

# Endogenous and exogenous dynamics of urban water quality degradation: Analysis of corrosion mechanisms and organic loading in Kinshasa, Democratic Republic of the Congo

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## ABSTRACT

### Introduction

In many sub-Saharan African cities, aging and intermittently pressurized drinking water distribution networks can compromise water quality beyond the treatment plant. In Kinshasa (Democratic Republic of the Congo [DRC]), hydraulic instability, pipe corrosion, and potential external contamination may alter the physicochemical quality of drinking water during distribution.

### Purpose

This study investigated physicochemical degradation processes occurring within the drinking water distribution networks of the communes of Lemba and Kalamu, with emphasis on free residual chlorine stability, corrosion processes, and potential external contamination.

### Methods

The distribution network was monitored through three grab-sampling campaigns conducted at selected households in the communes of Lemba and Kalamu. A total of 20 water samples were collected from 20 sampling points, including 10 in Lemba (L1-L10) and 10 in Kalamu (K1-K10), distributed along the network. Physicochemical parameters were analyzed using standard methods. Spearman correlation analysis was applied to identify relationships among variables and to infer dominant degradation mechanisms.

### Results

Free residual chlorine (FRC) decreased to 0.10 mg/L at distal points, falling below the World Health Organization's recommended range (0.2–0.5 mg/L), indicating insufficient disinfectant persistence. Two degradation patterns were identified. In Lemba, an endogenous process was observed, characterized by acidic pH (5.86), iron release (up to 0.15 mg/L) suggesting pipe corrosion, and possible localized nitrification (NO<sub>2</sub><sup>-</sup> up to 0.028 mg/L). In Kalamu, degradation appeared to be driven primarily by exogenous factors, including high turbidity (7.37 NTU), elevated phosphate concentrations (1.47 mg/L), and a strong correlation with organic matter (r = 0.91), suggesting potential intrusion of urban effluents.

### Conclusion

The drinking water distribution network functions as a reactive biogeochemical system rather than a passive conduit, with corrosion, organic loading, and hydraulic instability contributing to water quality degradation. These findings highlight the need for targeted infrastructure rehabilitation and adaptive chlorination strategies to ensure safe drinking water delivery.

## INTRODUCTION

The design of drinking water supply (DWS) systems is predicated on the imperative of providing populations with reliable, continuous, and safe water (Mesalie et al., 2021; Price et al., 2022). In a global context characterized by demographic pressure, rapid urbanization, and environmental change, the management of drinking water distribution networks has emerged as one of the most critical environmental challenges of the 21st century. These networks constitute complex and interconnected infrastructures whose function extends beyond simple conveyance: they act as “reactors” in which simultaneous chemical, microbiological, and physical processes occur, ultimately determining the quality of water delivered to consumers (Kanakoudis & Tsitsifli, 2017; Oluwaseye et al., 2018; Wang et al., 2024).

Despite advanced disinfection and monitoring protocols, distribution networks remain vulnerable to secondary contamination that can compromise treatment outcomes. Maintaining free residual chlorine (FRC) is a major technical challenge because its decay kinetics are modulated by complex interactions among water residence time, natural organic matter (NOM), and corrosion processes in unlined iron pipes (Ahmed et al., 2016; Souza et al., 2023). Prolonged stagnation in peripheral areas promotes chlorine depletion and microbial regrowth, while oxidation of dissolved ferrous iron ( $\text{Fe}^2$ ) further consumes disinfectant, reducing the effectiveness of the sanitary barrier. Conversely, excessive chlorination to compensate for these losses can accelerate the formation of disinfection by-products (DBPs), such as trihalomethanes (THMs) and haloacetic acids (HAAs), which pose recognized chronic health risks, including bladder cancer (Ding et al., 2019; Liu et al., 2019; Smith et al., 2021).

Although the influence of physicochemical parameters—such as pH, conductivity, and organic load—on chlorine stability is well documented under controlled conditions (Cao et al., 2025; Kwio-Tamale & Onyutha, 2024), data specific to the unique stresses of sub-Saharan African megacities remain limited. In Kinshasa, a major knowledge gap persists: existing studies have not quantitatively distinguished between endogenous degradation mechanisms inherent to the mineral and

organic composition of water and exogenous factors linked to infrastructure obsolescence, pipe failures, and pressure fluctuations. Without this differentiation, hydraulic and chemical models (e.g., EPANET) cannot be reliably calibrated to predict water age or identify zones at high risk of stagnation and infiltration (Angassa et al., 2025; Kumela et al., 2024; Trębicka, 2022).

Therefore, this study aimed to evaluate residual chlorine dynamics within the Kinshasa drinking water distribution network by integrating physicochemical analysis with spatial vulnerability assessment. Specifically, this research examines interactions among iron release, turbidity, and organic loading to characterize mechanisms driving chlorine decay. The findings are expected to support operational management by identifying priority areas for maintenance and optimizing chlorination strategies based on local network conditions. Ultimately, this study seeks to improve understanding of health risks in aging urban water infrastructures and to provide methodological tools transferable to other regions facing similar hydraulic constraints.

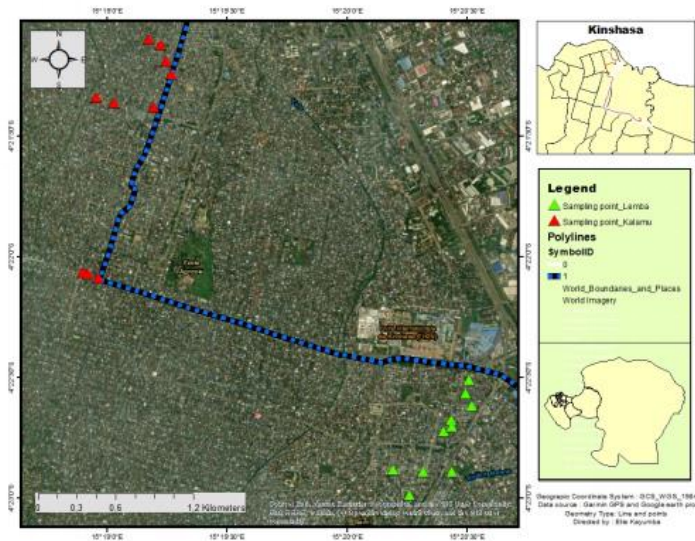
## METHODS

### *Study Area Overview*

The communes of Lemba and Kalamu were selected to characterize two contrasting degradation mechanisms within the REGIDESO drinking water distribution network in Kinshasa (Figure 1). These sites were chosen to distinguish chemical (endogenous) degradation processes from physical and environmental (exogenous) factors influencing the quality of distributed drinking water.

Figure 1:

Google Maps representation of the sampling locations: (a) location of Kinshasa in the Democratic Republic of the Congo; (b) detailed view of the communes of Lemba (sampling points L1-L10) and Kalamu (sampling points K1-K10).



### Lemba Commune

In the commune of Lemba, the distribution network is characterized by advanced structural obsolescence, consisting predominantly of cast iron and steel pipes installed during the colonial and post-colonial periods. The degradation of this infrastructure promotes internal corrosion processes.

These processes are intensified by water-pipe interactions, whereby the chemical aggressiveness of the distributed water contributes to progressive deterioration of pipe walls, metal leaching, and the formation of corrosion tubercles. These deposits act as sinks for free residual chlorine and provide favorable substrates for microbial biofilm development. To evaluate the extent of this degradation, 10 sampling points (L1-L10) were selected along the distribution network. Representative photographs of the sampling points are presented in Figure 2.

### Kalamu Commune

The distribution network in Kalamu, although also aged, is primarily affected by reduced pipe integrity and increased physical porosity. This context facilitates contamination from external sources due to the close proximity of pipelines to precarious sanitation infrastructure, including open drainage channels and septic tanks.

During episodes of hydraulic depression (e.g., water outages or pressure drops), suction phenomena (backsiphonage) may occur, allowing intrusion of runoff water and urban effluents through microfractures and defective joints. This structural vulnerability was assessed through 10 sampling points (K1-K10) located in sectors considered most exposed. Representative photographs are presented in Figure 2.

Figure 2:

Sampling locations in the communes of Lemba (L1-L10) and Kalamu (K1-K10), Kinshasa, Democratic Republic of the Congo (photographs by Mangaka, February 2026).



### Coding and Location of Sampling Points

To characterize physicochemical degradation along the distribution network—from the treatment plant outlet to consumer taps—sampling sites were organized as follows:

- **Lemba network (L series):** Points L1-L10 correspond to household taps connected to the distribution system, where water quality is expected to be influenced primarily by endogenous processes related to chemical deterioration of pipe materials.
- **Kalamu network (K series):** Points K1-K10 correspond to household taps in high-density urban areas, characterized by elevated risks of external pollutant intrusion.

This comparative approach enabled differentiation between the effects of chemical obsolescence (Lemba) and

physical vulnerability (Kalamu) on drinking water safety in Kinshasa.

#### *Sampling Strategy and Spatial Representativeness*

The sampling plan was designed to ensure spatial representativeness of the distribution network in Lemba and Kalamu. These communes were selected due to their high population density, variable infrastructure age, and hydraulic complexity, allowing assessment of water quality degradation during distribution.

To improve data reliability, inclusion and exclusion criteria were applied:

- **Inclusion criteria:** Active household taps directly connected to the official REGIDESO network with continuous or semi-continuous flow.
- **Exclusion criteria:** Taps connected to private underground storage tanks (cisterns), households using booster pumps (which may alter local pressure and turbidity), and points with visible external pipe damage or cross-connection risks were excluded to reduce localized bias.

#### *Water Sampling and Analytical Procedures*

Sampling operations were conducted in accordance with ISO 5667 guidelines (Parts 2, 3, and 5), which govern sampling design, collection procedures, and preservation methods for water intended for human consumption.

Monitoring was performed from October to December 2025, corresponding to the rainy season, in order to account for potential impacts of precipitation on raw water quality and infiltration risks within the distribution system. The study consisted of a single intensive sampling campaign, yielding a total of 20 samples ( $n = 20$ ). This sample size was intended to provide a representative snapshot of physicochemical variability in the two communes under peak seasonal stress.

#### *Collection and Preservation Procedures*

To ensure stability of physicochemical parameters, sampling followed ASTM D3370-18 (ASTM International, 2018), in addition to procedures described by Mavakala et al. (2016), Smith et al. (2021), and Nsiala et al. (2025).

At each sampling point, taps were flushed for approximately 2 min to remove stagnant water and obtain a representative sample from the main distribution line.

The following procedures were applied:

- **Sample containers:** Samples were collected in 500 mL high-density polyethylene (HDPE) bottles and rinsed three times with the sampled water.
- **Headspace prevention:** Following recommendations by Kapembo et al. (2021) and Mukeba et al. (2022), bottles were filled completely (zero headspace) to minimize gas exchange and oxidation that could alter ionic composition or residual chlorine concentration.
- **Transport and storage:** Samples were sealed, labeled, and stored in the dark in insulated coolers at  $4 \pm 2$  °C. They were transported to the laboratory and analyzed immediately to minimize physicochemical changes.

#### *Physicochemical and Ionic Analyses*

All parameters were analyzed using standardized methods (**Table 1**) to ensure measurement reproducibility.

1. **Free residual chlorine (FRC):** FRC was measured *in situ* immediately after sampling using the N,N-diethyl-*p*-phenylenediamine (DPD) colorimetric method, in accordance with ISO 7393-2 (2017) and APHA (2022), Method 4500-Cl G. This method is based on oxidation of the DPD reagent by free chlorine, producing a magenta color proportional to chlorine concentration, measured at 515 nm.
2. **Stability parameters:** Turbidity was determined by nephelometry (ISO 7027-1). pH and electrical conductivity were measured by electrometry (ISO 10523; ISO 7888).
3. **Ionic and organic analyses:** Anions ( $\text{NO}_3^-$ ,  $\text{NO}_2^-$ ,  $\text{PO}_4^{3-}$ , and  $\text{SO}_4^{2-}$ ) and metals (total iron) were quantified by molecular absorption spectrophotometry according to APHA (2022) procedures. Organic load was assessed indirectly using the permanganate index (ISO 8467).

#### *Quality Assurance and Compliance*

Analytical precision was verified using laboratory blanks and duplicate samples for each measurement series. Results were systematically compared with the *World*

Health Organization drinking water guideline values (WHO, 2017) to assess the sanitary compliance of the distributed water.

**Table 1:**  
Analyzed Parameters, Analytical Methods, and Instruments Used for the Physicochemical Characterization of Distributed Water

Parameter	Guideline Value (WHO, 2017)	Analytical Method	Main Reagents	Instrument/Equipment
Free residual chlorine (FRC)	0.2-0.5 mg/L	Colorimetry (DPD1)	DPD No. 1 tablets	CHECKIT® Chlorine DPD Comparator
pH	6.5-8.5	Electrometric measurement	–	IKAYAA multiparameter; HANNA HI 2211 pH meter
Conductivity	30-800 µS/cm	Electrometric measurement	–	HANNA HI 2316 conductometer; IKAYAA multiparameter
Turbidity	≤ 5 NTU	Nephelometric method	–	HANNA HI 88713 turbidimeter
Apparent color	≤ 15 Pt-Co (Hazen)	Colorimetry	–	HACH DR 3900 spectrophotometer
Nitrate (NO <sub>3</sub> <sup>-</sup> )	≤ 30 mg/L*	Spectrophotometry (cadmium reduction)	Nitraver® 5	HACH DR 3900 spectrophotometer
Nitrite (NO <sub>2</sub> <sup>-</sup> )	≤ 0.2 mg/L*	Spectrophotometry (diazotization)	Nitriver® 3	HACH DR 3900 spectrophotometer
Total iron (Fe)	≤ 0.3 mg/L	Spectrophotometry (1,10-phenanthroline)	Ferrover®	HACH DR 3900 spectrophotometer
Phosphate (PO <sub>4</sub> <sup>3-</sup> )	≤ 5 mg/L	Spectrophotometry	Phosver®	HACH DR 3900 spectrophotometer
Sulfate (SO <sub>4</sub> <sup>2-</sup> )	≤ 250 mg/L	Spectrophotometry	Sulfaver®	HACH DR 3900 spectrophotometer
Oxidizable matter	< 2 mg/L O <sub>2</sub>	Titrimetry (KMnO <sub>4</sub> redox)	KMnO <sub>4</sub> , N/80, Na <sub>2</sub> C <sub>2</sub> O <sub>4</sub> , N/80, H <sub>2</sub> SO <sub>4</sub> (25%)	Reflux heating titrimetric setup

Note: WHO guideline values are based on WHO (2017).

\*The values of 50 mg/L (nitrate) and 3 mg/L (nitrite) correspond to WHO (2017) health-based guideline values, whereas the lower values shown in this table reflect recommended operational/aesthetic thresholds used for monitoring.

### Potential Bias and Study Limitations

Despite rigorous application of sampling protocols, several limitations should be acknowledged. First, monitoring was conducted during a single rainy-season period (October–December), and therefore reflects short-term conditions rather than seasonal variability. Changes in raw water quality and treatment practices during the dry season may significantly alter chlorine decay dynamics.

Second, intermittent water supply and pressure fluctuations in the Kinshasa distribution network may promote sediment resuspension and biofilm detachment. Although pre-sampling flushing was applied, transient hydraulic disturbances may still have influenced turbidity and residual chlorine measurements.

### Data Processing and Statistical Analysis

Statistical analyses were performed using SigmaStat (version 11.0) and RStudio (version 1.3.1093) following a four-stage workflow.

#### 1. Variable Selection and Data Integrity

The dataset was screened for consistency, and no missing values were recorded (n = 20). Variables were grouped into (a) control parameters (pH, temperature, turbidity), (b) degradation indicators (organic matter, Fe, nitrate, phosphate), and (c) the target variable (free residual chlorine).

#### 2. Normality Testing

The Shapiro–Wilk test was used to evaluate distribution normality, as it is suitable for small sample sizes (n < 50). Because most parameters significantly deviated from normality (p < .05), nonparametric statistical methods were applied.

#### 3. Correlation Analysis

Relationships among variables were assessed using Spearman’s rank correlation coefficient (ρ). This method is robust to outliers and captures monotonic nonlinear relationships typical of chemical interactions in aging pipe networks. Correlation patterns were interpreted to distinguish endogenous processes (internal hydrochemistry) from exogenous degradation factors (infrastructure-driven contamination).

#### 4. Regression and Significance

Where statistically significant correlations were identified, regression analyses were performed to evaluate sensitivity of chlorine decline to specific indicators. Statistical significance was set at α = .05. Results are reported as mean ± standard deviation (SD). Correlation matrices were generated in RStudio to compare hydraulic and sanitary performance between communes.

## RESULTS

### *Physicochemical Quality Assessment and Regulatory Compliance*

The potability of distributed water was assessed by comparing measured values with WHO (2017) guideline values. Results from Lemba and Kalamu revealed marked divergence between treated water leaving the plant and water quality at consumer taps, indicating progressive physicochemical degradation during distribution.

### *Disinfectant Dynamics and Free Residual Chlorine Stability*

Results (Table 2) indicate insufficient disinfectant protection in several sectors, with pronounced spatial heterogeneity. In Lemba, free residual chlorine decreased to 0.10 mg/L at point L1, while in Kalamu it reached the minimum compliance level (0.20 mg/L) at point K7. These deficits may reflect prolonged residence time in dead-end sections of the network, promoting natural chlorine decay, or elevated oxidative demand linked to biofilms, organic matter, or infiltration of contaminated water.

Conversely, episodes of overchlorination were observed. Free residual chlorine reached 1.5 mg/L at points L2, L3, and L10, and up to 2.0 mg/L at points K4, K5, and K6 (Table 2). Such elevated levels may negatively affect organoleptic properties (taste and odor), potentially leading consumers to seek alternative, unregulated sources.

### *pH and Water Aggressiveness*

Table 2 highlights pronounced acidification in parts of Lemba, suggesting leaching and corrosion processes. Point L4 recorded a pH of 5.86, below the recommended range, indicating chemically aggressive water likely to enhance metal solubilization and electrochemical degradation of cast iron and steel pipes.

In Kalamu, mean pH remained relatively stable ( $6.80 \pm 0.22$ ), although the value measured at point K8 (6.44) indicates localized acidic conditions. Such acidity may reduce infrastructure lifespan and increase the release of corrosion products, thereby compromising distributed water quality.

### *Organoleptic Parameters: Turbidity and Apparent Color*

Results in Table 2 show major exceedances in Kalamu. Turbidity exceeded the guideline value of 5 NTU,

reaching 7.37 NTU at points K1, K2, and K9. This increase coincided with elevated apparent color, peaking at 31 Pt-Co units at point K1, which is more than double the WHO aesthetic threshold (< 15 Pt-Co).

Unlike Lemba, the marked elevation of turbidity and color in Kalamu suggests substantial exogenous particulate input. Suspended particles may act as microbial carriers and reduce chlorine efficiency through shielding effects. These results provide early evidence of potential cross-contamination, likely associated with infiltration of urban effluents or soil particles through microfractures, particularly during hydraulic depression events.

### *Indicators of Infrastructure Obsolescence: Total Iron*

Total iron concentrations generally remained below the guideline value of 0.3 mg/L. However, localized enrichment (0.15 mg/L at L4 and 0.17 mg/L at K9 and K10; Table 2) suggests progressive degradation of pipe materials.

In Lemba, iron release appears primarily linked to acidic pH, which promotes corrosion and metal solubilization. In Kalamu, elevated iron coincided with high turbidity and reduced chlorine residual, suggesting resuspension of internal deposits. These conditions may favor biofilm development and subsequent deterioration of distributed water quality.

**Table 2:**

Basic Physicochemical Parameters and Free Residual Chlorine in the Distribution Networks of Lemba and Kalamu

Commune	Point	FRC (mg/L)	pH	Turbidity (NTU)	Color (Pt-Co)	Iron (mg/L)
Lemba	L1	0.1	6.8	1.20	4	0.05
	L2	1.5	7.1	1.84	3	0.12
	L3	1.5	7.0	0.87	8	0.11
	L4	1.2	5.86	4.74	12	0.15
	L5	1.2	6.0	3.99	14	0.12
	L6	0.8	6.0	2.71	13	0.11
	L7	0.5	7.0	1.29	5	0.09
	L8	0.3	6.9	1.51	4	0.10
	L9	0.5	7.0	1.51	4	0.08
	L10	1.5	7.1	1.31	5	0.11
Kalamu	K1	1.2	6.7	7.37	31	0.04
	K2	1.1	6.7	5.85	23	0.08

		4				
K3	1.2	6.7	5.88	25	0.06	
		3				
K4	2.0	7.1	1.23	6	0.08	
		3				
K5	2.0	7.1	0.82	4	0.07	
		7				
K6	2.0	6.9	0.54	2	0.11	
		1				
K7	0.2	6.6	2.59	12	0.03	
		1				
K8	0.6	6.4	2.44	11	0.05	
		4				
K9	0.4	6.7	6.02	26	0.17	
		2				
K10	0.7	6.7	2.40	13	0.17	
		8				

Note: Guideline values are based on WHO (2017): FRC = 0.2–0.5 mg/L; pH = 6.5–8.5; turbidity < 5 NTU; color < 15 Pt-Co; total iron < 0.3 mg/L. L1–L10 and K1–K10 represent sampling sites in the Lemba and Kalamu networks, respectively.

### Organic Matter and Nitrogen Compounds ( $\text{NO}_3^-$ and $\text{NO}_2^-$ )

Organic matter concentrations (Table 3) were higher in Kalamu (mean = 2.38 mg/L), with a peak of 4.4 mg/L at point K1, exceeding the indicative threshold of 2.0 mg/L. Elevated organic matter provides a substrate for microbial growth, promoting development and persistence of bacterial communities within distribution pipelines.

Nitrate concentrations remained below the WHO (2017) health-based guideline value of 50 mg/L, with a maximum of 13.1 mg/L at point L2. However, their presence may reflect diffuse anthropogenic contamination, potentially linked to domestic wastewater. Nitrite concentrations remained below the WHO guideline value (3 mg/L). Nevertheless, detectable traces (up to 0.028 mg/L at point L4) correlated with iron concentrations, suggesting localized biological activity, potentially nitrification occurring within biofilms associated with pipe corrosion.

### Mineral Parameters: Phosphates and Sulfates

Although WHO has not established a strict health-based guideline value for phosphate, recorded concentrations peaked at 1.47 mg/L at point K8 (Table 3). Phosphate acts as a limiting nutrient that may stimulate bacterial proliferation. The negative association observed between phosphate and residual chlorine in Kalamu ( $\rho = -0.64$ ) suggests potential introduction through infiltration of domestic wastewater into the distribution network.

Sulfate concentrations were low and stable (8–9 mg/L), remaining far below the WHO (2017) aesthetic guideline

of 250 mg/L. This stability suggests limited influence of industrial sulfate-rich effluents in the study areas.

**Table 3:**

Organic Matter and Mineral Ion Concentrations in Distributed Water in the Lemba and Kalamu Communes

Commune	Point	Organic matter (mg/L)	$\text{NO}_3^-$ (mg/L)	$\text{NO}_2^-$ (mg/L)	$\text{PO}_4^{3-}$ (mg/L)	$\text{SO}_4^{2-}$ (mg/L)
Lemba	L1	1.2	4.7	0.019	1.30	8
	L2	1.7	13.1	0.016	0.71	8
	L3	1.5	6.9	0.016	0.87	9
	L4	2.5	4.6	0.028	1.08	9
	L5	3.0	4.8	0.024	1.41	8
	L6	2.7	4.2	0.017	0.85	9
	L7	1.5	3.7	0.009	0.86	9
	L8	1.3	4.6	0.012	0.85	9
	L9	1.4	4.7	0.009	1.08	8
	L10	1.2	8.0	0.013	0.86	8
Kalamu	K1	4.4	3.1	0.013	0.96	8
	K2	4.0	3.7	0.016	0.95	8
	K3	3.1	5.5	0.010	0.87	8
	K4	1.2	4.2	0.018	1.08	8
	K5	1.1	2.9	0.012	1.41	8
	K6	0.8	4.6	0.017	0.86	8
	K7	1.5	4.2	0.009	1.36	8
	K8	1.7	4.7	0.009	1.47	8
	K9	4.3	5.4	0.026	0.95	8
	K10	1.7	5.5	0.021	0.96	8

Note: WHO (2017) guideline values: organic matter (indicative) < 2.0 mg/L; nitrate < 50 mg/L; nitrite < 3 mg/L; sulfate < 250 mg/L. WHO does not specify a health-based guideline for phosphate. L1–L10 and K1–K10 represent sampling sites in the Lemba and Kalamu networks, respectively.

### Statistical Analysis: Identification of Degradation Mechanisms

Cross-analysis of results from Lemba and Kalamu indicates systemic degradation of water quality governed by interacting biogeochemical processes (Table 4). Spearman correlation analysis suggests that instability is driven by combined organic, chemical, and infrastructural factors.

First, the strong relationship between turbidity and organic matter ( $\rho = 0.92$ ) is supported by the highest values observed in Kalamu (e.g., K1: 7.37 NTU and 4.4 mg/L organic matter). Organic loading increases chlorine demand, acting as a major sink for disinfectant. Where organic matter exceeded 2.0 mg/L (e.g., L5 and K9), free residual chlorine tended to decrease. The negative correlation between FRC and turbidity ( $\rho = -0.29$  overall) further suggests that suspended particles contribute to reduced residual protection.

Second, acidification appeared to be a key driver of physicochemical destabilization. In Lemba, pH was strongly negatively correlated with turbidity ( $\rho = -0.87$ ), and the most acidic site (L4; pH 5.86) exhibited the highest turbidity (4.74 NTU). In Kalamu, pH was strongly correlated with chlorine persistence ( $\rho = 0.81$ ), as FRC remained high (2.0 mg/L) where pH exceeded 6.9 (K4–K6). In contrast, at K7 (pH 6.61), chlorine declined sharply to 0.2 mg/L, suggesting chemical instability linked to localized acidity.

Finally, the association between iron and nitrite ( $\rho = 0.66-0.75$ ) provides evidence of infrastructure degradation. Although total iron concentrations remained below the WHO limit (maximum 0.17 mg/L at K9 and K10), its correlation with nitrite (maximum 0.028 mg/L at L4) suggests biological activity within biofilms. Corrosion of cast iron pipes may release iron that supports nitrifying microbial communities, particularly in areas where chlorine residuals are insufficient.

Overall, these findings suggest a combined “cocktail effect,” in which acidity and organic matter enhance corrosion processes and chlorine consumption, reducing sanitary protection at distal points despite acceptable conditions at the treatment plant outlet.

**Table 4:** Spearman Rank Correlation Matrix ( $\rho$ ) Between Physicochemical and Ionic Parameters in Distributed Water (Lemba and Kalamu Communes)

Lemba										
Variable	FRC	pH	Turbidity	Color	Iron	Organic matter	NO <sub>3</sub> <sup>-</sup>	NO <sub>2</sub> <sup>-</sup>	PO <sub>4</sub> <sup>3-</sup>	SO <sub>4</sub> <sup>2-</sup>
FRC	1.00	0.41	-0.12	0.02	0.60	0.10	0.62	0.16	-0.26	-0.38
pH		1.00	-0.87	-0.85	-0.36	-0.86	0.26	-0.70	-0.28	-0.16
Turbidity			1.00	0.93	0.65	0.91	-0.23	0.81	0.21	0.19
Color				1.00	0.51	0.88	-0.14	0.73	0.01	0.23
Iron					1.00	0.47	0.33	0.75	-0.07	-0.11
Organic matter						1.00	-0.18	0.76	0.26	0.08
NO <sub>3</sub> <sup>-</sup>							1.00	-0.13	-0.56	-0.30
NO <sub>2</sub> <sup>-</sup>								1.00	0.06	0.05
PO <sub>4</sub> <sup>3-</sup>									1.00	0.12
SO <sub>4</sub> <sup>2-</sup>										1.00
Kalamu										
FRC	1.00	0.81	-0.64	-0.70	0.22	-0.64	-0.18	0.55	-0.18	NC
pH		1.00	-0.56	-0.62	0.33	-0.52	0.02	0.39	-0.07	NC
Turbidity			1.00	0.98	0.16	0.91	0.10	-0.09	-0.48	NC
Color				1.00	0.08	0.92	0.08	-0.02	-0.41	NC
Iron					1.00	0.15	0.68	0.73	-0.49	NC
Organic matter						1.00	0.09	0.16	-0.44	NC

Variable	FRC	pH	Turbidity	Color	Iron	Organic matter	NO <sub>3</sub> <sup>-</sup>	NO <sub>2</sub> <sup>-</sup>	PO <sub>4</sub> <sup>3-</sup>	SO <sub>4</sub> <sup>2-</sup>
NO <sub>3</sub> <sup>-</sup>							1.00	0.36	-0.52	NC
NO <sub>2</sub> <sup>-</sup>								1.00	0.10	NC
PO <sub>4</sub> <sup>3-</sup>									1.00	NC
SO <sub>4</sub> <sup>2-</sup>										NC

Note. NC = not calculable (parameter constant at 8 mg/L in Kalamu). Values  $\geq |0.70|$  indicate strong correlations.

### Synthesis of Degradation Mechanisms

Table 5 summarizes degradation typologies based on hydrochemical patterns in each commune. Two distinct vulnerability profiles were identified.

In Kalamu, degradation appears to be primarily exogenous. Organic matter peaked at 4.4 mg/L (K1), suggesting substantial external loading that rapidly increases disinfectant demand. The near-perfect correlation between turbidity and color ( $\rho = 0.98$ ) confirms that particulate pollution largely controls the water’s aesthetic characteristics. Under these conditions, chlorine becomes highly unstable: a moderate pH decline (from 7.17 to 6.61) was associated with a sharp decrease in FRC from 2.0 to 0.2 mg/L, leaving portions of the network without adequate sanitary protection.

In contrast, Lemba exhibited an endogenous degradation pattern dominated by internal physicochemical destabilization. Marked acidification (minimum pH of 5.86 at L4) strongly influenced turbidity ( $\rho = -0.87$ ), suggesting corrosion-driven sediment mobilization and release of internal deposits.

In both communes, infrastructure obsolescence is supported by the coupling of iron and nitrite ( $\rho \geq 0.66$ ). Although total iron remained below the WHO guideline value, the simultaneous detection of nitrite (up to 0.028 mg/L) suggests active biofilms in cast iron pipes. This combination of acidity, iron release, and organic matter supports the interpretation of the distribution network as a biogeochemical reactor capable of altering water quality before reaching consumers.

**Table 5:** Comparative Synthesis of Drinking Water Quality Degradation Mechanisms in Lemba (Endogenous) and Kalamu (Exogenous)

Analytical factor	Lemba (endogenous degradation)	Kalamu (exogenous degradation)
Dominant profile	Internal physicochemical reactions and corrosion	Instability driven by external intrusion and organic loading.

Analytical factor	Lemba (endogenous degradation)	Kalamu (exogenous degradation)
	processes.	
Statistical pivot	pH vs. turbidity ( $\rho = -0.87$ ): acidification drives physical destabilization.	FRC vs. pH ( $\rho = 0.81$ ): chlorine persistence depends strongly on pH.
Chlorine dynamics (FRC)	Progressive decline linked to residence time and moderate iron consumption ( $\rho = 0.60$ ).	Abrupt decline linked to high organic demand; FRC decreases from 2.0 to 0.2 mg/L with pH reduction.
Organic loading	Moderate concentrations (maximum 3.0 mg/L). Strong association with nitrite ( $\rho = 0.76$ ).	High concentrations (maximum 4.4 mg/L). Strong association with color ( $\rho = 0.92$ ).
Obsolescence indicator	Fe vs. $\text{NO}_2^-$ ( $\rho = 0.75$ ): corrosion-associated nitrification and biofilm activity.	Fe vs. $\text{NO}_3^-$ ( $\rho = 0.68$ ): advanced corrosion and nitrogen oxidation signature.
Visual impact	Persistent turbidity under acidic conditions (e.g., L4: 4.74 NTU).	Severe turbidity peaks linked to suspected intrusions (e.g., K1: 7.37 NTU).
Probable origin	Endogenous: water aging, stagnation, and corrosion-driven acidification.	Exogenous: intrusion through leaks and elevated chlorine demand from external organic inputs.

## DISCUSSION

The spatial assessment of drinking water quality in the communes of Lemba and Kalamu indicates a progressive breakdown of the sanitary barrier between the treatment plant and consumer taps. These results confirm that the Kinshasa distribution system is not a passive conveyance infrastructure but rather a reactive biogeochemical environment in which water quality is strongly influenced by pipe aging, hydraulic instability, and contamination risks (World Health Organization [WHO], 2017).

### *Mechanisms of Chlorine Degradation and Kinetic Instability*

The decline of free residual chlorine (FRC) to 0.10 mg/L at distal sampling points (L1 and K7) reflects a critical loss of disinfectant persistence. A moderate negative correlation between FRC and organic matter ( $\rho = -0.64$ ,  $p < .05$ ) indicates that chlorine demand is strongly influenced by oxidation of dissolved organic compounds. In aging unlined iron networks, residual chlorine may be rapidly depleted under active corrosion conditions, potentially within short residence times (Donghan et al., 2022). Furthermore, high ambient tropical temperatures (approximately 28–30 °C) may accelerate redox reactions and microbial activity, reducing chlorine half-life.

The concurrent increase in turbidity and reduction in FRC suggests that suspended particles and resuspended sediments act as additional chlorine sinks. Biofilms embedded in extracellular polymeric substances (EPS) may consume disinfectant before it reaches microorganisms located deeper within deposits, thereby reducing overall disinfection efficiency (Douterelo et al., 2014; Fish et al., 2017; Souza et al., 2023).

### *Endogenous Dynamics: Corrosion and Nitrification in Lemba*

In Lemba, degradation appears primarily driven by internal chemical processes resulting from aggressive water interacting with aging metallic pipes. The pH measured at point L4 (5.86) was well below the WHO guideline range (6.5–8.5). The strong negative correlation between pH and turbidity ( $\rho = -0.87$ ) supports the interpretation that acidification promotes destabilization and mobilization of internal deposits.

Elevated iron concentrations (0.15 mg/L) and their strong correlation with nitrite ( $\rho = 0.75$ ) suggest localized nitrification occurring within corrosion tubercles. This process may reflect the development of microbial communities within pipe-wall deposits. Such biological activity can further compromise disinfectant persistence, creating feedback mechanisms in which corrosion products support biofilm growth, thereby sustaining chlorine consumption and weakening sanitary protection.

### *Exogenous Dynamics: External Intrusion in Kalamu*

In Kalamu, water quality degradation appears largely controlled by exogenous contamination mechanisms associated with loss of pipeline integrity. Exceedances in turbidity (7.37 NTU) and apparent color (31 Pt-Co) showed strong association with organic matter ( $\rho = 0.91$ ). Elevated phosphate concentrations (up to 1.47 mg/L) further suggest inputs consistent with domestic wastewater intrusion.

Intermittent water supply and pressure drops can generate negative pressure conditions that facilitate the intrusion of contaminated groundwater or wastewater through defective joints, cracks, and microfractures (Calero et al., 2021; Kumpel & Nelson, 2016; Price et al., 2022; Weronika et al., 2021). Under such conditions, pathogen exposure risk increases, particularly because high particulate and organic loads may reduce chlorine

effectiveness through shielding effects and elevated oxidant demand.

#### *Public Health Risks and Operational Implications*

The combined occurrence of low FRC and high organic load presents a dual public health concern. First, insufficient residual chlorine increases the likelihood of microbial survival and regrowth, potentially including pathogens such as *Vibrio cholerae*. Second, compensatory overchlorination in high natural organic matter (NOM) environments may increase the formation of disinfection by-products (DBPs), including trihalomethanes (THMs), which are associated with chronic health risks.

From an operational perspective, the findings highlight the need for risk-based management strategies that integrate hydraulic control, corrosion mitigation, and targeted chlorination. Key interventions should include improved pH stabilization, systematic pipe replacement in high-corrosion zones, and real-time monitoring of pressure and chlorine residuals at vulnerable distal points.

#### *Study Limitations and Perspectives*

This study provides a baseline characterization of physicochemical degradation in the Kinshasa distribution network. However, the absence of microbial indicators (e.g., *Escherichia coli*) and DBP measurements (e.g., THMs) limits comprehensive microbial and chemical risk assessment. Future studies should integrate hydraulic modeling (e.g., EPANET) with microbiological monitoring and molecular approaches (e.g., metagenomics) to characterize biofilm ecology and contamination pathways. Longitudinal monitoring across rainy and dry seasons is also recommended to capture temporal variability in water age, stagnation, and chlorine decay.

## CONCLUSION

This study evaluated residual chlorine dynamics and identified key mechanisms of drinking water quality degradation within the Kinshasa distribution network. The results demonstrate that sanitary risks in the communes of Lemba and Kalamu do not primarily originate from treatment failure at the plant but rather from degradation processes occurring during distribution. Two distinct degradation patterns were identified: (a) an endogenous model in Lemba driven by acidification-induced corrosion and nitrification, and (b) an exogenous

model in Kalamu dominated by hydraulic intrusion and organic contamination consistent with domestic effluents.

#### *Implications for Public Health and Engineering*

The instability of free residual chlorine, decreasing to 0.10 mg/L at distal points, indicates a major breach of the WHO-recommended sanitary barrier (WHO, 2017). From an engineering perspective, the current reliance on booster chlorination is constrained by elevated chlorine demand associated with unlined iron pipes and high organic loads (> 3 mg/L). From a public health perspective, these conditions create a dual-risk scenario: increased probability of pathogen persistence and regrowth and increased potential for chronic exposure to DBPs generated under high-dose chlorination in NOM-rich water.

#### *Operational Recommendations*

To transition from reactive interventions to proactive and risk-based network management, the following measures are recommended for REGIDESO:

- **Infrastructure prioritization:** Implement a systematic pipe replacement program targeting unlined cast iron and steel pipelines, particularly in corrosion-prone sectors of Lemba. Replacement with high-density polyethylene (HDPE) is expected to reduce corrosion, metal leaching, biofilm development, and localized nitrification.
- **Pressure and leakage management:** Deploy continuous pressure monitoring and acoustic leak detection systems in Kalamu to identify and rapidly repair structural weaknesses. This strategy will reduce intrusion risks during intermittent supply and pressure-drop events.
- **Chlorination optimization and pH stabilization:** Shift from bulk high-dose chlorination toward multipoint (satellite) chlorination to maintain stable FRC levels while minimizing DBP formation. Post-treatment pH adjustment targeting 7.0–7.5 is recommended to reduce the chemical aggressiveness observed in Lemba (minimum pH = 5.86).
- **Integrated monitoring:** Establish routine monitoring combining FRC with turbidity and dissolved iron measurements. These parameters can serve as early-warning indicators of sediment

resuspension, pipe-wall destabilization, and contamination events.

Adoption of this integrated approach—combining infrastructure renewal, hydraulic stabilization, chemical optimization, and routine monitoring—would improve the safety and reliability of drinking water supply in Kinshasa and strengthen long-term public health protection.

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