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Chloroform Occurrence and Drivers of Disinfection By-Product Formation in Drinking Water in the Tropical Andean Region: Evidence from Four Colombian Municipalities

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Chloroform Occurrence and Drivers of Disinfection By-Product Formation in Drinking Water in the Tropical Andean Region: Evidence from Four Colombian Municipalities

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ABSTRACT

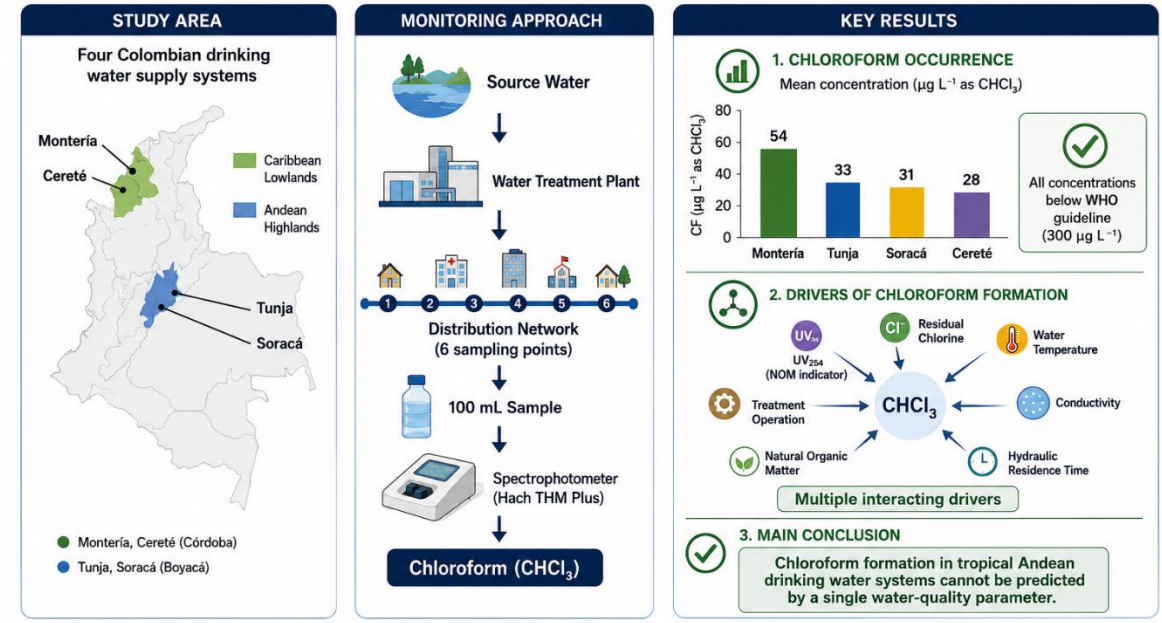
Chloroform (CF) is one of the most prevalent disinfection by-products (DBPs) generated during drinking water chlorination, yet field-based evidence about its occurrence in Colombian water supply systems (WSSs) remains limited. This study quantified CF concentrations and characterized their relationships with key water quality indicators for the first time in four Colombian municipalities: Montería, Cereté, Tunja, and Soracá. Drinking water samples were collected from six points within each WSS during the dry season. Field and laboratory measurements included turbidity (TB), pH, water temperature (WT), electrical conductivity (EC), free residual chlorine (Cl), ultraviolet absorbance at 254 nm (UV_{254}), and CF concentration. TB remained below 1.0 NTU in all municipalities, indicating compliance with Colombian and international guideline values. Cl exhibited spatial variability and frequently fell below the Colombian recommended minimum of 0.3 mg L^{-1} in Tunja and Soracá. Mean CF concentrations from highest to lowest were Montería (54 ± 8.28 µg L^{-1}) > Tunja (33 ± 6.62 µg L^{-1}) > Soracá (31 ± 8.07 µg L^{-1}) > Cereté (28 ± 8.31 µg L^{-1}). Response surface and correlation analyses indicated that CF occurrence was modulated by municipality-specific combinations of WT, EC, Cl, and UV_{254}, with WT and EC more relevant in Montería and Cereté and UV_{254} more influential in Tunja and Soracá. However, correlations were generally weak to moderate, indicating that CF formation was governed by the interaction of source water, treatment, and distribution system conditions rather than by a single predictor. These findings provide baseline evidence of CF occurrence in Colombian WSSs, and support routine DBP monitoring that integrates water quality, natural organic matter (NOM) reactivity, and WSS conditions.

Keywords: Chloroform; disinfection by-products; drinking water distribution systems; natural organic matter; residual chlorine.

HIGHLIGHTS

- First field-based evidence of chloroform occurrence is reported for four Colombian municipalities.
- Chloroform concentrations were detected but remained below the WHO drinking-water guideline value.
- Storage tanks and hydraulic residence time contributed to residual chlorine decay in some systems.
- Municipality-specific water quality conditions shaped chloroform formation patterns.
- Routine DBP monitoring should include individual THMs and HAAs in Colombian water supply systems.

GRAPHICAL ABSTRACT



INTRODUCTION

Drinking water is essential for public health and daily human activities. However, source water quality is increasingly impaired by climate change, intense storm events, agricultural runoff (Abalasei et al., 2025; Yuan et al., 2024a), and inadequately treated wastewater discharges (Yang et al., 2025). These pressures can deteriorate surface source water quality by mobilizing suspended solids, elevating turbidity, enriching natural organic matter (NOM), and increasing pathogen loads (Krasner et al., 2022; Xiao et al., 2024). To mitigate these risks, drinking water treatment plants (DWTPs) commonly employ conventional treatment trains consisting of coagulation, flocculation, sedimentation, filtration, and disinfection (C/F/S/D) (Aboubaraka et al., 2017). Nevertheless, reactions between chemical disinfectants such as chlorine (Cl_2) and NOM, along with naturally occurring bromide or iodide ions, can promote the unintended formation of persistent and potentially harmful disinfection by-products (DBPs) (Zimoch & Łobos, 2016; Li & Richardson, 2026). Consequently, modern drinking water regulations require strict monitoring of major DBP groups, particularly trihalomethanes (THMs) and haloacetic acids (HAAs), within water supply systems (WSSs) (Park et al., 2025).

The rate and extent of DBP formation are controlled by raw water characteristics (e.g., NOM concentration and aromaticity, pH, and water temperature), operational treatment conditions (e.g., coagulant type, chlorine dose, pH, and disinfectant contact time), distribution network properties (e.g., pipe material), and length of water storage time (Lacroix et al., 2024; Qin et al., 2026). Exposure to regulated, unregulated, and emerging DBPs in drinking water may potentially pose human health risks, including carcinogenicity, reproductive toxicity, and cytotoxicity (Imafidon et al., 2025; Shi et al., 2026). Several advanced treatment strategies have been implemented to attenuate DBP formation, including ultraviolet (UV) irradiation for pathogen inactivation, hydrogen peroxide (H_2O_2)-based advanced oxidation processes (AOPs), pre-chlorination coupled with ozonation, and multi-oxidant approaches involving ozone, chlorine dioxide, permanganate, or

ferrate (Du et al., 2026; Hu et al., 2026; Toor & Mohseni, 2007). However, for many utilities in developing regions, these advanced technologies remain financially or operationally constrained.

DBP occurrence in drinking water of the Andean tropical region has not been sufficiently investigated. In this region, the quality of natural waters is influenced by watershed land cover that impacts pollutant transport (Matovelle et al., 2026). Altitude has a major impact on water temperature, which is an important driver of DBP formation, particularly of THMs. In Colombia, guidelines set a maximum allowable concentration of total trihalomethanes (TTHMs) in WSSs at 200 $\mu g\ L^{-1}$, a threshold which is higher than both the U.S. EPA maximum contaminant level of 80 $\mu g\ L^{-1}$ for TTHMs, and the World Health Organization (WHO) guideline framework for individual THM species (USEPA, 2026; WHO, 2017). The TTHM group comprises four chemical species: chloroform (CF), bromodichloromethane (BDCM), dibromochloromethane (DBCM), and bromoform (BF). The WHO has established individual guideline values for these compounds in drinking water as follows: CF < 300 $\mu g\ L^{-1}$, BDCM < 60 $\mu g\ L^{-1}$, DBCM < 100 $\mu g\ L^{-1}$, and BF < 100 $\mu g\ L^{-1}$ (WHO, 2017). Among these species, CF has been widely documented as the most prevalent and abundant DBP in chlorinated distribution networks (Tafesse et al., 2023; Li et al., 2021).

This study aimed to quantify for the first time the variability of CF concentrations across the WSS networks of four Colombian municipalities located in the tropical Andean region: Montería and Cereté in the Department of Córdoba, and Tunja and Soracá in the Department of Boyacá. In addition, we characterized statistical relationships between CF occurrence and key operational water quality indicators, including turbidity (TB), pH, water temperature (WT), electrical conductivity (EC), and ultraviolet absorbance at 254 nm (UV_{254}), which is used to characterize NOM. We also measured free residual chlorine (Cl) using an accessible colorimetric method. This study addresses a critical monitoring gap by providing field-based evidence of chloroform occurrence and its physicochemical drivers in Colombian WSSs, while demonstrating that low-cost colorimetric approaches can support DBP surveillance when access to advanced analytical infrastructure is limited.

MATERIALS AND METHODS

Sampling and field measurements

Four municipalities were selected to characterize drinking water quality and evaluate CF formation within their WSSs: Montería and Cereté in the Department of Córdoba, and Tunja and Soracá in the Department of Boyacá, Colombia (Fig. 1). The population of these municipalities from the highest to the lowest are as follows: Montería 531.000; Tunja 172.550; Cereté 108.410 and Soracá 5.350 These municipalities are located at altitudes ranging from 14 m to 2820 m above sea level, affecting the quality of source water and its seasonal temperature. Water samples were collected on different days during the dry season of January 2024. Six sampling locations were established in each municipality to represent the geographic distribution of users throughout the WSS, including the presence of public and residential facilities such as hospitals, schools, restaurants, and households, and to provide representative coverage with respect to both the distance from the water treatment plant (WTP), an indicator surrogate of the hydraulic residence time. In Monteria, monitoring

only covered approximately one-third of the total distribution system, because the municipality is supplied by seven WTPs. Our sampling was restricted to the service area supplied by Sierra Chiquita WTP, the largest treatment plant in Montería.

The WTPs in Montería and Cereté use the Sinú River as their source, and employ a conventional treatment train comprising coagulation, flocculation, sedimentation, filtration, and disinfection (C/F/S/D). The Tunja WTP is supplied by reservoir water and applies a similar conventional treatment train. In contrast, the Soracá WTP treats water from a small stream using a multistage filtration (MSF) system that includes roughing filtration, slow sand filtration, and final disinfection (González-Galvis et al., 2024).

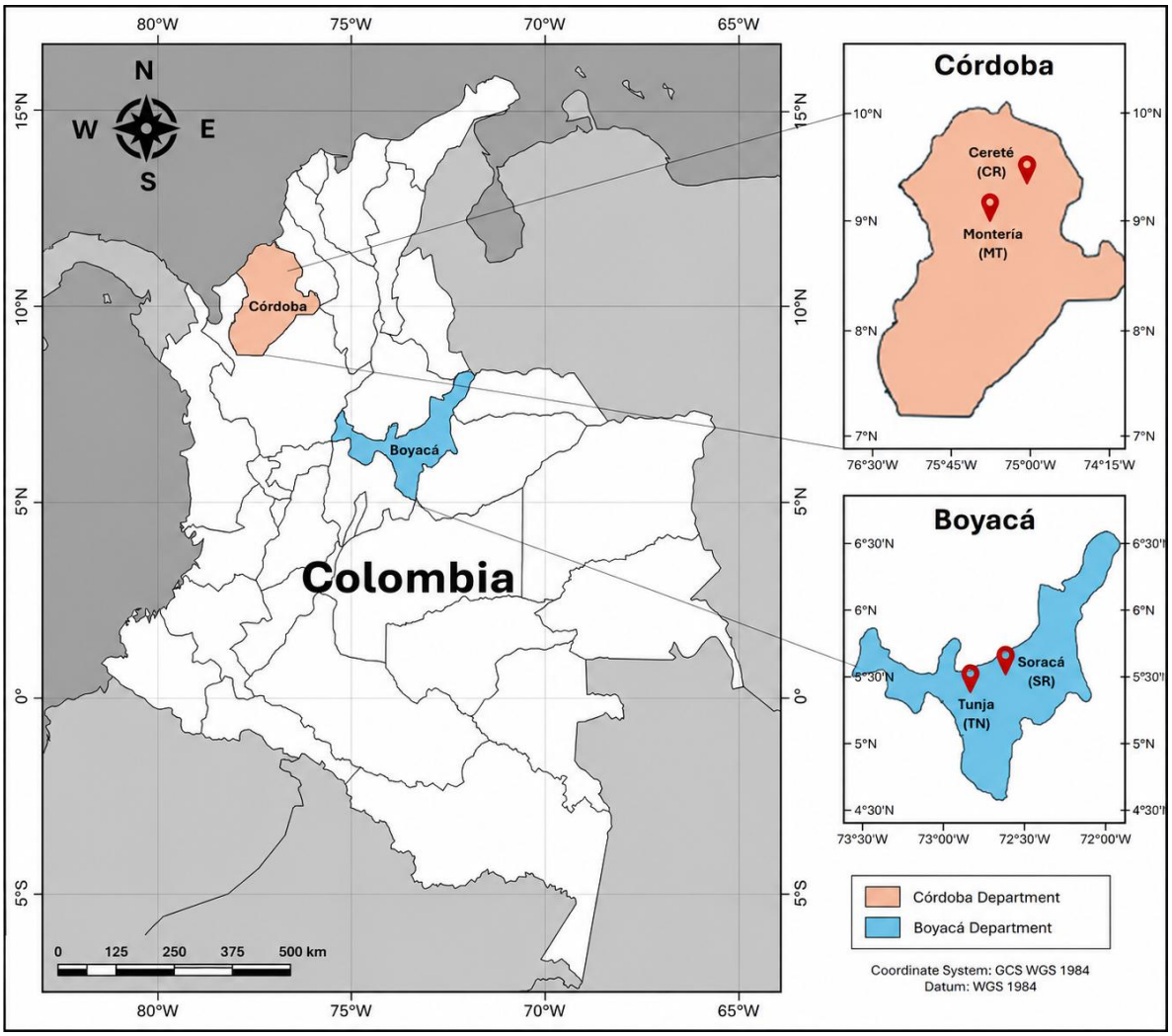


Figure 1. Locations of Colombian municipalities Montería, Cereté, Tunja, and Soracá where disinfection by-products were studied.

Field measurements included turbidity (TB), electrical conductivity (EC), pH, water temperature (WT), and free residual chlorine (Cl). TB was measured using a Hach 2100Q portable turbidimeter (Hach, London, ON, Canada) with an accuracy of ± 2% of the reading plus stray light and a resolution of 0.01 nephelometric

turbidity units (NTU). The instrument was calibrated before use with 0.1 and 20 NTU standards supplied by the manufacturer. EC was measured using a Multi 340i conductivity meter (WTW, Weilheim, Germany) and reported in µS cm^{-1}. WT and pH were measured simultaneously using a waterproof pH meter with a resolution of 0.01 pH units and an accuracy of ± 0.1 pH units; WT was reported in °C. Free residual chlorine was determined using a Hach DR300 portable colorimeter (Hach, London, ON, Canada) with a measurement range of 0.1–8.0 mg L^{-1} as Cl_2. Natural organic matter (NOM) was characterized using ultraviolet absorbance at 254 nm (UV_{254}) as a surrogate parameter. UV_{254} measurements were conducted using a Real UV_{254} field meter (Real Tech Instruments, Whitby, ON, Canada) equipped with a 1-cm quartz cell, with an accuracy of ± 0.5% full-scale and a resolution of 0.001 cm^{-1}.

Chloroform determination

To determine chloroform (CF) concentrations, tap water samples were collected in 100-mL Whirl-Pak® sampling bags (Sigma-Aldrich, Oakville, ON, Canada). Sampling bags were pre-dosed with sodium thiosulfate pentahydrate to quench residual chlorine and prevent further disinfection by-product (DBP) formation after sampling. The bags were filled carefully to avoid air entrapment. Samples were stored in the dark at 4°C and transported to the laboratory for analysis within 12 hours. The Hach Trihalomethane Formation Potential Method 10224 (Hach®, Loveland, CO, USA) was applied to quantify chloroform in collected tap water samples after chlorine quenching, but omitting the incubation step which is used to determine additional formation potential. Briefly, 10-mL aliquots of each sample were transferred to spectrophotometric cells and reacted sequentially with THM Plus Reagents 1, 2, and 3 according to the manufacturer's instructions. The reaction procedure included controlled heating, cooling, reagent addition, and color development steps to convert chloroform into a measurable-colored complex. A reagent blank prepared with deionized water was included for instrument calibration and quality control. Following color development, absorbance was measured using a calibrated spectrophotometer, and CF concentrations were determined directly from the instrument readings and expressed as µg L^{-1} $CHCl_3$. All analysis was performed in accordance with the manufacturer's protocols. A schematic summary of the analytical procedure is presented in Fig. 2. Quality assurance and quality control (QA/QC) measures included reagent blanks, instrument calibration before sample analysis, and duplicate measurements to verify analytical precision. Residual chlorine quenching, refrigerated storage, and protection from light were implemented to minimize changes in CF concentrations during the time period between sample collection and laboratory analysis.

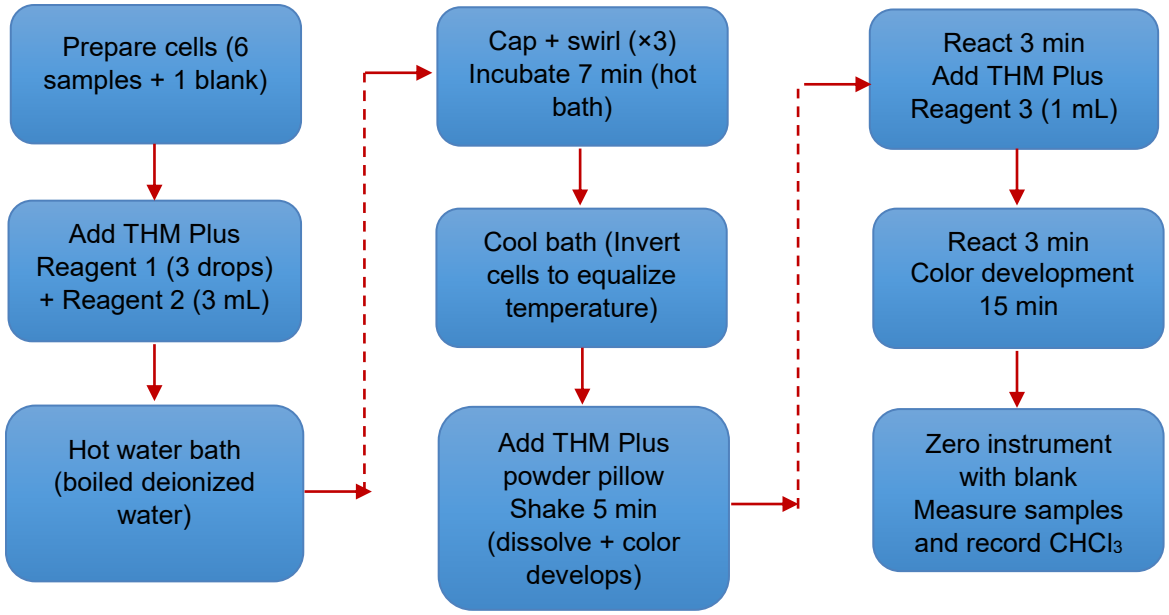


Figure 2. Summary of procedure to determine chloroform concentration (based on Hach THM Plus™ Method 10132, Hach®, Loveland, CO, USA).

Statistical analysis

A one-way analysis of variance (ANOVA) was performed to evaluate differences in CF concentrations among sampling locations within each municipality. CF concentration comparisons between Montería and Cereté as well as Tunja and Soracá were conducted. A Spearman's rank correlation coefficient (*r*) was used to investigate the relationships between CF concentrations and the measured water quality parameters, including pH, WT, TB, EC, UV_{254}, and Cl. Response surface analysis (RSA) was conducted to determine the impact of different water quality parameters on CF formation.

RESULTS AND DISCUSSION

Tap water quality and regulatory compliance

Table 1 presents the mean values of the tap water quality parameters for the different municipalities in this study.

Table 1. Mean tap water quality parameters for Cereté, Montería, Soracá, and Tunja.

Parameter	Cereté	Montería	Soracá	Tunja	Colombian Guidelines
pH	7.7 ± 0.19	7.3 ± 0.16	7.2 ± 0.19	8.7 ± 0.21	6.5 – 9.0
WT (°C)	31.5 ± 0.75	32.4 ± 1.43	22.7 ± 1.64	20.9 ± 0.93	NR
TB (NTU)	0.99 ± 0.37	0.59 ± 0.25	0.77 ± 0.15	0.55 ± 0.13	≤ 2.0
EC (µS cm^{-1})	210 ± 8.35	217 ± 4.01	104 ± 1.92	37 ± 2.75	1000
UV_{254} (cm^{-1})	0.0082 ± 0.003	0.0087 ± 0.002	0.0186 ± 0.001	0.0205 ± 0.003	NR
Cl (mg L^{-1})	0.35 ± 0.16	0.45 ± 0.09	0.16±0.13	0.10 ± 0.10	0.3 – 2.0
CF (µg L^{-1})	28 ± 8.31	54 ± 8.28	31±8.07	33 ± 6.62	NR

Values are reported as mean ± standard deviation (SD).
NR = Not regulated under the Colombian guideline values considered in this study
WT = Water Temperature

TB = Turbidity
EC = Electrical Conductivity
Cl = Free residual chlorine
CF = Chloroform

During the dry season, mean pH values across all sampling locations were close to neutral (Table 1). Tunja exhibited the highest mean pH (8.7 ± 0.21), indicating slightly alkaline conditions compared to the other municipalities. This elevated pH is likely attributable to the addition of lime during treatment to increase alkalinity and optimize coagulation performance by promoting the appropriate speciation of aluminum hydroxide and NOM (Dayarathne et al., 2021; González-Galvis et al., 2024). Nevertheless, pH values in all municipalities complied with Colombian drinking water quality standards (Table 1).

Mean TB values throughout the WSSs were below 1.0 NTU in all municipalities, meeting both Colombian regulatory requirements and international drinking water quality guidelines (Table 1) (WHO, 2017). These low turbidity levels indicate effective removal of suspended particles and colloids and demonstrate satisfactory treatment plant performance. Maintaining low turbidity within distribution systems is particularly important because it reduces the potential for microbial contamination and enhances the effectiveness of disinfection processes (Aboubaraka et al., 2017). Furthermore, turbidity is increasingly recognized as a useful operational indicator for assessing treatment plant robustness and for identifying the need for short-term operational adjustments during periods of elevated raw water turbidity associated with storms and extreme rainfall events (Nwankwo et al., 2026; Reza et al., 2026).

WT varied considerably among the municipalities, ranging from 20.9 to 32.4°C. The lowest temperatures were observed in Tunja and Soracá (the municipalities with the highest altitudes), whereas the highest temperatures were recorded in Montería and Cereté (the municipalities with the lowest altitudes) (Table 1). Since Colombia is tropical, water temperature is more influenced by altitude than by seasonal conditions. WT is an important driver of DBP formation, particularly THM formation, because higher temperatures generally accelerate reactions between disinfectants and organic precursors (Gordon et al., 1998). In addition, higher WT has been associated with increased human exposure to chloroform during domestic water-use activities such as bathing (Forczek et al., 2016). Consequently, WT affects both DBP formation kinetics and potential exposure risks associated with chlorination by-products.

EC was measured as an indicator of dissolved ionic constituents that may have influenced water chemistry and the formation of DBPs. Conductivity in natural waters is governed by the presence of dissolved anions, including chloride, nitrate, sulfate, and phosphate, as well as cations such as sodium, magnesium, calcium, iron, and aluminum (Benavente et al., 2025). EC values were substantially higher in Montería and Cereté than in Tunja and Soracá (Table 1). These elevated conductivity levels may reflect greater concentrations of dissolved constituents in the Sinú River, potentially associated with agricultural runoff and mining activities within the watershed (Marrugo-Negrete et al., 2017).

Previous studies have reported that conductivity can influence chlorine decay dynamics within water distribution systems (Tafesse et al., 2023). In the present study, a strong positive linear correlation was observed

between EC and free residual chlorine in Montería ($R^2 = 0.73$), whereas a very low linear correlation was found in Cereté ($R^2 = 0.092$). Conductivity values were lower in Tunja and Soracá compared to Montería and Cereté, likely related to the characteristics of their source waters. Tunja obtains water from a reservoir with limited direct influence from agricultural activities, while Soracá is supplied by a spring-fed stream with relatively low concentrations of dissolved constituents (González-Galvis et al., 2024).

Free residual chlorine (Cl) concentrations were monitored throughout the WSSs as an indicator of disinfection effectiveness and water quality preservation. Overall, residual chlorine concentrations in Montería and Cereté remained within Colombia's recommended range of 0.3–2.0 mg L^{-1} throughout the distribution systems. In contrast, chlorine concentrations in Tunja and Soracá frequently fell below the recommended minimum, regardless of the distance from the WTP (Fig. 3). Although chlorine decay within distribution systems is influenced by several factors, including the initial chlorine dose, water quality characteristics, and conductivity (Kwio-Tamale & Onyutha, 2024), the low residual chlorine concentrations observed in Tunja and Soracá do not appear to be associated with deficiencies in treatment plant operation. Instead, they are likely related to the use of both elevated and underground storage tanks that increase hydraulic residence time and promote chlorine consumption (Angassa et al., 2025). As expected, residual chlorine concentrations generally decreased as the distance from the treatment plant increased (Zimoch et al., 2025), a trend that was particularly evident in the Montería distribution system (Fig. 3).

A pronounced decline in chlorine concentrations was observed at sampling point 3 in Cereté, Tunja, and Soracá, corresponding to facilities equipped with underground or elevated storage tanks where it loses its chlorine, including hospitals and commercial buildings. This decline in chlorine does not impact downstream sampling sites, because the water in storage tanks does not return to circulation. Beyond sampling point 4, chlorine concentrations continued to decrease, reflecting the natural consumption of chlorine through reactions with NOM and other oxidizable compounds that may also act as precursors for DBP formation (Bond et al., 2012; Tafesse et al., 2023). In contrast, Montería exhibited a slight increase in chlorine concentrations between sampling points 4 and 6 (Fig. 3) (Dong et al., 2022; Sime & Kansal, 2024).

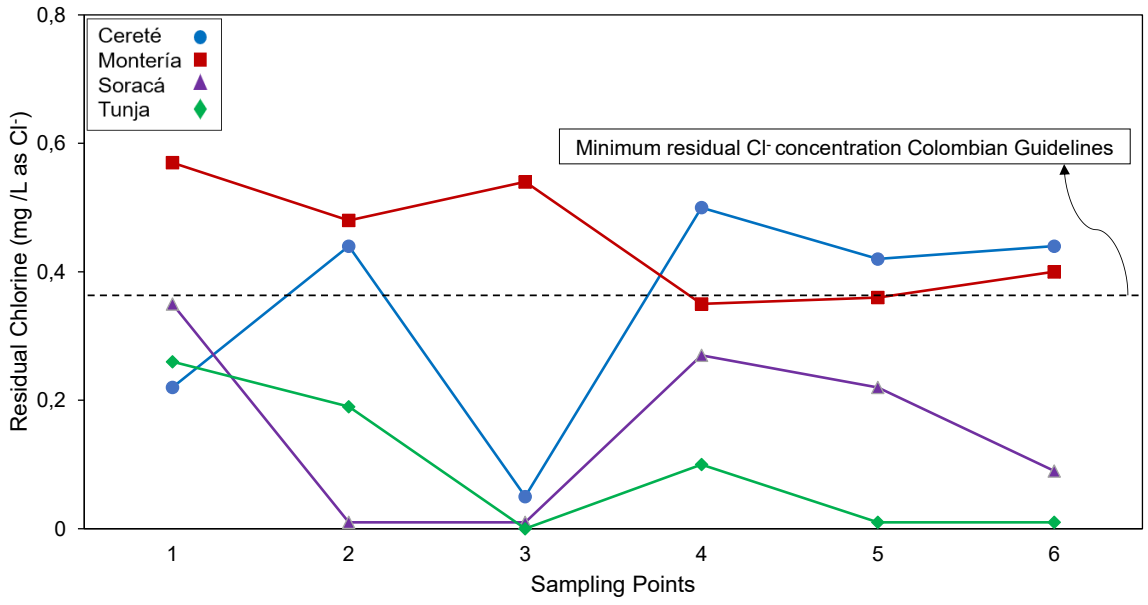


Figure 3. Free residual chlorine (Cl) concentrations in Cereté, Montería, Soracá, and Tunja as a function of distance from the water treatment plant (WTP).

Characterization of NOM using UV_{254}

UV_{254} absorbance provides valuable information on the composition and aromaticity of natural organic matter (NOM) present in water (Anderson et al., 2023). Absorbance at 254 nm is commonly associated with aromatic organic compounds, and has been widely used as a surrogate indicator of NOM fractions that can act as precursors for DBP formation (Pifer & Fairey, 2014; Weishaar et al., 2003). Among the municipalities studied, the highest UV_{254} values were observed in Tunja and Soracá (Table 1). Although the mean UV_{254} value in Tunja was slightly higher than that in Soracá, the difference was not statistically significant (t-test; $p > 0.05$). The elevated UV_{254} values measured in Tunja and Soracá suggest the presence of NOM enriched in aromatic constituents, which are commonly associated with humic and fulvic substances derived from natural watershed processes (Chear et al., 2025). Despite the substantial differences in treatment configurations between Tunja and Soracá (i.e., C/F/S/D versus MSF), both systems produced treated water with comparable turbidity and UV_{254} levels (Table 1).

These findings indicate that the MSF system implemented in Soracá can achieve NOM removal efficiencies similar to those obtained through conventional treatment processes. The lower UV_{254} absorbance observed in Soracá may be partly attributed to the biological activity occurring within the roughing and slow sand filtration units. Previous studies have shown that biofiltration processes can effectively remove biodegradable organic matter, total organic carbon (TOC), biopolymers, protein-like substances, and other high-molecular-weight NOM fractions that contribute to UV_{254} absorbance (Hamidi et al., 2020; Cheng et al., 2016).

In contrast, Montería and Cereté exhibited the lowest UV_{254} values among the evaluated municipalities, and no statistically significant differences were observed between these systems (t-test; $p > 0.05$) (Table 1). The lower UV_{254} absorbance measured in MT and CR likely reflects the effective removal of NOM through conventional treatment processes, particularly coagulation and subsequent solid–liquid separation steps. These treatment processes are known to reduce aromatic organic matter and other DBP precursors, thereby improving finished water quality and reducing the potential for chlorination by-product formation (Ruth et al., 2026b).

Chloroform concentrations and spatial variability

In this study, CF was selected as an indicator of THM formation because it is one of the most frequently detected halogenated DBPs in drinking water distribution systems and very often constitutes the predominant THM species in chlorinated waters (Li et al., 2021; Chu et al., 2009; Rodríguez & Sérodes, 2001) (Table 1). The formation of DBPs is influenced by a complex interaction of source water characteristics, including pH, alkalinity, and the concentration and composition of NOM, as well as operational factors associated with water treatment and distribution systems (Valenti-Quiroga et al., 2026; Yuan et al., 2024). These operational factors include coagulant type and dose, disinfectant type and dosage, contact time, distribution system characteristics, pipe materials, and water age (García-Avila et al., 2024; Ramírez et al., 2023; Gough et al., 2014). Detailed

operational information regarding coagulation and disinfection practices was not available for the participating water treatment plants. Consequently, the assessment of CF formation was based on the physicochemical parameters measured during the field sampling campaign and subsequent laboratory analyses. The median CF concentrations observed in each municipality are presented in Fig. 4.

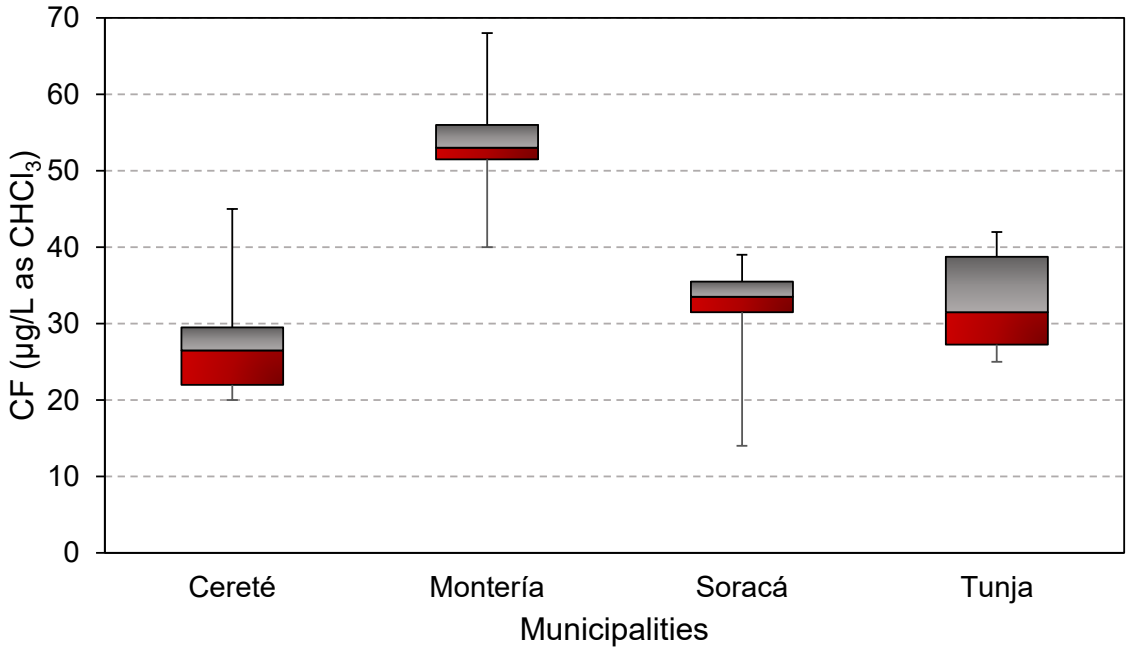


Figure 4. Chloroform (CF) concentrations in Cereté, Montería, Soracá, and Tunja.

Although Montería and Cereté are supplied by the Sinú River and employ similar conventional treatment processes, substantial differences in CF concentrations were observed between the two WSSs (Fig. 4). A one-way ANOVA revealed a statistically significant difference in mean CF concentrations between the municipalities ($p < 0.05$), with the concentration in Montería (54 ± 8.28 µg L^{-1}) significantly higher than in CR (28 ± 8.31 µg L^{-1}) (t-test < 0.05) (Table 1).

Several factors may explain this difference. First, variations in source water quality between the two water intakes may result from tributary inflows, agricultural and urban runoff, and sediment resuspension processes occurring along the Sinú River. These factors can alter the concentration and composition of NOM, thereby influencing DBP precursor availability and subsequent CF formation. Second, differences in treatment plant operation, including coagulant type and dose, disinfectant type and dose, filtration performance, and chlorine contact time, may contribute to the observed differences in CF concentrations despite the use of similar treatment trains (i.e., C/F/S/D). Because detailed operational data were not available for this study, the relative contribution of these factors could not be quantified. Future investigations incorporating treatment plant operational records and source water characterization would be necessary to clarify the mechanisms driving CF formation in these systems.

In contrast, no statistically significant differences in mean CF concentrations were observed between Tunja and Soracá (t-test $p > 0.05$) (Fig. 4). This finding suggests that the conventional treatment process employed in TN and the MSF system used in SR produced comparable CF concentrations in the finished water, despite differences in source water characteristics and treatment configurations.

Hydraulic residence time (HRT), often represented by water age or distance from the WTP, is recognized as an important factor influencing DBP formation and variability within drinking water supply systems (Guilherme & Rodriguez, 2015; Dong et al., 2022). Therefore, we evaluated the potential influence of distance from the WTP on CF concentrations across the four municipalities. Elevated CF concentrations were detected at sampling locations closest to the treatment plants (Fig. 5), indicating that a substantial proportion of CF formation likely occurred during chlorination and/or within the clearwell storage facilities prior to distribution. This observation suggests that the initial reaction between chlorine and NOM precursors generated most of the CF detected throughout the distribution systems (Alver et al., 2025; Ranjbar et al., 2026).

Beyond the first sampling locations, CF concentrations remained relatively stable throughout the distribution networks, indicating that limited additional CF was generated during water transport. Studies of other distribution systems have similarly reported that most of the DBP formation occurs during the initial treatment and early storage of the water rather than during downstream distribution (Lacroix et al., 2024; Park et al., 2025). The relatively stable CF concentrations observed in this study may reflect the limited availability of reactive NOM precursors, as indicated by the generally low UV_{254} values measured in the treated waters (García-Villanova et al., 1997). Although CF alone does not provide a direct estimation of TTHMs, all measured CF concentrations were below the U.S. EPA maximum contaminant level for TTHMs of 80 µg L^{-1}, and below the WHO guideline value for chloroform of 300 µg L^{-1} (USEPA, 2026; WHO, 2017) (Fig. 5). These findings highlight the widespread occurrence of CF within the studied systems, and underscore the importance of continued monitoring of DBPs in drinking water distribution networks.

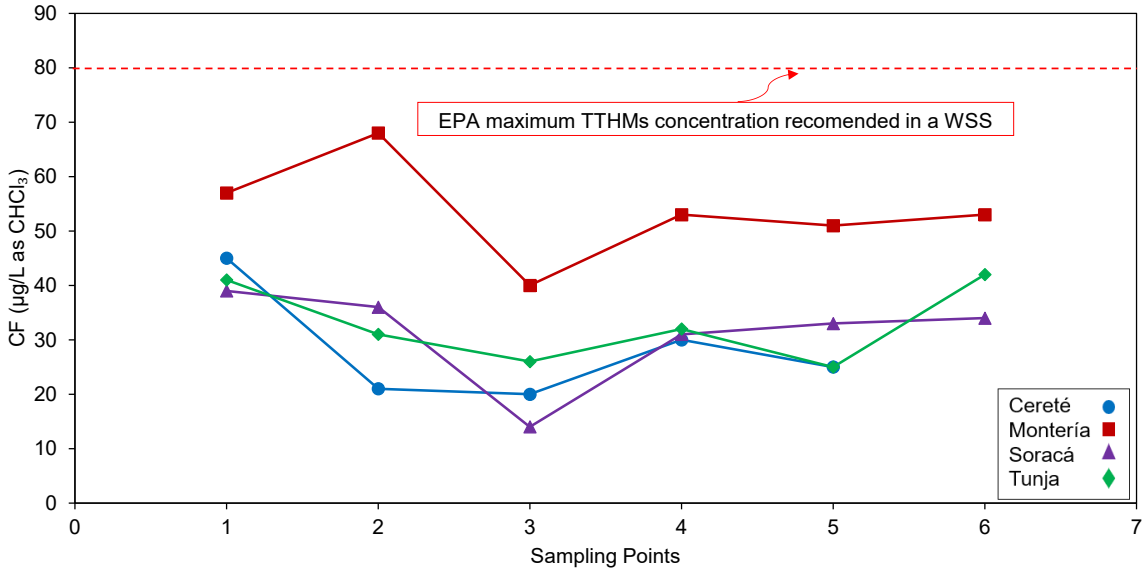


Figure 5. Chloroform (CF) concentrations at the different sampling points in Cereté, Montería, Soracá, and Tunja. (1 = nearest to the water treatment plant; 6 = farthest from the water treatment plant).

The detection of CF throughout the water supply systems provides evidence of DBP formation during chlorination, and suggests the potential occurrence of other DBPs, including haloacetic acids (HAAs), brominated and iodinated DBPs, as well as carbonyl compounds such as ketones and aldehydes (Paschoalato et al., 2026; Truzsi et al., 2022; Krasner et al., 2022). Although these compounds were not quantified in the present study, their formation is commonly associated with the reaction of disinfectants with NOM and other precursors present in source waters. The widespread occurrence of CF observed in this study highlights the need to strengthen the regulatory framework for DBP monitoring in Colombia. Current regulations establish a maximum allowable concentration of 200 μg L^{-1} for total trihalomethanes (TTHMs); however, they do not include specific limits for individual DBPs such as CF or HAAs. Given the growing body of evidence regarding the potential health risks associated with long-term exposure to DBPs, future regulatory efforts should consider establishing guideline values for individual DBP species and expanding routine monitoring programs within drinking water supply systems.

Drivers of CF formation and correlation analysis

Linear regression analyses were first conducted to evaluate the relationship between CF concentrations and the water quality parameters measured in each municipality. Subsequently, response surface analysis (RSA) was applied using the parameters most likely to influence CF formation. In Cereté, the response surface analysis (RSA) suggested that CF formation was modulated by both WT and Cl concentration; however, the relationships were weak and non-linear, as indicated by the low coefficients of determination ($R^2 = 0.12$ and $R^2 = 0.02$, respectively). Despite this variability, the highest CF concentrations (> 40–45 μg L^{-1}) were generally associated with elevated WT and moderate Cl concentrations (approximately 0.2 mg L^{-1}) (Fig. 6a). These patterns indicate that WT may enhance CF formation under the conditions evaluated, although additional factors not measured in this study, such as chlorine contact time, coagulant dose, DOC concentration, and bromide levels, likely exert substantial control over DBP formation.

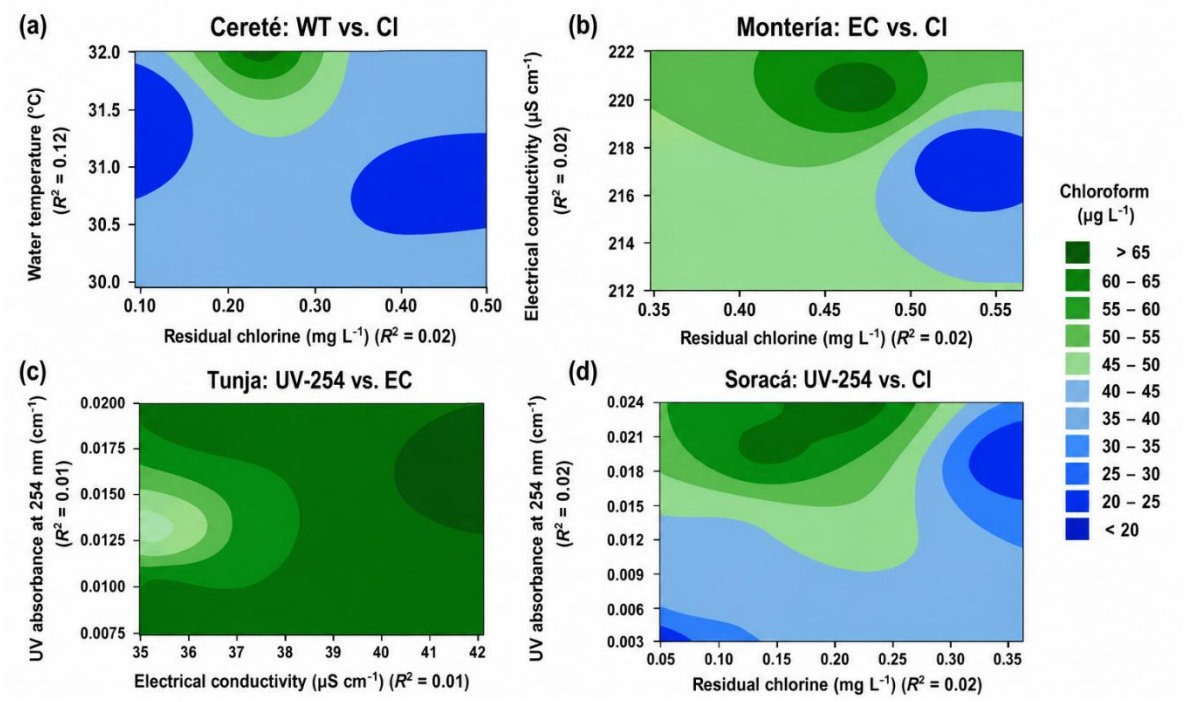


Figure 6. Contour response surface plots for chloroform concentration in (a) Cereté, (b) Montería, (c) Tunja, and (d) Soracá. WT = water temperature; EC = electrical conductivity.

Note: Chloroform concentrations (µg L^{-1}) are represented by the colour scale shown on the right. The same colour scale is used in all panels to facilitate comparison.
R^2 values in axis labels correspond to the coefficient of determination for the overall response surface model in each panel.

The observed association between WT and CF concentrations in Cereté (Fig. 6a) is consistent with previous studies demonstrating that elevated WT accelerates reaction kinetics between disinfectants and NOM, thereby promoting the formation of THMs and other DBPs (Masoud et al., 2019; Ma et al., 2024). In addition, higher temperatures may also increase the solubility and reactivity of organic compounds, enhancing precursor availability for DBP formation (Jiang et al., 2026; Li & Richardson, 2026). Similarly, WT can substantially influence THM concentrations, with warmer systems exhibiting concentrations up to two times higher than comparable treatment plants operating under cooler conditions (Rodríguez & Sérodes, 2001).

In Montería, higher CF concentrations were generally associated with elevated EC values, with the response surface indicating maximum CF concentrations (> 60–65 µg L^{-1}) at EC values close to 220 µS cm^{-1} (R^2= 0.16) (Fig. 6b). This pattern suggests that the dissolved constituents contributing to conductivity may be indirectly associated with conditions favorable for CF formation. However, because EC is not a direct precursor of DBPs, the observed relationship likely reflects broader source water characteristics and treatment conditions that influence both parameters (Peng et al., 2026).

In contrast, CF concentrations in Tunja and Soracá appeared to be more closely associated with UV_{254} absorbance, a surrogate indicator of aromatic NOM and potential DBP precursors (Fig. 6c and 6d). In Tunja, the highest CF concentrations (> 37.5–40 µg L^{-1}) were observed at UV_{254} values of approximately 0.023 cm^{-1}

and EC values ranging from 36 to 39 μS cm^{-1} (Fig. 6c). Although UV_{254} exhibited a stronger association with CF than with EC, the relationship was moderate ($R^2 = 0.40$), while EC had virtually no explanatory power ($R^2 = 0.0068$). These findings suggest that NOM characteristics may play a more important role than dissolved ionic constituents in governing CF formation in this system (Zhao et al., 2013; Bond et al., 2012).

Similarly, the highest CF concentrations in Soracá were associated with UV_{254} values of approximately 0.0185 cm^{-1} and free residual chlorine concentrations near 0.30 mg L^{-1} (Fig. 6d). Nevertheless, the relationships between CF and both UV_{254} and Cl were weak ($R^2 = 0.0071$ and $R^2 = 0.26$, respectively). These results indicate that neither parameter alone adequately explains the variability in CF concentrations observed in Soracá. Instead, CF formation is likely influenced by multiple interacting factors, including NOM composition, chlorine contact time, source water characteristics, and treatment plant operational conditions that were not evaluated in the present study (Peng et al., 2026; Kali et al., 2021).

Overall, the response surface analysis suggests that CF formation was controlled by different municipality-specific drivers. WT and EC appeared to be more relevant in the warmer systems (Montería and Cereté, i.e., those with the lowest altitudes), whereas UV_{254} absorbance showed a stronger association with CF occurrence in the cooler systems (Tunja and Soracá, i.e., those with the highest altitudes). Because the coefficients of determination were generally low, these response surfaces should be interpreted as exploratory indicators of potential controlling conditions rather than as predictive models. The results indicate that CF formation in the studied systems cannot be explained by any single measured parameter, and is more likely governed by the combined effects of source water chemistry, NOM reactivity, chlorine residual decay, hydraulic residence time, and treatment plant operation.

Spearman Correlation analysis of chloroform and water quality indicators

To further characterize the influence of water quality parameters on CF occurrence, we generated Spearman correlation heat maps for each municipality. The analysis quantified monotonic associations between CF concentrations and the measured physicochemical indicators, namely pH, WT, TB, EC, Cl, and UV_{254} absorbance (Fig. 7).

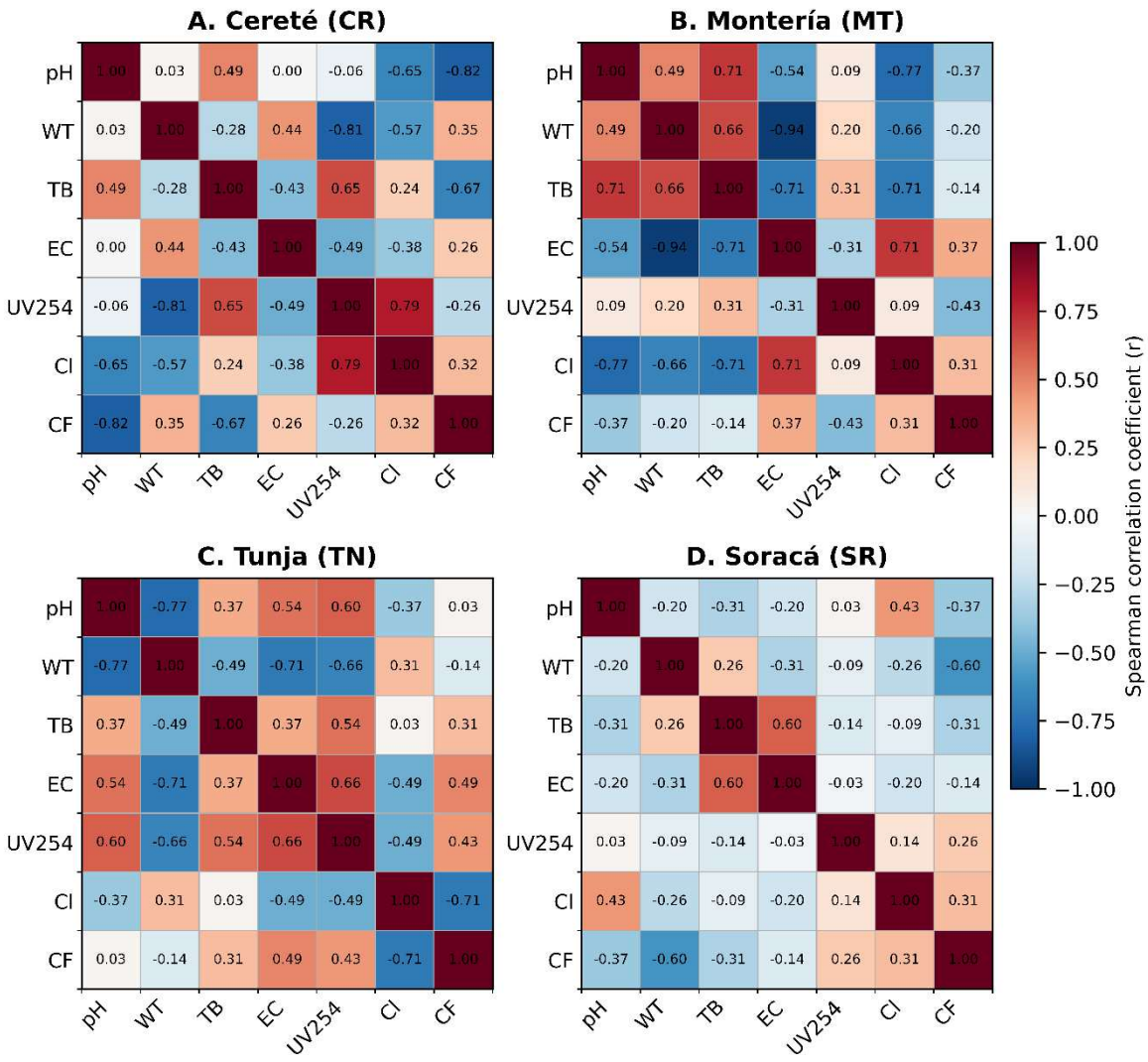


Figure 7. Spearman correlation heat maps between chloroform (CF) concentration and water quality parameters in the studied municipalities: (a) Cereté, (b) Montería, (c) Tunja, and (d) Soracá. WT = water temperature; TB = turbidity; EC = electrical conductivity.

In Cereté, Spearman correlation analysis revealed weak positive associations between CF concentrations and both WT (r = 0.35) and Cl (r = 0.32) (Fig. 7a). These results suggest that while WT and Cl may play a role in CF dynamics, neither variable exerted a sufficiently strong influence to be considered a dominant controlling factor. This is consistent with previous studies indicating that DBP formation typically depends on the combined effects of multi-parametric water quality characteristics and treatment conditions, rather than on individual physicochemical parameters alone (Ebsa & Dibaba, 2022; Eckard et al., 2020). Similarly, in Montería, EC and Cl exhibited weak positive correlations with CF concentrations (r = 0.37 and r = 0.31, respectively) (Fig. 7b). Although these associations indicate that CF concentrations tended to increase alongside higher EC and Cl values, the low correlation coefficients suggest that these variables explain only a limited proportion of the observed variance. Because EC is not directly involved in THM formation pathways, its relationship with CF likely reflects broader source water characteristics or specific operational conditions that simultaneously influence both parameters.

In Tunja, the correlation analysis showed that UV_{254} and EC had moderate positive relationships with CF concentrations ($r = 0.43$ and $r = 0.49$, respectively) (Fig. 7c). Conversely, in Soracá, UV_{254} and Cl displayed weaker positive correlations with CF ($r = 0.26$ and $r = 0.31$, respectively) (Fig. 7d). The generally weak-to-moderate correlations observed across all monitoring zones suggest that unmeasured variables may exert a stronger influence on CF formation than the standard physicochemical parameters evaluated during this campaign. Dissolved organic carbon (DOC), total organic carbon (TOC), NOM fractions, bromide concentrations, chlorine dosage, disinfectant type, and hydraulic residence time are well-documented drivers of THM formation and should be integrated into future investigations (Rodriguez et al., 2007; Lemus-Pérez & Rodríguez Susa, 2020; Yang et al., 2024). Incorporating these parameters would provide a more mechanistic understanding of CF dynamics within Colombian drinking water distribution systems. Overall, none of the evaluated parameters showed a strong correlation with CF concentrations across all of the municipalities of this study. This lack of a single dominant predictor underscores the complex, non-linear nature of DBP formation, which is governed by simultaneous interactions among disinfectant dose, contact time, precursor composition, pH, and treatment plant configuration. Consequently, CF variability cannot be adequately characterized or predicted using a single conventional water quality indicator.

CONCLUSIONS

This study provides field-based evidence of chloroform (CF) occurrence as an indicator of disinfection by-product (DBP) formation in four Colombian water supply systems. Mean CF concentrations from highest to lowest occurred in Montería (54 ± 8.28 µg L^{-1}) > Tunja (33 ± 6.62 µg L^{-1}) > Soracá (31 ± 8.07 µg L^{-1}) > Cereté (28 ± 8.31 µg L^{-1}), while free residual chlorine frequently fell below the Colombian guideline value in Tunja and Soracá, suggesting the need to optimally maintain levels of residual chlorine where storage and HRT accelerate chlorine decay. CF occurrence showed weak-to-moderate correlations with WT, EC, Cl, and UV_{254}, but the influence of these parameters varied among municipalities, confirming that CF formation is controlled by the interaction of source water, treatment, and distribution-system conditions rather than by a single predictor. Although CF alone does not provide a direct estimation of total trihalomethanes (TTHMs), average concentrations remained below the U.S. EPA benchmark for TTHMs and the WHO guideline value for chloroform. These findings support strengthened DBP monitoring in Colombia, including of individual THMs and haloacetic acids (HAAs), as well as future studies integrating detailed natural organic matter characterization, HRT, and operational data to improve precursor control and risk management in drinking water distribution systems. Finally, this study underscores the importance of monitoring and characterizing DBPs in tropical regions, where multiple environmental, operational, and climatic factors can influence their formation. This is particularly relevant in the Andean region, where extreme weather events associated with El Niño and La Niña may alter source water quality and increase the complexity of DBP management.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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