

## Physico-chemical and bacteriological analysis of the water quality of the REGIDESO distribution network, Boma Center during the dry season 2025 in Kongo Central (D.R. Congo).

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International Journal of Science and Research Archive, 2026, 19(01), 084-104

Publication history: Received on 22 February 2026; revised on 02 April 2026; accepted on 04 April 2026

Article DOI: <https://doi.org/10.30574/ijrsra.2026.19.1.0608>

### Abstract

The quality of drinking water in distribution networks constitutes a major public health issue in Sub-Saharan Africa, notably due to the aging of infrastructures and operational constraints. This study aims to evaluate the physico-chemical and bacteriological quality of water distributed by REGIDESO in Boma (D.R. Congo) during the dry season 2025, to analyze its spatio-temporal variability and to identify the critical points of the network.

A total of 264 samples were analyzed for physico-chemical parameters (pH, residual chlorine, turbidity) and 120 samples for bacteriological parameters (*Escherichia coli*, Total and Fecal Coliforms). The data were processed using descriptive and multivariate statistical analyses (PCA and HCA).

The results indicate a low compliance of residual chlorine (41.7%) and a total non-compliance of turbidity (0%), while pH remains globally within standards. No contamination by *Escherichia coli* was detected, but contamination by total coliforms was observed (up to 41.7% depending on the method). The PCA highlights a principal gradient dominated by residual chlorine, while the HCA distinguishes two groups of sites corresponding to contrasted levels of quality.

These results reveal a vulnerability of the distribution network, requiring a strengthening of operational control and infrastructures.

**Keywords:** Drinking Water; Microbiological Quality; *Escherichia Coli*; Waterborne Diseases; Dry Season; Sub-Saharan Africa.

### 1. Introduction

The supply of quality drinking water represents a strategic challenge for population health and sustainable development. According to the joint report of the World Health Organization (WHO) and UNICEF (2023), water intended for human consumption must be free from any microbial contamination and from undesirable physical and chemical

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substances likely to harm the health of consumers. Despite progress achieved in many countries, the degradation of water quality within distribution networks remains an important concern, particularly in cities of low- and middle-income countries.

The physical and chemical quality of water (pH, turbidity, residual chlorine, etc.) influences not only its organoleptic properties, but also its capacity to limit microbial growth and the degradation of pipes. Moreover, bacteriological quality, determined by the detection of indicator bacteria of fecal contamination (*Escherichia coli*) and total coliforms, constitutes a fundamental criterion of compliance for consumption (Edzwald, 2011; WHO & UNICEF, 2023).

In a distribution network, various factors can deteriorate the fundamental quality of treated water, notably: the aging of pipes, pressure variations, water stagnation, intrusions, insufficient disinfectant. All these elements listed above can lead to a new microbial contamination and changes in physical and chemical factors, thus exposing populations to waterborne diseases such as cholera, diarrhea, and typhoid fever (WHO, 2017).

It is in this context that the regular monitoring of the physical and chemical and bacteriological quality of distributed water appears essential to guarantee the sanitary safety of consumers and to guide actions on necessary adjustments.

The World Health Organization requires the total absence of *Escherichia coli*, fecal and total coliforms in 100 mL of water intended for human consumption (WHO, 2022). However, in many urban piping systems in Africa, maintaining the bacteriological integrity of the network remains a fundamental issue due to leaks, illegal connections, pressure fluctuations and insufficient residual chlorine (Wright *et al.*, 2004; Fisher *et al.*, 2015).

In the Democratic Republic of the Congo, treated water piping structures are confronted with significant structural and operational constraints, more precisely in secondary cities. Despite the fact that access to improved sources of drinking water has undergone significant progress at the national level, the published data concerning the microbiological quality of distributed water remain worrying, only 43% of the Congolese population have access to at least a basic drinking water service in 2024, which is one of the lowest rates in Africa. Only 15% of this population have access to basic sanitation services, which directly affects water quality and public health (WHO/UNICEF, 2025).

Several studies carried out in Central and West Africa have reported high rates of coliform contamination in urban networks, notably during the rainy season, a period during which runoff and infiltration phenomena increase microbial loads (Machdar *et al.*, 2013; Dongzagla *et al.*, 2021).

Seasonal variability constitutes a determining factor in the epidemiology of waterborne diseases. The increase in precipitation can promote the contamination of raw water resources, reduce the effectiveness of disinfection and compromise the tightness of pipes (Checkley *et al.*, 2020; Watts *et al.*, 2023). Several works have focused on water from wells, springs, rivers and boreholes (Kyowire *et al.*, 2024; Keboy *et al.*, 2025). Moreover, research on distribution network water remains non-existent in the DRC, and rare in Africa as a whole.

The city of Boma, being part of the secondary cities of the Democratic Republic of the Congo, located in the province of Kongo Central, is confronted with these difficulties. Given that it has the only water distribution company (REGIDESO) intended for human consumption and that this is done intermittently, scientific studies deserve to be carried out in order to determine the physico-chemical and bacteriological profile of the water of this distribution network.

In view of the above, this research consists of: (i) evaluating the physico-chemical and bacteriological quality of the drinking water distribution network of REGIDESO in Boma during the dry season 2025; (ii) analyzing the spatial and temporal variability using multivariate statistical analyses; (iii) identifying the critical points of the network.

It is in this context that the regular monitoring of the physical and chemical and bacteriological quality of distributed water appears essential to guarantee the sanitary safety of consumers and to guide actions on necessary adjustments.

Even if the water undergoes quality treatment, in accordance with potability standards as set by the WHO (2022) at the outlet of the plant, its quality can deteriorate throughout the distribution network. This situation can raise several varied questions: are the main physical and chemical parameters (pH, turbidity and free residual chlorine) of the water distributed by the water distribution company (REGIDESO) compliant with the standards of the World Health Organization? Is the required concentration of residual chlorine maintained from one end of the network to the other to ensure its microbiological protection? Are there significant variations in water quality between the different sampling points?

In view of the above, this research consists of: (i) evaluating the physico-chemical and bacteriological quality of the drinking water distribution network of REGIDESO in Boma during the dry season 2025; (ii) analyzing the spatial and temporal variability using multivariate statistical analyses; (iii) identifying the critical points of the network.

### 1.1. Study area

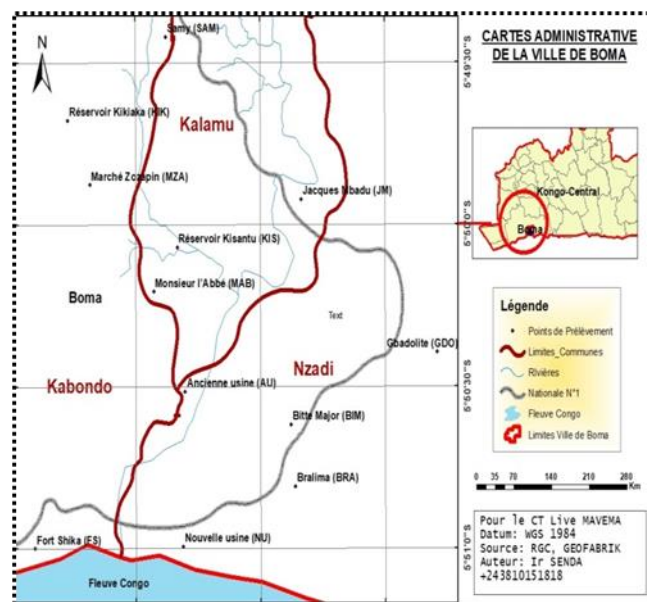
This research was conducted in the historical city of Boma, located in the province of Kongo Central, in the southwest of the Democratic Republic of the Congo. The city is established on the right bank of the Congo River and constitutes an important port connected both to river routes and to the sea, thus allowing the transport of goods of the country. It is crossed by National Road No. 1 (RN1), a strategic axis linking the interior of the national territory to the Atlantic coast (Mavema, 2023).

This city is positioned at the coordinates 05°50'55" S and 13°03'22" E, at an altitude which generally varies between 5 and 150 meters, of which the average is about 47 m, and covers an estimated area of 4,332 km<sup>2</sup> (Mavema, 2023). The relief is mainly composed of hills and weakly elevated plateaus. The whole extent of this territory is dominated by hills extending from east to west, which influences water drainage (<https://www.dioceseboma.org>).

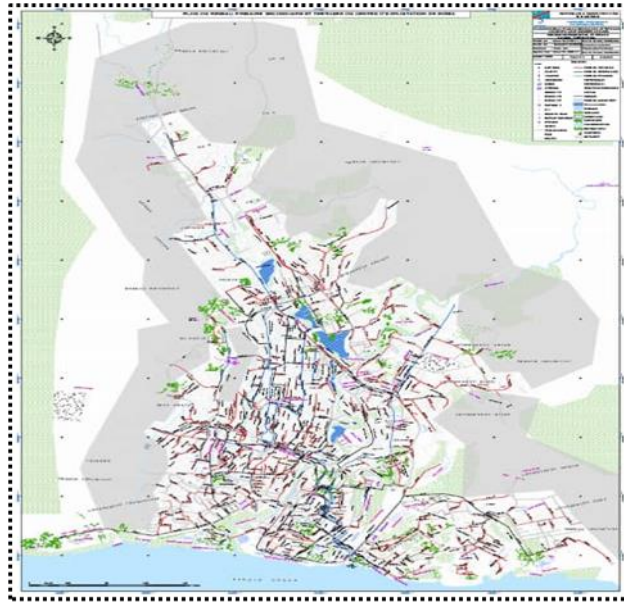
The city of Boma has a humid tropical climate of type Aw according to the Köppen classification, distinguished by the alternation of two seasons: (i) a rainy season, from mid-October to mid-May, marked by torrential rains; (ii) a dry season, from May to mid-October, characterized by low precipitation. The average annual temperature ranges between 24 and 25 °C, the relative humidity rises up to about 80% (Climate-Data.org., 2024).

Boma is a city located about 470 km west of Kinshasa, 125 km from Matadi, the capital of the Kongo Central province and 117 km from Moanda. The city is also crossed by two local rivers, Kabondo and Kalamu. The geographical position of the city of Boma places it in the western part of the country, an area limited to the north by the Republic of Congo and the Angolan enclave of Cabinda, to the south by Angola, to the east by the region of Matadi and to the west by the Atlantic Ocean (<https://www.dioceseboma.org>, consulted on 05/03/2026).

According to the annual report of the City Hall of Boma (2024), the city of Boma hosts a population of about 414,391 inhabitants (413,680 nationals and 711 foreigners), with a distribution by municipality of 122,534 for Nzadi, 121,376 for Kabondo and 170,481 inhabitants for Kalamu.



**Figure 1** Administrative map of the city of Boma including the sampling points by municipality (Source: Congolese Geographic Network, GEOFABRIK, 2025)



**Figure 2** Mapping of the primary, secondary and tertiary network of the REGIDESO/Boma operation center (Source: Mapping and studies section, Technical service, Distribution division, REGIDESO, Regional Directorate of Kongo Central/Matadi, 2023)

**Table 1** Geospatial coordinates of sampling points in the Boma water distribution network

Sampling points	Latitude	Longitude	Altitude (m)	Distance from plant outlet (km)
Old plant (AU)	S 05°50'56.5"	E 013°03'29.0"	47 m	1,225
Kikiaka reservoir (KIK)	S 05°49'43.2"	E 013°02'55.3"	115 m	3,700
Kisantu reservoir (KIS)	S 05°50'07.1"	E 013°03'14.5"	83 m	2,795
New plant (NU)	S 05°51'34.3"	E 013°03'41.2"	7 m	0,000
Fort Shika (FS)	S 05°51'20.2"	E 013°01'58.2"	22 m	3,205
Gbadolite (GDO)	S 05°49'41.3"	E 013°04'07.1"	39 m	3,566
Samy (SAM)	S 05°48'28.6"	E 013°02'49.4"	22 m	5,920
Monsieur l'Abbé (MAB)	S 05°49'35.8"	E 013°03'10.2"	54 m	3,751
Bralima (BRA)	S 05°51'01.7"	E 013°04'21.9"	16 m	1,605
Marché Zozapin (MZA)	S 05°50'06.1"	E 013°03'08.6"	69 m	2,895
Jacques Mbadu (JM)	S 05°49'09.9"	E 013°03'18.9"	14 m	4,475
Bitte Major (BIM)	S 05°50'40.2"	E 013°03'59.0"	13 m	1,747

The geospatial coordinates (latitude, longitude and altitude) were measured using a Garmin MAP 60 CSx GPS. Distances were calculated from the new plant which is the outlet point of water at the treatment plant.

The distance in kilometers (km) of each sampling point from the plant outlet varies from 1.225 km at the nearest point (Old Plant) to 5.920 km at the farthest point (Samy).

## 2. Methods

### 2.1. Study design

The present study, of analytical and prospective type, concerns the microbiological quality of water of the distribution network operated by REGIDESO center of Boma. The sampling and analysis campaigns were carried out during the dry season 2025 (May 2025 to October 2025) in twelve (12) sampling points of the said network.

Two sampling series per month were carried out in duplicate sampling for each point, i.e. ten (10) campaigns in total and one hundred twenty (120) samples intended for bacteriological analyses.

### 2.2. Sampling and sampling techniques

#### 2.2.1. Site selection

The choice of sampling points was based on three elements:

- Selection linked to strategic infrastructures of the distribution network (plants and reservoirs: NU, AU, KIS, KIK);
- Randomized selection covering different service areas (GDO, BIM, MAB, FS, MZA);
- Stations previously identified as being vulnerable to bacterial contamination (BRA, SAM), based on a previous study (Mavema, 2023).

The mapping of the network was respected in order to ensure spatial and rational representativeness of the distribution network.

#### 2.2.2. Sampling procedure

The different samplings were carried out according to the recommendations of the World Health Organization (2022) and ISO standards 5667-5 (2006), ISO 19458 (2006) and ISO 5667-3 (2018).

Before sampling, 0.25 mL of 10% sodium thiosulfate solution was placed in each sterilized bottle (250 mL) in order to neutralize residual oxidants (free chlorine and chloramines) to prevent bacterial inhibition.

An alcohol burner (70%) was used to flame metal taps for one minute, while plastic taps were aseptized with sodium hypochlorite. Then, the water was allowed to flow for 2 to 5 minutes to rinse the disinfectant and remove detached microbes.

The samples collected and analyzed in duplicate were taken under antiseptic conditions, without any manual contact with the inside of the bottle. After filling the bottle up to the mark, the bottles were immediately closed, wrapped with aluminum foil and labeled (code, site, date, time, temperature), then placed in a cooler at  $4 \pm 2$  °C and transported to the laboratory for analysis within the prescribed time.

### 2.3. Analysis methods

The bacteriological analyses concerned: *Escherichia coli*; fecal coliforms and total coliforms. Two complementary methods were used in two different laboratories in order to compare analytical performances.

#### 2.3.1. Method 1: Inoculation in Petri dishes (M1)

This method was carried out in the REGIDESO laboratory Center of Boma, according to the prescriptions of Rodier et al. (2009). It consists in inoculating a volume of sample directly onto a solid culture medium to allow the development and counting of viable bacteria.

A known volume of 1 mL of water sample was sterilely inoculated into sterile Petri dishes, followed by the addition of 10 mL of molten medium (maintained at  $44 \pm 1$  °C). After homogenization, the dishes were incubated in inverted position at  $37 \pm 2$  °C for 24 to 48 hours.

Two media were used, namely: MacConkey agar (total coliforms and *Escherichia coli*) and Simmons citrate (complementary identification tests, notably for *Klebsiella* spp.). The colonies were counted manually or using a colony

counter (Biolock Colony Counter). The results were expressed in colony forming units per milliliter (CFU/mL), in accordance with ISO 9308-1 (2014).

### 2.3.2. Method 2: Membrane filtration (M2)

This second method was carried out in the provincial laboratory of REGIDESO/Matadi, according to ISO 9308-1 (2014), WHO recommendations (2017) and APHA standards (2017).

Two media were also used: m-Endo agar (search for total coliforms and *Escherichia coli*) and Simmons citrate (complementary identification tests). After 24 to 48 hours of incubation in a Memmert incubator, characteristic colonies were counted and expressed in CFU/100 mL, according to international standards.

A volume of 100 mL of sample was filtered under moderate vacuum through a sterile membrane with porosity 0.45  $\mu\text{m}$ . The membrane, retaining the bacteria, was placed on a selective medium and incubated at:  $37 \pm 2 \text{ }^\circ\text{C}$  (total coliforms and *Escherichia coli*);  $44 \pm 0.5 \text{ }^\circ\text{C}$  (fecal coliforms).

## 2.4. Expression and validation of results

The results obtained were interpreted according to the recommendations of the World Health Organization, which require the total absence of *Escherichia coli* in 100 mL of water intended for human consumption. The analyses were carried out in duplicate for various advantages, notably: ensuring reproducibility, scientific credibility and reliability of results.

## 2.5. Analyses of physico-chemical parameters of water

Four (4) sampling campaigns per month (i.e. once per week) were carried out for each sampling point, for a total of twenty-two (22) campaigns and two hundred sixty-four (264) samples analyzed.

The main physical and chemical parameters recommended by the World Health Organization for water in a distribution network concerned free residual chlorine (mg/L), pH and turbidity (NTU).

Given that these parameters are very dynamic, pH and free residual chlorine were evaluated respectively in situ, using a multiparameter probe of brand OAKTON PCD650 and by the colorimetric method with DPD1, using a colorimetric comparator.

Turbidity is the only factor that was measured in the laboratory of the REGIDESO authority, center of Boma using a spectrophotometer of brand LOVIBOND.

## 2.6. Statistical analyses

The software PAST (Paleontological Statistics), version 4.03 was used for statistical processing of data (Hammer *et al.*, 2001). Three analytical approaches were selected, namely:

Descriptive statistics: for the calculation of means, medians and standard deviations to describe the distribution and variability of physico-chemical and microbiological parameters.

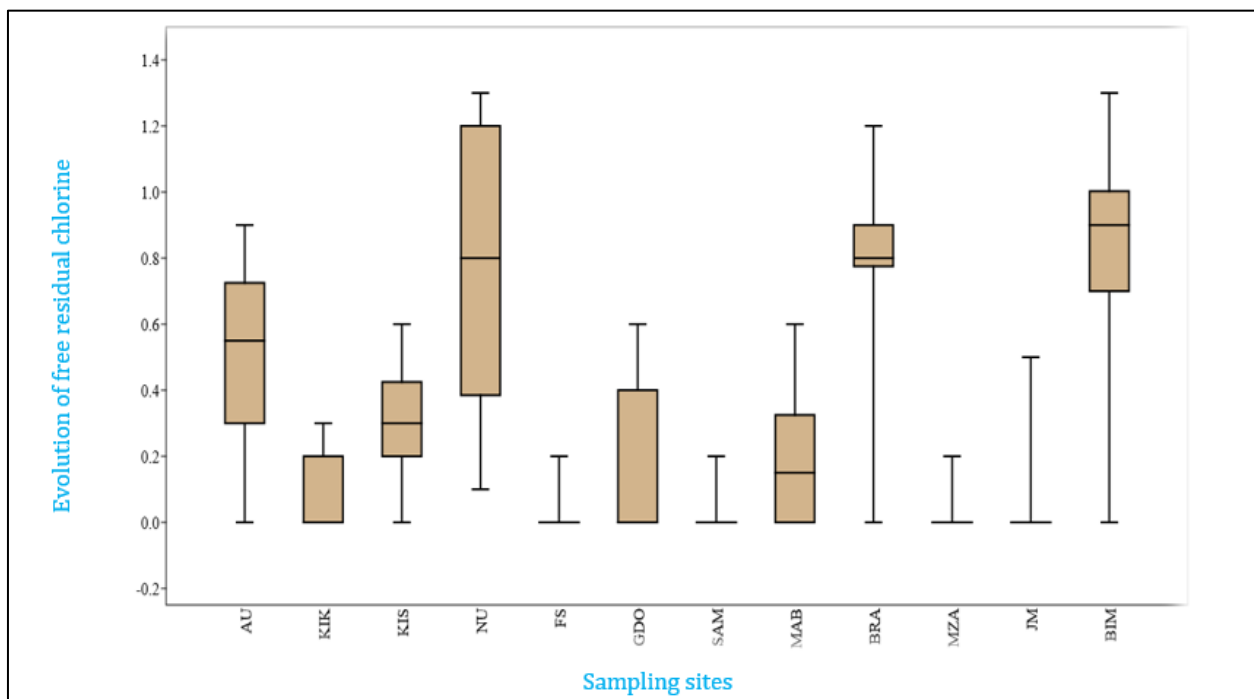
Inferential analyses : this approach allowed the use of the non-parametric Kruskal–Wallis test in order to compare the medians of different parameters between sampling sites and study methods used, due to the non-normal distribution of bacteriological data (Ter Braak, 1987; Palmer, 1993).

Multivariate analysis : this was used for the simultaneous exploration of interactions between several environmental and sanitary variables. Two complementary methods were used (Saporta, 2011): Principal Component Analysis (PCA), to extract correlations between physico-chemical and bacteriological parameters and to identify the main gradients reflecting the structuring of sampling points (Ter Braak, 1988; Ter Braak & Šmilauer, 1998) as well as Hierarchical Ascending Classification (HAC), which allowed to highlight the degrees of similarity or dissimilarity between sampling points based on their physico-chemical and bacteriological characteristics, thus favoring the identification of homogeneous groups of sampling locations (Lebart, Morineau & Piron, 2006).

### 3. Results and Interpretation

#### 3.1. Physico-chemical parameters

##### 3.1.1. Evolution of free residual chlorine: ( $\geq 0.5$ and $0.2$ mg/L) (WHO, 2022)



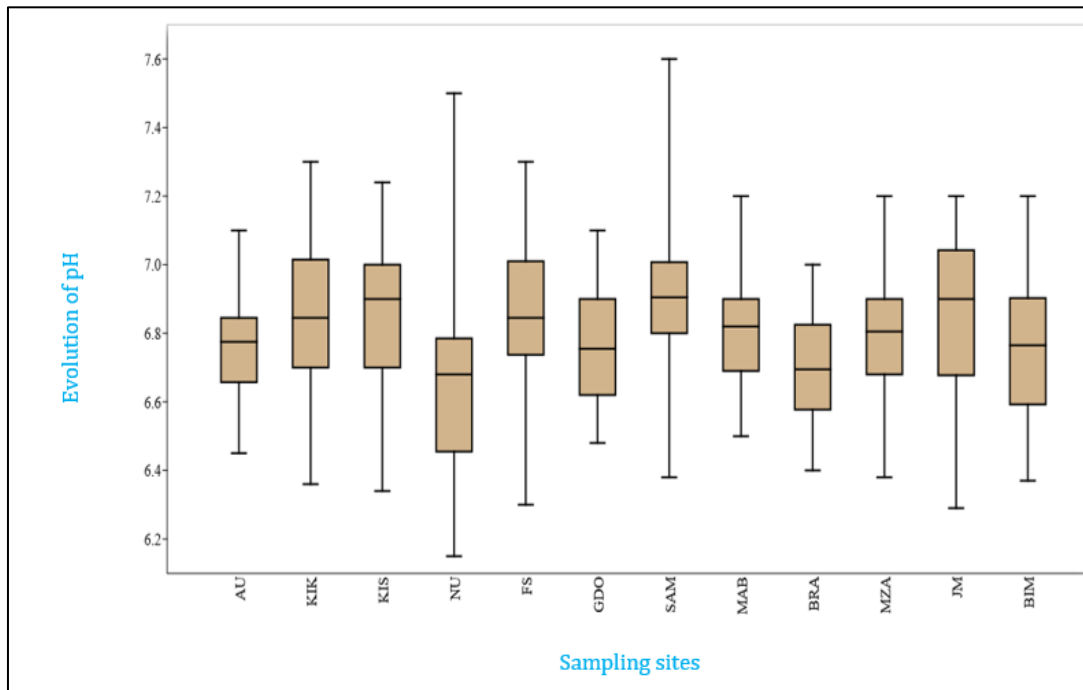
**Figure 3** Evolution of residual chlorine (mg/L) in the sampling points of the REGIDESO distribution network center of Boma during the dry season 2025

The variations of free residual chlorine in the distribution network showed that the highest median was recorded at station BIM (0.90 mg/L), with an interquartile interval of 0.303 mg/L ( $Q1 = 0.70$  mg/L;  $Q3 = 1.003$  mg/L). Conversely, the lowest median (zero) was observed in several stations, notably KIK, FS, GDO, SAM, MZA and JM (median = 0 mg/L), reflecting a quasi-total absence of residual chlorine in these sections of the network.

The variable interquartile ranges, ranging from 0 to 0.815 mg/L, indicate a strong spatial heterogeneity of chlorine distribution. Globally, the average concentrations fluctuate around  $0.31 \pm 0.30$  mg/L, which remains below WHO recommendations (0.2–0.5 mg/L in the network). This dispersion reflects a progressive degradation of residual chlorine along the distribution network, likely to compromise the microbiological safety of water.

The Kruskal-Wallis statistical test indicates a highly significant difference in residual chlorine concentrations between the different sampling points and the plant outlet ( $H_c = 183.5$ ;  $p < 0.05$ ), this significant variability could be due to the high turbidity content throughout the distribution network. This requires a correction of the treatment from the production plant.

### 3.1.2. Evolution of pH: (Slightly acidic) (WHO, 2022)



**Figure 4** Evolution of pH in the sampling points of the REGIDESO distribution network center of Boma during the dry season 2025

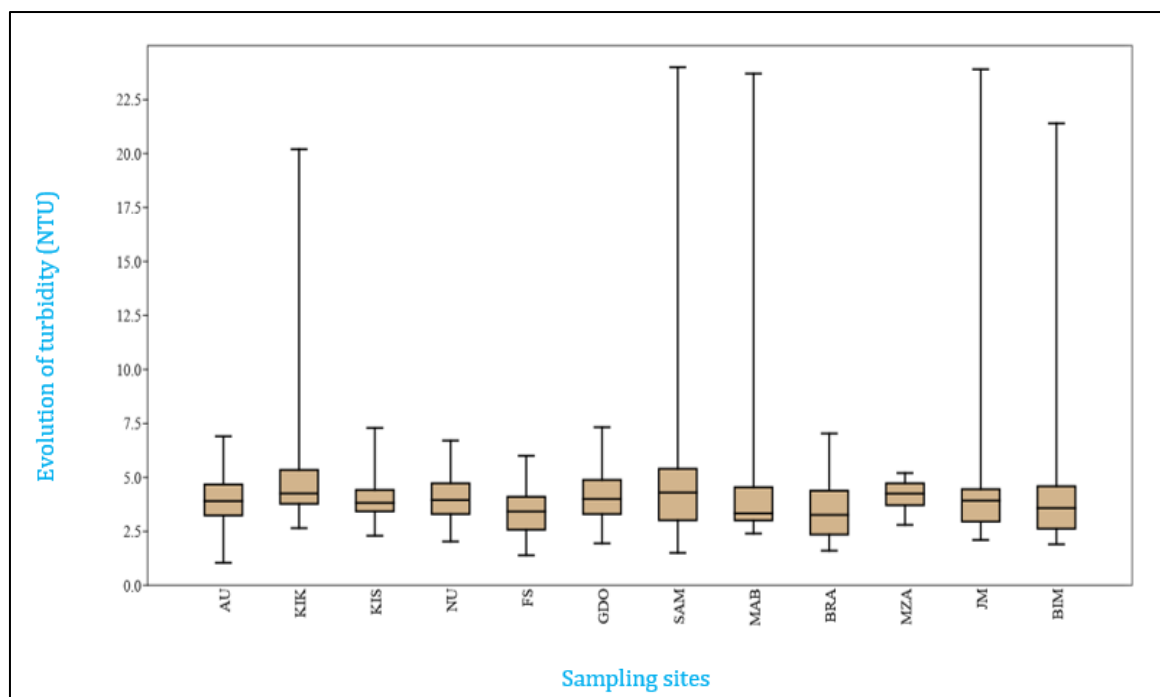
The variations of water pH in the distribution network indicated that the highest median was observed at station KIK (6.775), with an interquartile interval of 0.36 (Q1 = 6.54; Q3 = 6.90). The lowest median was recorded at station SAM (6.565), with an interquartile interval of 0.483 (Q1 = 6.3; Q3 = 6.78).

The relatively low interquartile intervals (between 0.25 and 0.55 pH units) reflect a moderate dispersion and a good spatial homogeneity of pH in the network. Globally, waters present average values around  $6.67 \pm 0.31$ , indicating slightly acidic water but compliant with WHO recommendations. This stability of pH is favorable to treatment efficiency and to the organoleptic quality of distributed water.

The non-parametric Kruskal-Wallis test shows that there is a very significant difference in pH between sampling points and the plant outlet ( $H_c = 33.06$ ;  $p < 0.05$ ). The pH presents a trend close to neutrality with partially low differences between the different sampling points.

### 3.1.3. Evolution of turbidity: (Clearer water, $\approx \leq 1$ NTU) (WHO, 2022).

The variations of turbidity showed that the highest median was recorded at station KIK (4.255 NTU), with an interquartile interval of 1.573 NTU (Q1 = 3.775 NTU; Q3 = 5.348 NTU). The lowest median was observed at station BRA (3.26 NTU), with an interquartile interval of 2.03 NTU (Q1 = 2.35 NTU; Q3 = 4.38 NTU).



**Figure 5** Evolution of turbidity (NTU) in the sampling points of the REGIDESO distribution network center of Boma during the dry season 2025

The relatively high interquartile ranges (up to 2.39 NTU) indicate a notable variability of turbidity between sampling points. The average values are around  $4.27 \pm 1.80$  NTU, largely higher than the value recommended by WHO ( $\leq 1$  NTU). This situation reflects a generalized turbidity in the distribution network, probably linked to an inefficiency of treatment (coagulation/flocculation) and/or to a resuspension of particles in pipes.

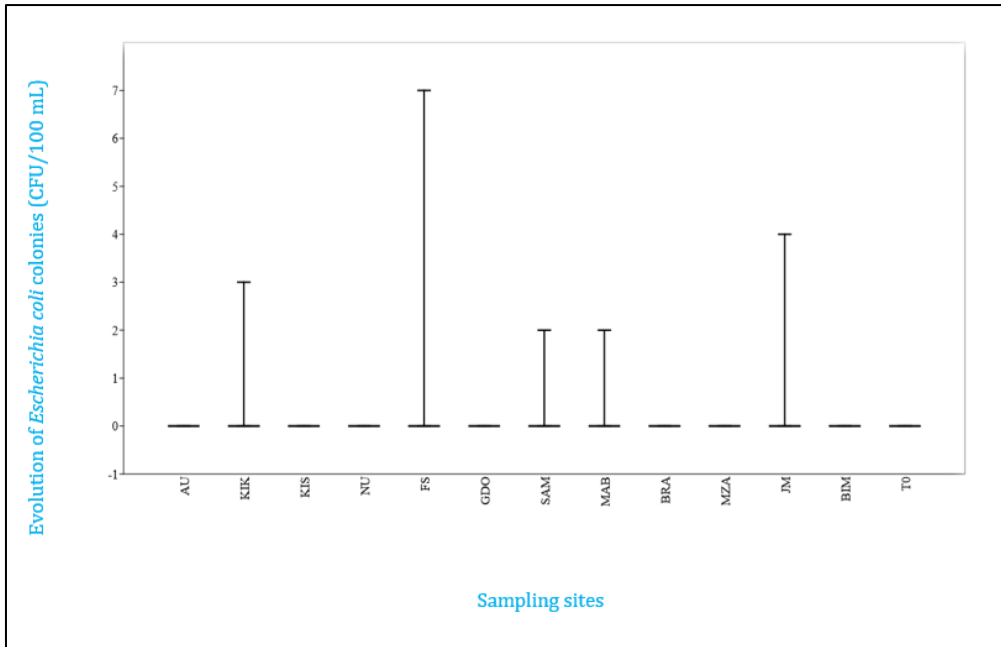
During this season, the non-parametric Kruskal-Wallis test indicates that there is no significant difference in turbidity between the different sampling points and the plant outlet ( $H_c = 16.76$ ;  $p > 0.05$ ). The null hypothesis being acceptable, there is no significant difference. This sufficiently proves that the water in the network is turbid and is not compliant with WHO assessment (2022). This requires an effective coagulation in the water treatment chain.

### 3.2. Bacteriological parameters (WHO, 2022)

#### 3.2.1. *Escherichia coli*: 0 CFU/100 mL (WHO, 2022)

Method of inoculation in simple Petri dishes

The results relating to *Escherichia coli* showed a zero median (0 CFU/100 mL) in all stations, with interquartile intervals also zero ( $Q_1 = 0$ ;  $Q_3 = 0$ ), reflecting a quasi-total absence of fecal contamination.

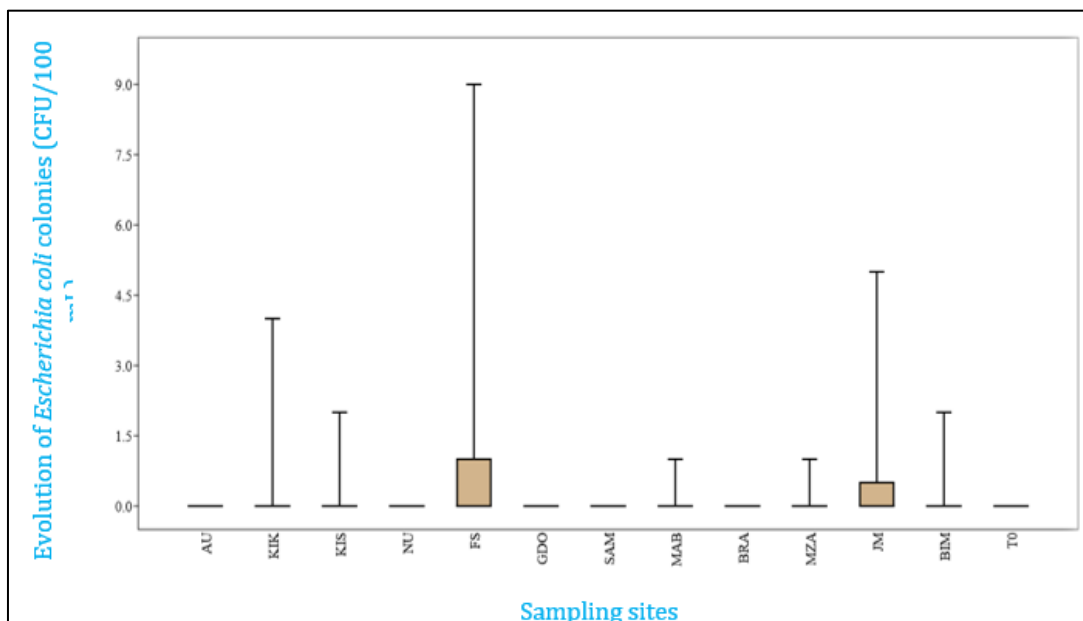


**Figure 6** Evolution of *Escherichia coli* colonies (CFU/100 mL) in the sampling points of the REGIDESO distribution network center of Boma during the dry season 2025

Some punctual maximum values were observed, notably at station FS (7 CFU/100 mL) and JM (4 CFU/100 mL), but without impact on the central tendency. Globally, waters present a very low mean ( $\approx 0.17 \pm 0.63$  CFU/100 mL), indicating a good bacteriological quality compliant with WHO recommendations (0 CFU/100 mL).

The Kruskal-Wallis test ( $H_c = 8.258$ ;  $p > 0.05$ ) indicates the absence of a significant difference in *Escherichia coli* colonies between sampling points and the new plant. The good bacteriological quality of water expressed throughout the network can be justified by the lack of surface water runoff as well as inputs of organic matter.

Membrane filtration method



**Figure 7** Evolution of *Escherichia coli* colonies (CFU/100 mL) in the sampling points of the REGIDESO distribution network center of Boma during the dry season 2025

The variations of *Escherichia coli* obtained by membrane filtration confirm the previous trend, with a zero median (0 CFU/100 mL) in all stations and a generally zero interquartile interval.

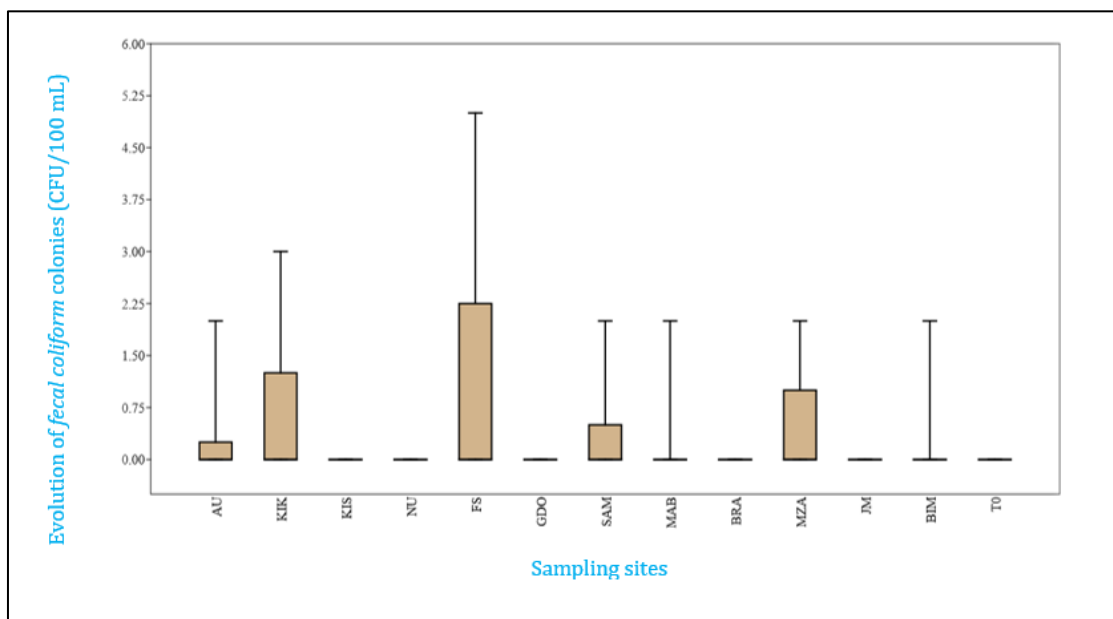
The highest median remains zero in all stations, although higher maximum values were observed at FS (9 CFU/100 mL). The means remain low ( $\approx 0.33 \pm 1.10$  CFU/100 mL), indicating very limited contamination.

This homogeneity of medians and the weakness of dispersions reflect an absence of significant fecal contamination in the network during the dry season.

The application of the non-parametric Kruskal-Wallis test indicates a value of  $H_c = 14.43$  and  $p > 0.05$  justified by the absence of a significant difference in *Escherichia coli* colonies between sampling points and the new plant. The general trend of *Escherichia coli* in the dry season by the second method is characterized by an extremely low contamination of colonies, reflecting water of good bacteriological quality during this study period.

### 3.2.2. Fecal coliforms: 0 CFU/100 mL (WHO, 2022)

Method of inoculation in simple Petri dishes



**Figure 8** Evolution of *fecal coliform* colonies (CFU/100 mL) in the sampling points of the REGIDESO distribution network center of Boma during the dry season 2025

The results of fecal coliforms obtained by the inoculation method in Petri dishes showed a zero median (0 CFU/100 mL) in all stations, with also zero interquartile intervals ( $Q_1 = 0$ ;  $Q_3 = 0$ ), indicating a generalized absence of fecal contamination.

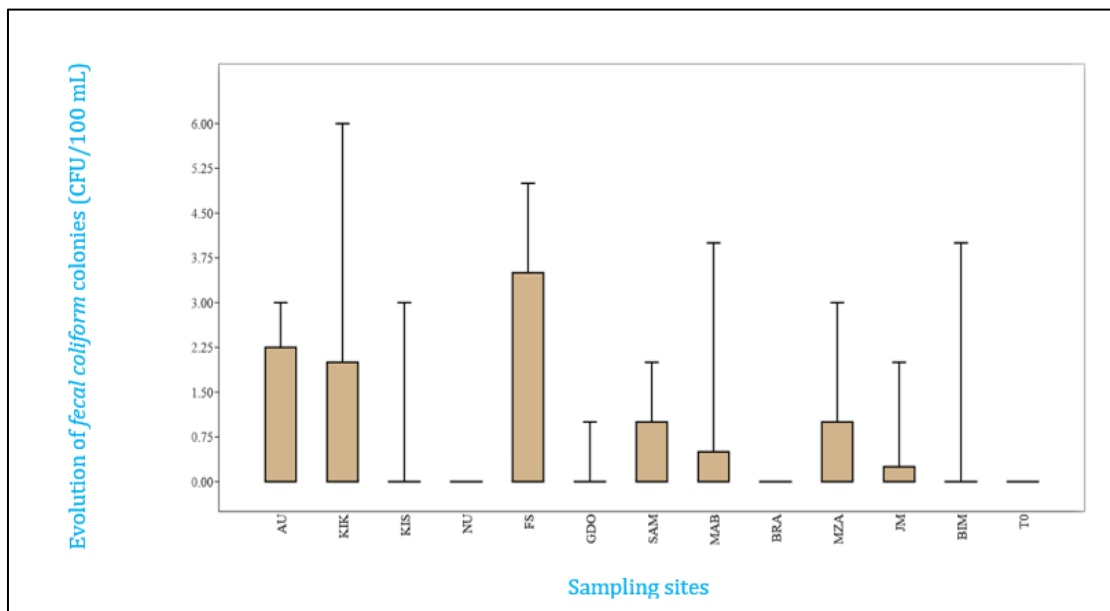
However, some isolated maximum values were observed, notably at station FS (6 CFU/100 mL) and JM (3 CFU/100 mL), without influencing the central tendency of the data. The average values remain very low ( $\approx 0.15 \pm 0.58$  CFU/100 mL), thus confirming a satisfactory microbiological quality of the water.

The application of the Kruskal-Wallis test ( $H_c = 6.274$ ;  $p > 0.05$ ) indicates that there is no significant difference in fecal coliform concentrations between the different sampling points and the plant outlet. This homogeneity suggests an absence of diffuse fecal contamination in the distribution network during the dry season.

Membrane filtration method

The results obtained by membrane filtration confirm the previous observations, with a zero median in all stations and very low dispersion (interquartile interval = 0 in the majority of cases). Some maximum values were recorded at station FS (8 CFU/100 mL) and JM (4 CFU/100 mL), but these values remain isolated and do not affect the overall distribution. The mean values ( $\approx 0.25 \pm 0.90$  CFU/100 mL) remain low and compliant with WHO standards. The Kruskal-Wallis test

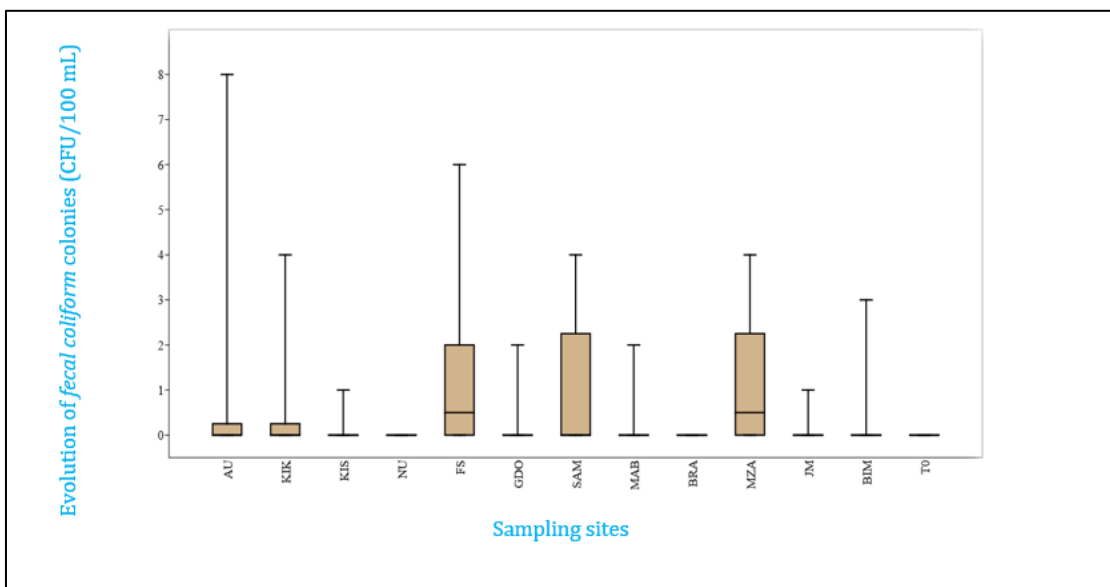
( $H_c = 10.32$ ;  $p > 0.05$ ) also indicates the absence of a significant difference between stations. These results confirm a good bacteriological quality of water with regard to fecal contamination.



**Figure 9** Evolution of fecal coliform colonies (CFU/100 mL) in the sampling points of the REGIDESO distribution network center of Boma during the dry season 2025

### 3.2.3. Total coliforms: 0 CFU/100 mL (WHO, 2022)

Method of inoculation in simple Petri dishes

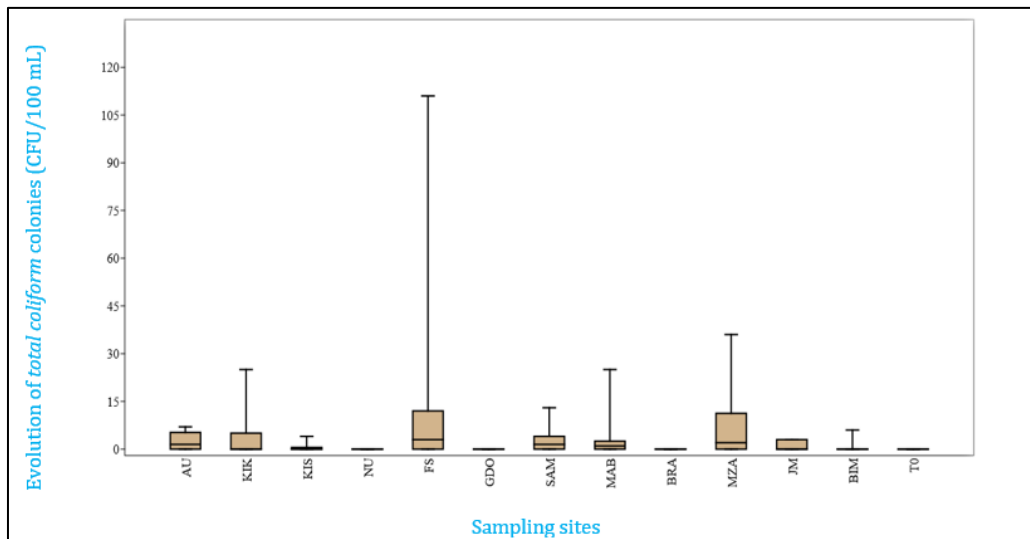


**Figure 10** Evolution of total coliform colonies (CFU/100 mL) in the sampling points of the REGIDESO distribution network center of Boma during the dry season 2025

The analysis of total coliforms revealed a variability between stations. The highest median was recorded at station FS (2 CFU/100 mL), with an interquartile interval of 3 (Q1 = 0; Q3 = 3), while several stations present a zero median. The average values fluctuate around  $0.83 \pm 1.47$  CFU/100 mL, indicating a low but detectable presence of total coliforms in certain points of the network. The Kruskal-Wallis test ( $H_c = 29.91$ ;  $p < 0.05$ ) indicates a significant difference between the sampling points and the plant outlet, suggesting a heterogeneous distribution of total coliforms in the network. This

presence of total coliforms, although moderate, reflects a probable secondary contamination, likely linked to the degradation of the network or to insufficient residual chlorine.

#### Membrane filtration method



**Figure 11** Evolution of *total coliform* colonies (CFU/100 mL) in the sampling points of the REGIDESO distribution network center of Boma during the dry season 2025

The results obtained by membrane filtration show a more marked variability of total coliforms. The highest median is observed at station FS (3 CFU/100 mL), with an interquartile interval of 4 (Q1 = 0; Q3 = 4). The mean values ( $\approx 1.67 \pm 2.85$  CFU/100 mL) are higher than those obtained by the first method, indicating a greater sensitivity of membrane filtration. The Kruskal-Wallis test ( $H_c = 36.58$ ;  $p < 0.05$ ) confirms a significant difference between stations, reinforcing the hypothesis of a heterogeneous contamination within the network. These results confirm that total coliforms constitute the main indicator of deterioration of water quality in the distribution network.

### 3.3. Compliance of physico-chemical and bacteriological parameters

#### 3.3.1. Corrélations entre différents paramètres durant la saison sèche 2025

The Principal Component Analysis (PCA) performed on the physico-chemical and bacteriological parameters shows that the first two factorial axes explain 97.97% of the total variance, with 72.73% for axis 1 (PC1) and 25.25% for axis 2 (PC2). This high cumulative variance indicates that the data structure is well represented in the factorial plane (PC1–PC2), allowing a robust interpretation of the relationships between variables.

The main axis PC1 is strongly structured by a marked positive correlation with total coliforms (TC:  $r = 0.906$ ) and a moderate negative correlation with free residual chlorine ( $Cl_2$ :  $r = -0.422$ ). This opposition reflects a gradient of microbiological water quality, where an increase in total coliforms is associated with a decrease in residual chlorine. This result highlights the determining role of chlorine in controlling bacterial contamination within the distribution network.

In contrast, the variables pH ( $r \approx 0$ ) and turbidity ( $r \approx 0.02$ ) show very weak contributions on this axis, suggesting a limited influence in the main structuring of the data during the dry season. Similarly, *Escherichia coli* and fecal coliforms exhibit null loadings, confirming their absence or very low variability across all analyzed samples.

The secondary axis PC2 is mainly positively correlated with free residual chlorine ( $r = 0.893$ ) and, to a lesser extent, with total coliforms ( $r = 0.421$ ), while turbidity shows a moderate negative contribution ( $r = -0.160$ ). This axis appears to reflect a secondary gradient related to treatment processes and chlorine dynamics, independently of the main microbiological contamination signal.

The analysis of station projections shows that the points FS (0.328; 0.054), MZA (0.251; 0.005), and SAM (0.152; -0.041) are located on the positive side of the PC1 axis, indicating an association with relatively high levels of total coliforms

and/or low disinfection efficiency. Conversely, the stations NU, BRA, BIM, and KIS, located on the negative side of PC1, are associated with relatively better microbiological quality conditions, characterized by lower coliform levels.

Overall, this structuring highlights that the variability of water quality in the network is mainly governed by the balance between disinfection (residual chlorine) and bacterial contamination (total coliforms), while conventional physico-chemical parameters (pH, turbidity) play a secondary role in differentiating sampling stations during the dry season.

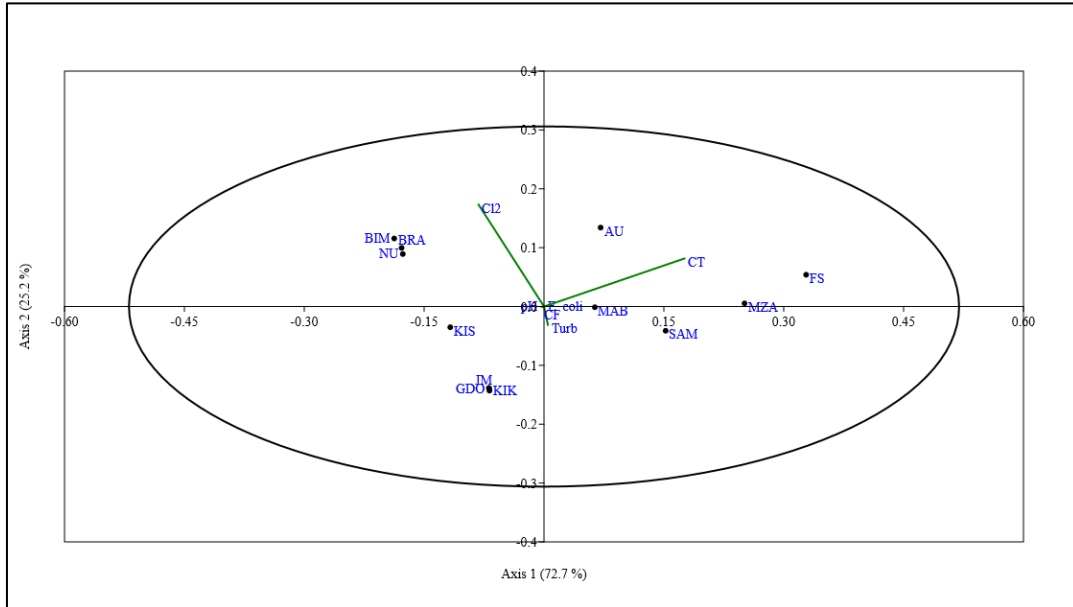


Figure 12 Correlations between physico-chemical and bacteriological parameters in the drinking water distribution network of REGIDESO Centre of Boma during the 2025 dry season (May 2025 to October 2025)

3.3.2. Hierarchical Cluster Analysis of water sampling points

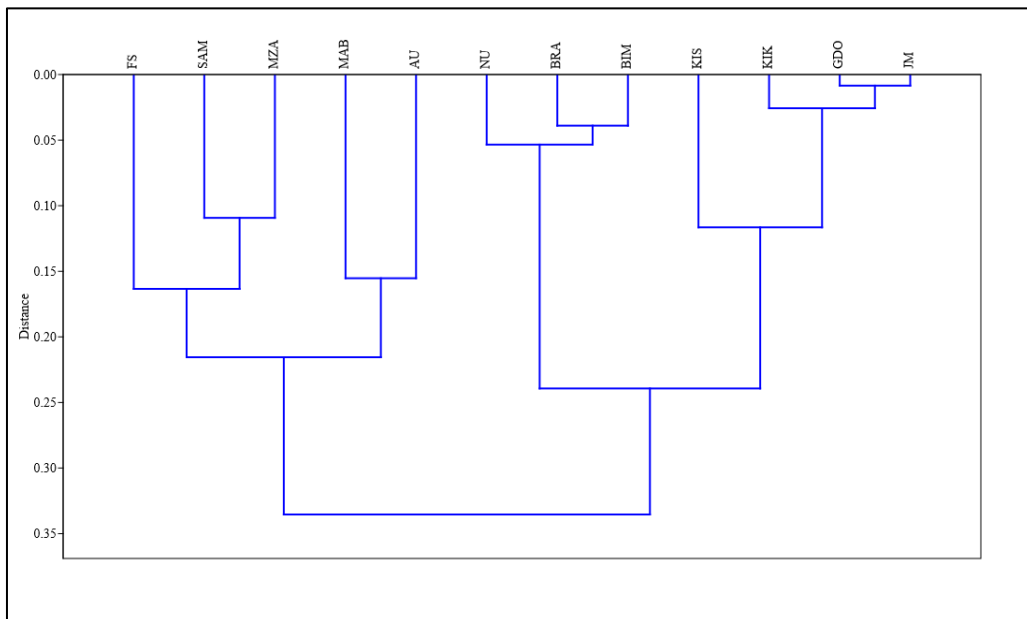


Figure 13 Hierarchical Cluster Analysis of water sampling points in the drinking water distribution network of REGIDESO Centre of Boma during the 2025 dry season (May 2025 to October 2025)

The Hierarchical Cluster Analysis (HCA) applied to the sampling points of the distribution network highlights two main groups of stations, reflecting a spatial structuring of water quality.

The first class includes the stations FS, SAM, MZA, MAB, and AU. This group is subdivided into two distinct sub-classes: a first sub-class consisting of MAB and AU, characterized by relatively intermediate conditions;

- A second sub-class grouping FS, SAM, and MZA, which appear as stations more affected by a relative degradation of microbiological quality, consistent with their position in the PCA (association with total coliforms).

This first class generally corresponds to areas of the network showing greater variability and increased vulnerability, probably linked to factors such as distance from the treatment plant, water stagnation, or the condition of the pipelines.

The second class includes the stations NU, BRA, BIM, KIS, KIK, GDO, and JM, and is also subdivided into two sub-groups:

the first sub-group (NU, BRA, BIM) corresponds to relatively homogeneous stations, characterized by overall better water quality;

the second sub-group (KIS, KIK, GDO, and JM) groups stations with similar characteristics, with lower levels of bacterial contamination and/or better preservation of residual chlorine.

The structure obtained from the HCA is consistent with the PCA results, confirming the existence of a spatial gradient of water quality within the distribution network. This classification highlights the probable influence of operational and hydraulic factors such as:

- Distance from the treatment plant,
- Water residence time in the pipelines,
- And the integrity of the distribution network.

In summary, the HCA reveals that certain areas of the network, particularly those belonging to the first class, show increased sensitivity to water quality degradation, requiring enhanced monitoring and targeted corrective actions.

### 3.4. Compliance and contamination rates of the analyzed samples

**Table 2** Compliance rate of analyzed water samples for physico-chemical parameters during the 2025 dry season according to WHO standards (2022)

<b>Parameters: Sampling points:</b>	<b>Free residual chlorine (Cl<sub>2</sub>) (≥ 0.5 and 0.2 mg/L)</b>	<b>pH (No strict limit) — Slightly acidic ≤ 6.5</b>	<b>Turbidity (Clearer water) (≤ 1 NTU)</b>
AU	0.55	6.77	3.90
KIK	0.00	6.84	4.25
KIS	0.30	6.90	3.82
NU	0,80	6.68	3.95
FS	0.00	6.84	3.41
GDO	0.00	6.75	4.00
SAM	0.00	6.90	4.30
MAB	0.15	6.82	3.33
BRA	0.80	6.69	3.26
MZA	0.00	6.80	4.25
JM	0.00	6.90	3.92
BIM	0.90	6.76	2.62
Compliance rate (%)	41.70	100.00	0.00

The physical and chemical results presented in Table 5.1 show that the analyses carried out during the dry season (2025) exhibit basic heterogeneity with respect to the compliance of the different water samples analyzed according to WHO (2022) standards.

- Free residual chlorine shows a compliance rate of 41.7% with WHO standards (2022);
- pH exhibits 100.0% compliance, considered acceptable according to WHO (2022);
- Turbidity shows 0.0% compliance according to WHO recommendations (2022).

**Table 3** Compliance rate of analyzed water samples for bacteriological parameters during the 2025 dry season according to WHO standards (2022) (M1 / M2 = sampling campaigns or replicates)

Parameters Methods Samples	<i>Escherichia coli</i> (0 UFC/100mL)		Fecal coliforms (0 CFU/100 mL)		Total coliforms (0 CFU/100 mL)		Contamination rate
	M1	M2	M1	M2	M1	M2	
AU	0	0	0	0	0	1,5	16,7
KIK	0	0	0	0	0	0	0,0
KIS	0	0	0	0	0	0	0,0
NU	0	0	0	0	0	0	0,0
FS	0	0	0	0	0,5	3	33,3
GDO	0	0	0	0	0	0	0,0
SAM	0	0	0	0	0	1,5	16,7
MAB	0	0	0	0	0	1	16,7
BRA	0	0	0	0	0	0	0,0
MZA	0	0	0	0	0,5	2	33,3
JM	0	0	0	0	0	0	0,0
BIM	0	0	0	0	0	0	0,0
Compliance rate	0,0	0,0	0,0	0,0	83,3	58,3	41,7

*Escherichia coli*: 0.0% (M1) and 0.0% (M2); Fecal coliforms: 0.0% (M1) and 0.0% (M2); Total coliforms: 83.3% (M1) and 58.3% (M2); Overall contamination rate: 41.7%

Interpretation (implicit from the table):

- *Escherichia coli* and *fecal coliforms* are absent in all samples (full compliance with WHO standards).
- However, total coliforms are present in several stations (notably FS, SAM, MAB, MZA, and AU), indicating partial contamination of the distribution network.
- The overall contamination rate of 41.7% reflects moderate bacteriological degradation of water quality in certain parts of the network during the dry season.
- With regard to the compliance rate with WHO standards (2022): *Escherichia coli* (100%, M1/M2), fecal coliforms (100%, M1/M2), and total coliforms (M1: 83.3%; M2: 58.3%);
- With regard to the contamination rate: overall, 41.7% of the sampling points show contamination by total coliforms, namely AU (16.7%), FS (33.3%), SAM (16.7%), MAB (16.7%), and MZA (33.3%).

#### 4. Discussion

During the 2025 dry season, the analysis of water quality in the REGIDESO distribution network at the Boma center highlights significant contrasts between physico-chemical and bacteriological parameters, revealing partial dysfunctions in the treatment and distribution system.

The results show that only 41.7% of the samples have a residual chlorine concentration compliant with the recommendations of the World Health Organization (WHO, 2022), indicating insufficient disinfection in a significant portion of the network. This deficiency in residual chlorine may promote microbial survival and proliferation in the pipelines, particularly in the presence of biofilms (LeChevallier et al., 2003).

Compared with other studies, the observed values show notable variations. For example, Bastaraud (2019) reports a mean concentration of  $1.1 \pm 0.4$  mg/L, clearly higher than the levels observed in this study. Similarly, Mavema (2023) reports values ranging between 0.1 and 1.13 mg/L, with a higher compliance rate (Mavema *et al.*, 2022: 58.3%). These differences could be explained by variations in treatment conditions, distance within the network, or the state of infrastructure (WHO, 2022).

In contrast, pH shows a compliance rate of 100%, with values comparable to those reported in the literature, notably by Cheikh (2007) and Thiam (2020), who place pH between 7.0 and 7.1. These results indicate satisfactory chemical stability of the distributed water, which limits the risks of corrosion or metal dissolution in the network (WHO, 2022).

Conversely, turbidity shows a non-compliance rate of 100%, which constitutes a critical indicator of water quality degradation. High turbidity can protect microorganisms from the action of chlorine and reduce the effectiveness of disinfection (Edzwald & Tobiason, 1999). The values obtained are higher than those reported by Mahamat (2015) and Yiged (2023), who indicate levels generally below 5 NTU.

Bacteriological analyses reveal total compliance (100%) for *Escherichia coli* and fecal coliforms, indicating the absence of recent fecal contamination in the distributed water. These results are consistent with those of El Houcine Hajioubi et al. (2017) and Mavema (2010), who also observed an absence of fecal contamination in certain well-controlled networks.

However, the presence of total coliforms in 41.7% of the samples (AU, FS, SAM, MAB, and MZA) suggests secondary contamination within the distribution network. Total coliforms are indicators of distribution system failure, particularly in relation to biofilm formation, infiltration of contaminated water, leaks, or pressure drops (LeChevallier *et al.*, 2003).

These results are more favorable than those reported by Mavema *et al.* (2022) and Mavema (2023), who indicate much higher contamination levels, including *Escherichia coli* and *fecal coliforms*.

The combined analysis of PCA and Hierarchical Cluster Analysis (HCA) highlights a structured organization of water quality within the REGIDESO distribution network in Boma, revealing mechanisms of progressive degradation linked to hydraulic and infrastructural conditions.

The PCA indicates that axis 1, explaining 72.73% of the total variance, is strongly dominated by total coliforms (TC) and residual chlorine. This result highlights a main gradient opposing properly disinfected areas to zones vulnerable to secondary contamination.

The inverse correlation observed between residual chlorine and total coliforms reflects a well-documented mechanism in distribution networks: when the disinfectant concentration decreases, particularly with increasing distance from the treatment point, the probability of bacterial regrowth increases (LeChevallier *et al.*, 2003). This phenomenon is often amplified by water stagnation, pressure drops, and the presence of deposits in the pipelines.

Thus, the PCA reveals a functional gradient of network performance rather than a simple random variability of parameters.

Axis 2 (25.25% of variance) is mainly associated with turbidity and residual chlorine, suggesting an interaction between particulate load and disinfection efficiency. High turbidity, observed in 100% of the samples, plays a critical role by protecting microorganisms from the action of chlorine, promoting the formation of ecological niches within biofilms, and increasing chlorine demand (Edzwald & Tobiason, 1999).

This relationship explains why some points may show an absence of *Escherichia coli* while still exhibiting the presence of total coliforms: this indicates environmental contamination or internal bacterial regrowth, rather than direct fecal contamination.

The HCA reinforces this interpretation by identifying two spatially coherent groups:

Class 1: vulnerable zones (FS, SAM, MZA, MAB, AU). This class corresponds to points characterized by a stronger contribution on the positive side of axis 1, an association with total coliforms, and a probable decrease in residual chlorine. These sites can be interpreted as critical areas of the network, potentially located at the ends of the network, in low-pressure zones, or in sectors with aging pipelines.

The subdivision into two sub-classes suggests differentiated levels of degradation, indicating internal heterogeneity even within risk zones.

Class 2: relatively preserved zones (NU, BRA, BIM, KIS, KIK, GDO, JM). This class groups points associated with low values on axis 1 and better control of contamination. These zones may correspond to sectors closer to the treatment plant, benefiting from better hydraulic continuity or having more recent infrastructure.

One of the most important findings of this study lies in the consistency between multivariate statistical approaches and microbiological observations : the absence of *Escherichia coli* and *fecal coliforms* indicates effective initial treatment (absence of recent fecal contamination). The presence of *total coliforms* (41.7%) reflects secondary contamination within the network.

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## 5. Conclusion

The study of the physico-chemical and bacteriological quality of water in the REGIDESO distribution network in Boma during the 2025 dry season highlights a contrasting situation. On the one hand, compliant pH (100%) and the absence of contamination by *Escherichia coli* and fecal coliforms indicate relative effectiveness of the initial water treatment. On the other hand, the low compliance of residual chlorine (41.7%) and the total non-compliance of turbidity (100%) reveal major shortcomings in maintaining water quality within the distribution network.

The presence of total coliforms in 41.7% of the samples highlights secondary contamination, probably linked to structural failures in the network (leaks, intrusions, biofilms). Multivariate analyses (PCA and HCA) confirm this spatial heterogeneity and emphasize the existence of high-risk zones.

These results call for strengthening the maintenance of residual chlorine in the network, improving filtration to reduce turbidity, rehabilitating aging infrastructure, and ensuring regular monitoring of water quality.

The sustainable improvement of drinking water quality represents a major public health issue in the Democratic Republic of the Congo, particularly in relation to the prevention of waterborne diseases and the achievement of the Sustainable Development Goals (WHO, 2022).

This study demonstrates that the quality of water distributed in the REGIDESO network in Boma during the 2025 dry season is characterized by a dissociation between initial microbiological quality and secondary degradation within the network.

The combined PCA–HCA approach made it possible to reveal a structured spatial gradient of contamination, dominated by the interaction between residual chlorine, turbidity, and total coliforms. This structuring highlights the existence of critical zones where hydraulic and infrastructural conditions favor bacterial regrowth.

The absence of *Escherichia coli* confirms the effectiveness of the initial treatment, while the presence of total coliforms highlights the vulnerability of the distribution network. This paradox is characteristic of drinking water supply systems subject to operational and structural constraints.

Thus, improving water quality does not depend solely on treatment, but above all on the integrated management of the distribution network, including: maintaining residual disinfectant, controlling turbidity, and targeted rehabilitation of infrastructure.

These results contribute to a better understanding of the dynamics of drinking water degradation in secondary African cities and provide a scientific basis for guiding sustainable management strategies, in line with WHO recommendations and the Sustainable Development Goals.

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## Compliance with ethical standards

### *Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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