 – 18,00	14,90	0,026	Yes

The Dunn-Bonferroni post-hoc test identified the sources responsible for the differences observed in the Kruskal–Wallis test. For cobalt, a significant difference was observed between

Wells 1 and 2 (adjusted $p = 0.017$). Iron levels differed significantly between Well 3 and REGIDESO ($p < 0.001$). For calcium, magnesium, and sulfates, significant differences were found between Wells 1 and 3, with adjusted p -values of 0.044, 0.002, and 0.042, respectively. Zinc levels differed significantly between Well 1 and REGIDESO ($p = 0.016$). Chloride levels showed more inter-source differences: Well 3 differed significantly from Well 1 ($p = 0.010$), Well 2 ($p = 0.003$), and REGIDESO ($p = 0.026$). In contrast, despite a significant overall difference for manganese in the Kruskal–Wallis test, no pairwise comparison remained statistically significant after the Bonferroni correction (adjusted $p > 0.05$).

Table 10. Proportion of samples exceeding WHO guideline values according to source of supply.

Parameter	WHO guideline/reference values (mg/L) and basis	Source	n/N (%) exceeding GV	Median (mg/L)	Max (mg/L)
Lead (Pb)	0,01	Well 1	6/10 (60 %)	0,010	0,040
		Well 2	8/10 (80 %)	0,0115	0,020
		Well 3	5/10 (50 %)	0,010	0,020
		Regideso	4/10 (40 %)	0,010	0,016
Cadmium (Cd)	0,003	Well 1	10/10 (100 %)	0,008	0,009
		Well 2	7/10 (70 %)	0,010	0,080
		Well 3	10/10 (100 %)	0,008	0,010
		Regideso	9/10 (90 %)	0,0095	0,012
Iron (Fe)	0,3	Well 1	0/10 (0 %)	0,070	0,310
		Well 2	1/10 (10 %)	0,065	0,470
		Well 3	3/10 (30 %)	0,280	0,370
		Regideso	0/10 (0 %)	0,035	0,080

Legend: GV = Guideline Value; n/N = number of samples exceeding the guideline value out of the total number of samples for the source in question.

The proportion of samples exceeding guideline values varied according to the parameter and the supply source. For lead, exceedances were observed in 60% of samples from Well 1, 80% from Well 2, 50% from Well 3, and 40% from the REGIDESO supply. Cadmium showed the highest frequencies of exceedance, reaching 100% for Wells 1 and 3, 90% for the REGIDESO supply, and 70% for Well 2. Regarding iron, exceedances of the 0.3 mg/L reference value were limited to Well 2 (10%) and Well 3 (30%).

4. Discussion

4.1. Boiling and storage practices

In this study, the average water boiling time ranged from 6.60 ± 3.03 to 8.00 ± 2.58 minutes depending on the source, while the post-treatment storage period ranged from 1.50 to 1.80 days. These results highlight the frequent use of boiling as a household water treatment method. However, its effects on chemical quality vary. Ma et al. (2024) demonstrated that boiling can reduce certain disinfection by-products specifically trihalomethanes and haloacetonitriles depending on the contaminant and heating conditions. Similarly, Zha et al. (2025) reported changes in hardness, pH, and nitrite levels that can persist during storage. Furthermore, Rajabi et al. (2025) observed that repeated boiling can concentrate certain compounds, such as nitrates, through evaporation. Thus, the effectiveness of boiling depends on the contaminant, heating conditions, and storage practices.

4.2. Physicochemical parameters

Analysis of the physicochemical parameters showed that the mean pH of the 40 samples was 7.48 ± 0.43 , with values ranging from 6.29 to 8.22. No significant difference was observed among the four sources ($\chi^2 = 4.855$; $p = 0.432$), indicating relatively homogeneous acid-base conditions. Although pH is not a direct indicator of toxicity, it influences water chemical stability, material corrosion, and the mobility of certain metals. Zha et al. (2025) reported a slight increase in pH after boiling. The discrepancy with our findings could be attributed to the initial water composition, heating conditions, and post-treatment storage.

Chlorides had an average concentration of 10.31 ± 6.62 mg/L, with a higher value at well 3 (19.44 ± 5.56 mg/L). The differences between sources were significant ($p = 0.001$). However, the concentrations observed remained well below 250 mg/L, suggesting a possible variation in mineralization

between sources rather than a worrying situation. Likewise, sulfates reached an average of 46.19 ± 26.35 mg/L, with a significant difference between sources ($p = 0.027$), particularly between wells 1 and 3 ($p = 0.042$). This interpretation is consistent with the observations of Kazapoe et al. (2024) and Gwira et al. (2024) in Ghana, where the hydrogeochemical characteristics of waters in a mining context were jointly influenced by geology and anthropogenic activities.

Calcium (115.03 ± 52.31 mg/L) and magnesium (56.97 ± 30.74 mg/L) varied significantly between the sources (respectively $p = 0.031$ and $p = 0.004$), particularly between wells 1 and 3. These differences could reflect the variable dissolution of minerals present in the geological formations crossed by the groundwater. In contrast, total hardness (33.26 ± 11.97 °F) did not differ significantly between sources ($p = 0.257$). Zha et al. (2025) showed that boiling can change the hardness of water. However, the absence of measurements before boiling in our study does not make it possible to directly attribute the variations observed to heat treatment. Overall, the physicochemical differences observed therefore seem to mainly reflect the heterogeneity of the mineralization of the sources studied.

4.3. Metal elements

The analysis of metallic elements highlights variable contamination depending on the sources, without however indicating any major health concern for copper, cobalt, iron, manganese, zinc and nickel at the concentrations observed. Copper had a mean concentration of 0.032 ± 0.022 mg/L, with no significant difference between sources ($p = 0.183$). These low concentrations could result from geogenic processes or, for distributed water, from corrosion of network materials. Studies carried out in mining regions of Ghana have also shown that metal concentrations in water can vary considerably depending on geological characteristics and the intensity of anthropogenic activities (Owusu et al., 2024).

Cobalt had an average concentration of 0.019 ± 0.010 mg/L, with a higher value at well 1 (0.0272 ± 0.0093 mg/L). The difference between sources was significant ($p = 0.013$), particularly between wells 1 and 2 ($p = 0.017$). This heterogeneity could reflect local geochemical characteristics or the influence of mining activities. However, the concentrations observed remained lower than the reference value used in this study (0.05 mg/L).

Iron reached on average 0.134 ± 0.126 mg/L, with a concentration significantly higher in well 3 (0.267 ± 0.061 mg/L) compared to REGIDESO (0.043 ± 0.030 mg/L; $p <$

0.001). This variation could be linked to the dissolution of iron minerals and the geochemical conditions of the aquifer. Manganese, with a mean of 0.012 ± 0.004 mg/L, also varied between sources ($p = 0.030$), although no pair-to-pair differences remained after Bonferroni correction. Variations in iron and manganese have also been reported in groundwater in African mining regions (Tabi et al., 2024; Asare et al., 2026).

Finally, zinc concentrations (0.045 ± 0.070 mg/L) varied significantly among the sources ($p = 0.010$), unlike nickel (0.016 ± 0.008 mg/L; $p = 0.211$). Their concentrations remained low relative to the selected reference values. Overall, these results suggest that the observed metal variations primarily reflect the geochemical heterogeneity of the sources and, potentially, certain anthropogenic influences.

4.4. Lead and cadmium: key health concerns:

The presence of lead (Pb) and cadmium (Cd) represents the primary health concern identified in this study. The mean lead concentration was 0.014 ± 0.007 mg/L, with a median of 0.010 mg/L and a maximum of 0.040 mg/L. This mean exceeds the reference value of 0.010 mg/L adopted for the study (WHO, 2017). However, no statistically significant difference was observed among the four sources ($\chi^2 = 5.410$; $p = 0.559$). This lack of difference does not imply an absence of health concerns; rather, it indicates that lead concentrations were relatively comparable across the sources. Consequently, the health-related interpretation must focus more on the level of contamination relative to the reference value than on a mere statistical comparison between supply points.

In the context of the Panda neighborhood located in a region characterized by extensive mining activity several potential sources of lead can be considered. Lead may originate from the natural weathering of geological formations, mining discharges and tailings, contaminated dust, and surface runoff. Corrosion of distribution infrastructure and leaching from cooking or storage vessels also constitute potential sources. However, the study protocol does not allow for the identification of the exact origin of the detected lead. In mining communities in Ghana, Owusu et al. (2024) also reported the presence of lead in groundwater, while Sagoe et al. (2025) highlighted the combined influence of geogenic and anthropogenic processes on water quality.

The situation also appears concerning regarding cadmium, with a mean concentration of 0.014 ± 0.018 mg/L, a median of 0.008 mg/L, and a maximum of 0.080 mg/L. Well 2 showed the highest mean (0.0291 ± 0.0330 mg/L), though differences between sources were not statistically significant ($p = 0.077$).

Cadmium warrants particular attention due to its chronic toxicity, specifically its renal effects following prolonged exposure. In Lubumbashi, Muhaya and Badarhi (2022) also reported the presence of trace elements in the groundwater of the Katuba and Kenya communes.

These observations align with findings from other African mining regions. In Tarkwa, Ghana, Gwira et al. (2024) identified several elements of concern in groundwater including cadmium and highlighted potential risks associated with chronic exposure, particularly among children. Owusu et al. (2024) also detected cadmium and other metals in borehole water within mining communities. In the DRC, Mudunga et al. (2024) reported metal contamination in water and sediments, while Myango et al. (2025) demonstrated the significance of water-rock interactions and mineral weathering in determining groundwater composition in mining environments.

5. Conclusion

The study on the physicochemical quality and metal contamination of boiled water consumed in the Panda neighborhood of Likasi aimed to characterize the physicochemical quality of water from various supply sources after boiling and storage.

The study analyzed 40 water samples, comprising ten samples from each of the four sources investigated: three wells and the REGIDESO municipal supply network. Analyses covered physicochemical parameters (pH, chlorides, sulfates, calcium, magnesium, hardness, and alkalinity) as well as metals (copper, cobalt, iron, manganese, zinc, nickel, lead, and cadmium). Metal concentrations were determined using atomic absorption spectrometry, while other parameters were measured using standardized methods. Comparisons between sources were performed using the Kruskal-Wallis test, supplemented by Dunn's post-hoc test with Bonferroni correction.

This study highlights variations in the physicochemical quality and metal composition of boiled water consumed in the Panda neighborhood of Likasi depending on the supply source. Significant differences between sources were observed for cobalt, iron, manganese, calcium, magnesium, zinc, sulfates, and chlorides, whereas pH, copper, cadmium, nickel, and lead levels did not differ significantly.

Most measured parameters fell below the adopted guideline or reference values. However, lead and particularly cadmium were the primary elements of concern. Their mean concentrations were 0.014 ± 0.007 mg/L and 0.014 ± 0.018

mg/L, respectively, exceeding the guideline values of 0.010 mg/L and 0.003 mg/L. Depending on the source, lead levels exceeded limits in 40–80% of samples, and cadmium levels in 70–100%, indicating that the contamination was not limited to a single supply source.

These results highlight the need to strengthen monitoring of the chemical quality of water consumed in the Panda neighborhood and to investigate potential sources of metal contamination. However, the lack of water analysis prior to boiling makes it impossible to attribute the observed concentrations to the boiling process itself. Further studies involving sampling before and after treatment, exposure assessment, and characterization of contamination sources are required.

6. Recommendations

• To health and administrative authorities

- Implement regular monitoring of water quality (chemical and microbiological), paying particular attention to lead and cadmium.
- Strengthen oversight of wells, Régideso operations, and mining areas.
- Raise public awareness regarding the limitations of boiling water as a method to remove metal contaminants.

• To Régideso and water supply managers

- Strengthen regular monitoring of distributed water quality, particularly regarding lead and cadmium levels.
- Inspect the condition of pipes and reservoirs to prevent metal contamination.
- Regularly inform the public about analysis results and preventive measures.

• To the residents of the Panda neighborhood

- Continue boiling properly to reduce microbiological risks and consume the treated water promptly.
- Store boiled water in clean, covered, and suitable containers, without mixing it with previously stored water.

- Protect wells from sources of contamination and report any unusual changes in the water to the relevant authorities.
- **To mining and industrial operators**
 - Strengthen measures to prevent groundwater pollution.
 - Ensure proper management of mining and industrial waste.
 - Avoid the direct discharge of effluents and potentially toxic substances into the environment.
 - Participate in environmental monitoring programs for water resources in the vicinity of operational sites.
- **To researchers**
 - Conduct further studies comparing water before boiling, after treatment, and after various storage periods.
 - Expand analyses to include arsenic, mercury, and chromium, and quantify the risks associated with chronic exposure to lead and cadmium.
 - Conduct seasonal studies with larger sample sizes and more sampling points to improve the representativeness of the results.

7. Study limitations

This study has certain limitations.

- The lack of measurements of physicochemical parameters prior to boiling makes it impossible to precisely estimate the changes attributable to heat treatment.
- The relatively short shelf life of the boiled water (1.5 to 1.8 days) limits the assessment of quality changes during prolonged storage.
- Seasonal variations were not examined in depth, even though they can influence water quality.

- Lack of a comprehensive quantitative health risk assessment: The study did not calculate estimated daily intake, Hazard Quotients, or carcinogenic risk.
- Convenience sampling and limited generalizability of the results.
- Lack of data on storage container materials for each household; inability to assess their contribution to Pb and Cd levels.
- Absence of microbiological analyses: the study does not allow for an assessment of the health benefits of boiling.
- Short sampling period : seasonal variations in groundwater quality were not taken into account.

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Conflict of Interest

This work was conducted impartially and with complete independence. No conflicts of interest were reported.

Ethical Considerations

Ethical approval for this study was obtained from the Ethics Committee of the Higher Institute of Medical Techniques of Kinshasa (ISTM/KIN), Democratic Republic of the Congo, under reference No. 311 CBE/ISTM/KIN/RDC/PMBBL/2025, dated December 15, 2025. All procedures were carried out in accordance with ethical standards, particularly regarding informed consent and confidentiality.

Ethics and Informed Consent

Free and informed written consent was obtained from each head of household participating in the study. Prior to inclusion, the study objectives, the nature of the sampling, the terms of participation, the absence of risk to participants, and their right to withdraw at any time without consequence were clearly explained.

Author Contributions

- B.B.P designed, collected, analyzed, and interpreted the data and wrote the main manuscript.
- A.S. A: contributed to the interpretation of the results and to the formatting of the manuscript.
- A.F.O: contributed to data entry and analysis using SPSS software, and to reviewing the presentation of results in tables.
- N.K.J.P supervised and validated the data, contributed to the discussion, and approved the final version.
- M.D reviewed the final version and approved it.

All authors have read and approved the final version of the manuscript.

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