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Comparative Analysis of Dissolved Air Flotation and Sedimentation Processes for Treating High Turbidity Waters in Colombia

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ABSTRACT

Dissolved air flotation (DAF) is a prominent technology that permits the treatment of water using higher hydraulic loading rates and lower retention times than sedimentation (SED). This study presents a comparative evaluation of DAF and SED for the treatment of two high-turbidity surface water sources (14-50 NTU) in Colombia. The water samples analysed were collected from the Chiquinquirá River (CR) and the Quebrada Madron Creek (QM), both located in Boyacá, Colombia. The optimal coagulant dosages were identified as 30 mg/L of aluminium sulphate for CR and 60 mg/L for QM using jar testing. Under these conditions, the turbidity removal efficiencies were 86% for DAF and 93% for SED in CR, and 91% for DAF and 93% for SED in QM. The apparent colour removal reached 86% for CR and 83% for QM. The removal of the ultraviolet absorbance at 254 nm (UV_{254}), used as a surrogate for natural organic matter (NOM), was 67% for SED and 64% for DAF in CR, with both processes achieving 73% removal in QM. Overall, SED consistently outperformed DAF in turbidity removal for both source waters, while the apparent colour and NOM reductions were comparable between the two technologies. The findings from this work provide valuable insights for optimizing the clarification processes in drinking water treatment plants managing high-turbidity surface waters in Colombia.

HIGHLIGHTS

This study compares two clarification processes, namely, sedimentation and dissolved air flotation, for the removal of high turbidity in water. Furthermore, the efficiency of both methods in eliminating natural organic matter from the treated samples is evaluated and compared. The results highlight the specific advantages of sedimentation over dissolved air flotation when applied two high-turbidity surface water sources.

1. INTRODUCTION

Colombia is recognized as one of the richest countries in terms of freshwater resources globally (World Bank, 2022), possessing a potential annual water extraction capacity of approximately 13 billion cubic meters (Domínguez et al., 2010). However, these water sources are adversely affected by the mineral extraction activities in artisanal mining, which can introduce large quantities of solids and heavy metals, significantly diminishing their suitability as source waters for potable water production (Casso-Hartmann et al., 2022; Caballero-Gallardo et al., 2022; Wright et al., 2014). Drinking water treatment plants (WTPs) typically employ processes such as coagulation, flocculation, sedimentation (C/F/SED) or, dissolved air flotation (C/F/DAF) (Teixeira and Rosa, 2006; Zou et al., 2011) coupled with conventional filtration, or membrane filtration and chlorine disinfection (Edzwald and Haarhoff, 2011; Vlaski, 2020).

Dissolved air flotation (DAF) is a clarification technology that has been effectively integrated globally into the drinking water treatment sector (Khiadani et al., 2014; Pera do Amaral et al., 2013). Unlike sedimentation (SED), which relies on gravity to achieve the separation of particles and floc

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agglomerates from water, DAF uses microbubbles to facilitate the separation (Kempeneers et al., 2001; Duan et al., 2025; Han et al., 2024; Benjamin and Lawler, 2013). In contrast, SED is considered more appropriate for river waters exhibiting mineral turbidity below 100 NTU. Nevertheless, there are no reported studies directly comparing the performance of DAF and SED for treating waters with turbidity in the intermediate range of 10 to 50 NTU in Colombia. DAF technology is generally recommended for the treatment of raw waters with turbidity levels up to 50 NTU, although its upper operational limit has been reported to reach as high as 100 NTU with short flotation times (Benjamin and Lawler, 2013). Other studies, however, have suggested that DAF performs optimally when treating raw waters with turbidity below 20 NTU (Edzwald and Haarhoff, 2011). A process selection diagram proposed by (Valade et al., 2009) indicates that DAF is suitable for waters with either mineral or non-mineral turbidity below 10 NTU, and that it can also be effectively applied to reservoir waters with non-mineral turbidity below 100 NTU. Comparative studies have assessed the performance of SED and DAF on various water sources, including reservoirs and rivers, which were all characterized by low turbidity, alkalinity and colour (Chu et al., 2011; González-Galvis et al., 2024). Other studies have compared the two clarification processes in terms of their efficiency in removing algae, cyanobacteria, disinfection by-product precursors (DBPs), and Cryptosporidium (French et al., 2000). A comparison of these two treatment processes has also been carried out to determine the most effective option as a pre-treatment stage for membrane filtration (Ladouceur and Narbaitz, 2022).

The flocculation stage, which serves as a pre-treatment for both SED and DAF, is typically designed with hydraulic retention times (HRT) ranging from 10 to 30 min (Crittenden et al., 2012). However, investigations regarding the influence of flocculation duration on DAF for treating low-turbidity waters revealed that just 5 min may suffice for effective turbidity removal (González-Galvis et al., 2024; Edzwald, 1995). Conversely, SED is generally designed with an HRT of 1.5 to 4 h, although laboratory jar tests are often performed with sedimentation times of 20 to 30 min (Chemeda and Fitamo, 2025). While full-scale DAF uses short separation times in line with those used in laboratory jar testing experiments, the situation is much different for full-scale SED units tanks because of allowance for turbulence, density currents, dead zones and room for sludge storage. Studies have addressed the optimal sedimentation durations for turbidity reduction using a jar test apparatus (Chemeda and Fitamo, 2025). However, there is a lack of research concerning the impact of flocculation time on DAF and SED when treating highly turbid waters. Consequently, the primary objectives of this research are to: 1) conduct a comparative study of DAF and SED for the treatment of two distinct natural surface waters with high turbidity levels (14 NTU to 50 NTU) in Colombia utilizing bench-scale DAF and SED jar test apparatus; 2) perform jar tests with an aluminium sulphate-based coagulant to determine whether the optimal coagulant dosage identified for SED is consistent with that required for DAF; 3) compare the effects of 10 and 15 min of flocculation time on turbidity removal efficacy in both SED and DAF for both water types; and 4) evaluate the impact of three different sedimentation durations (15, 20, and 30 min) on the turbidity removal for both water types.

2. METHODOLOGY

2.1 Water tested

The experiments were conducted utilizing two distinct surface water sources, namely, the Chiquinquirá River (CR) and b) the Quebrada Madron Creek (QM), which were characterized by high turbidity levels (ranging from 14 NTU to 50 NTU). Water samples were collected from locations nearest to the roadway along the CR and QM basins. The CR is a small river that traverses the Town of Chiquinquirá, situated in the Boyacá department of Colombia, before flowing into the larger Suárez River. While the Suárez River serves as a primary water source for Chiquinquirá, the CR could potentially serve as an alternative water source in the future. Conversely, the QM is a nearby small stream, water samples were collected 8 km from the city center. The water from the QM is used primarily for agricultural activities, such as crop irrigation, but it holds potential for future use as an alternative drinking water source. Water samples were collected during two separate campaigns in February and March 2023. For this study, six buckets, each containing 20 liters of water from both the CR and QM sources, were collected during each sampling campaign. The samples were stored at a controlled temperature of 4±1°C to prevent biological degradation of the solids and organic matter before analysis. Figure 1 illustrates the locations of the CR and QM in relation to the Town of Chiquinquirá.

2.2 DAF and SED jar test

Coagulation, flocculation, and dissolved air flotation (DAF) jar tests were conducted following the protocol established by (Zou et al., 2011), which consists of the following stages: (1) rapid mixing at 100 rpm (shear rate (G) of 368 1/s) for 1 min; (2) slow mixing at 40 rpm (G=67 1/s) for 15 min; and (3) flotation for a duration of 10 min. Previous research has indicated that variations in the recycle ratio (RR) and saturator pressure (SP) do not significantly influence the turbidity removal of a bench-scale DAF apparatus (González-Galvis and Narbaitz, 2022). Consequently, typical values RR and SP were used (i.e. RR of 10% by volume using deionized water and SP of 70 PSI) for all the tests. The SED jar tests were carried out under the same rapid and slow mixing conditions as those applied in the DAF tests, with a settling period of 20 min.

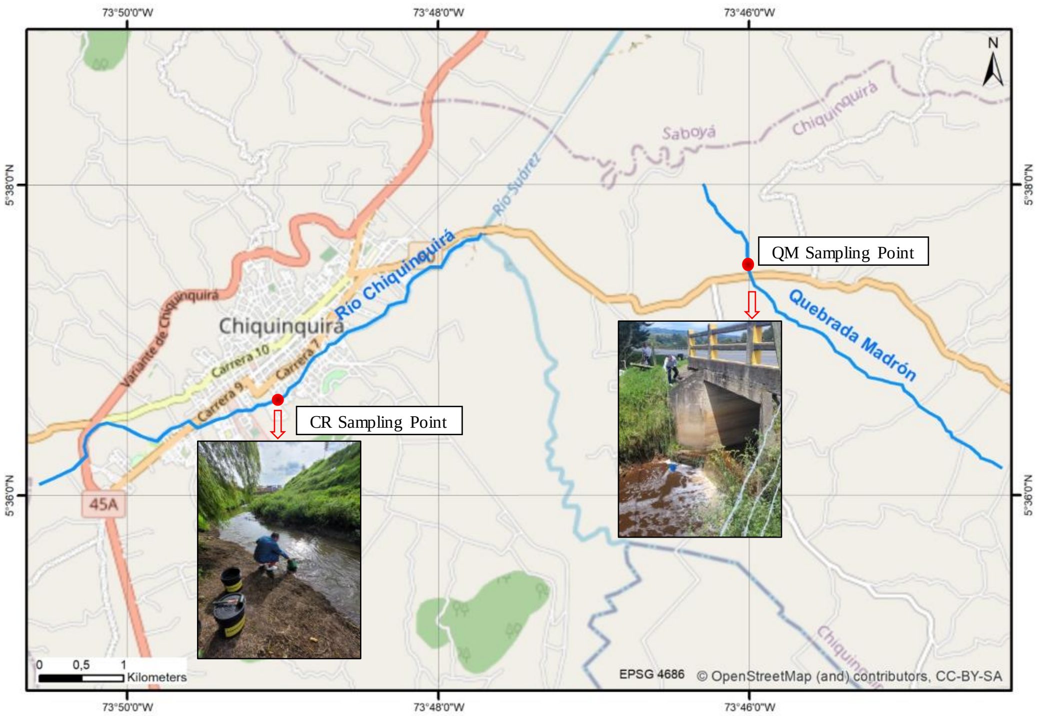

Figure 1. Localization of CR and QM with reference to the Town of Chiquinquirá

The, C/F/SED and C/F/DAF experiments considered aluminium sulphate ($Al_2(SO_4)_3$) dosages of 30, 40, 50, and 60 mg/L to treat the raw CR water and 60, 70, 80, and 90 mg/L for the raw QM water. Following the C/F/SED and C/F/DAF experiments, the turbidity, pH, apparent colour, and ultraviolet absorbance at 254 nm (UV_{254}), serving as an indicator for the aromatic components of the NOM, were measured immediately using standardized methods for water examination (APHA, 2017). The C/F/DAF experiments were replicated to ensure result reliability, with data reported as the arithmetic average of the two trials. The Figure 2 illustrates the DAF jar test setup and the corresponding flotation procedure.

2.3 Floc settling velocity test

The floc settling velocity (SV) tests were performed using a standard jar test apparatus equipped with 2-liter round beakers. A series of experiments were conducted to evaluate the SV of the flocs by measuring the turbidity following varying settling times ranging from 1.5 min to 30 min (1.5, 4.3, 7.0, 10, 15, 20, and 30 min). The SV experiments were performed at the optimal coagulant dose previously determined for treating the CR and QM water samples, respectively. Rapid mixing was carried out at 100 rpm (G=368 1/s) for a duration of 1 min, followed by slow mixing at 40 rpm (G=67 1/s). For detailed methodology regarding the procedure for standard jar tests, refer to (Pivokonský, 2022).

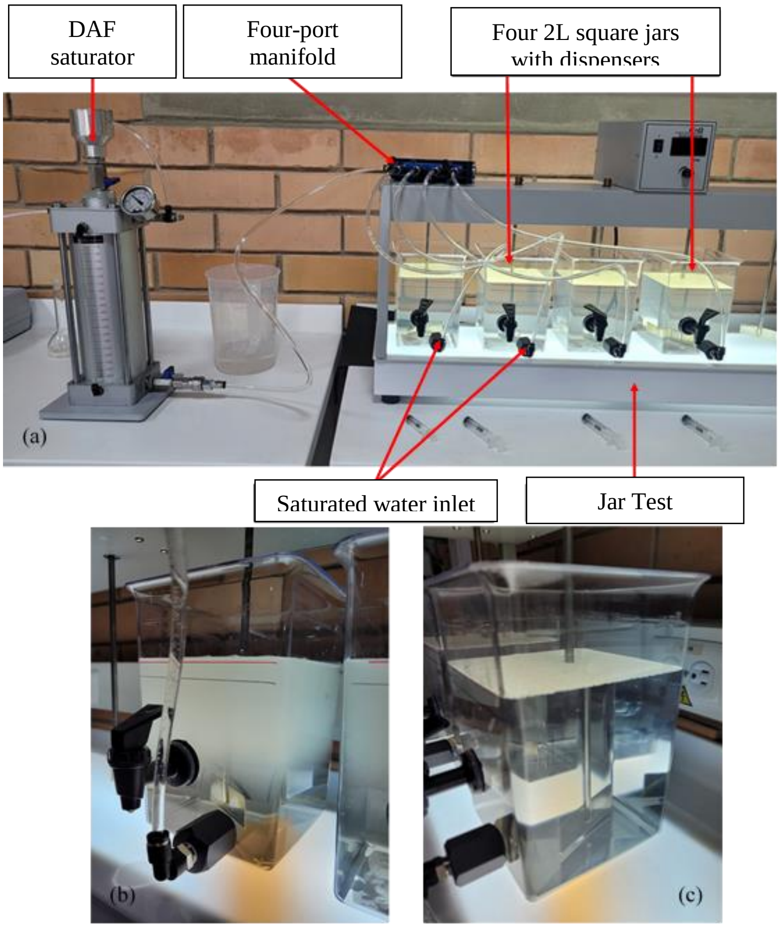

Figure 2. Experimental Setup: (a) DAF jar test apparatus; (b) bubble generation device; and (c) DAF white-water blanket

2.4 Flocculation time impact on turbidity removal

The formation of flocs during the coagulation and flocculation is known to significantly influence the turbidity removal. Factors such as floc size, structure, and density are affected by the agitation intensity, polymer concentration, mixing time and solids concentration during flocculation (Klimpel and Hogg, 1986). Consequently, this research investigated two distinct flocculation times (FT) of 10 min and 15 min to evaluate their effects on turbidity removal. The FT experiments were conducted using the optimum coagulant doses identified for treating the CR and QM water samples, respectively. Rapid mixing was performed at 100 rpm (G=368 1/s) for 1 min, followed by slow mixing at 40 rpm (G=67 1/s) during the respective flocculation times. Figure 3 provides a summary flow diagram depicting the study design and methodology.

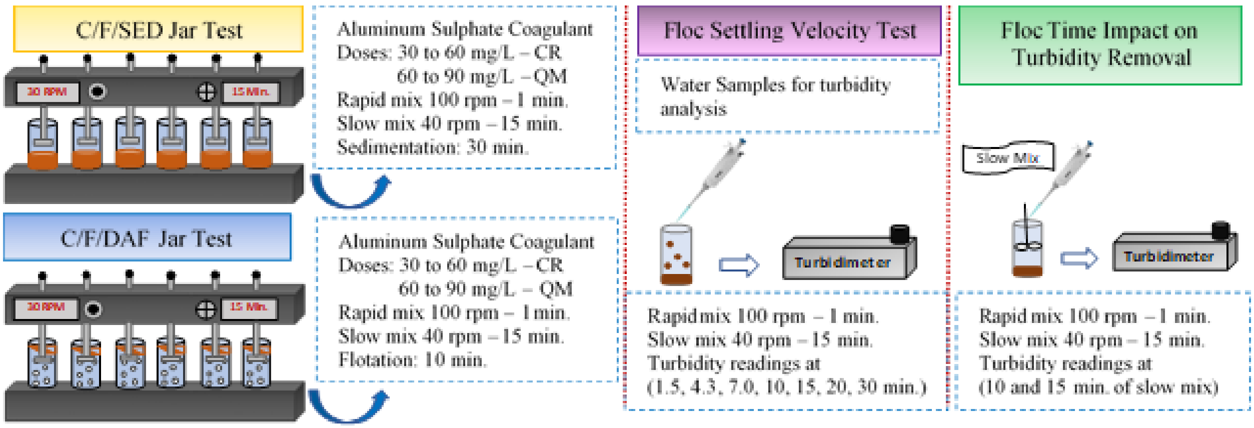

Figure 3. Flow diagram of the study design and method

2.5 Analytical methods

The pH of all water samples was measured using a HANNA HI9125 pH meter (Smithfield, Rhode Island, USA). The turbidity and apparent colour were determined using a Nanocolour® VIS II spectrophotometer (MACHEREY-NAGEL Inc., Allentown, PA, USA). Prior to analysis, the nephelometric turbidity meter was calibrated with 0.1 NTU and 20 NTU standards provided by MACHEREY-NAGEL Inc. The minimum turbidity detectable by the instrument was 0.1 NTU, with a reported measurement repeatability of ±1% or ±0.01 NTU, as specified by the manufacturer. The ultraviolet absorbance at 254 nm (UV_{254}) was measured using the same Nanocolour® UV/VIS II spectrophotometer, operating within a wavelength range of 190-1,100 nm. Before UV_{254} analysis, the water samples were filtered using 0.45 µm syringe filters (Membrane Solutions AUBURN, WA, USA) and analysed using a 1.0-cm path length quartz cell. The total hardness, alkalinity, and heavy metal concentrations were determined using an upgraded drinking water test kit (Tespert Biotechnology Co, Ltd. Wanchai, Hong Kong).

3. RESULTS AND DISCUSSION

Table 1 presents the characterization of the raw CR and QM waters collected during the sampling campaigns in February and March 2023, respectively. The reported water quality parameters correspond to the arithmetic average of three replicate measurements for each sample. A notable difference in turbidity levels was observed between the two sources, with QM exhibiting higher turbidity values than CR. The turbidity of the raw CR water (15.8 NTU) is primarily attributed to surface runoff from agricultural activities, as agricultural land use accounts for over 80% of the 129.16 km² CR basin (CAR, 2006).

The high turbidity of the raw QM water is primarily attributed to the presence of suspended solids and particulate matter originating from the runoff of agricultural soils within the surrounding basin. Additionally, the apparent colour of the QM is quite elevated (i.e., 819 Pt-Co), markedly higher than that observed in the CR samples. The colour of the QM source water is a yellowish-brown hue, characteristic of the presence of iron (Fe), which was found to be present at a concentration of 2.0 mg/L as Fe.

Table 1. Raw water characterization of the CR and QM

Parameter	CR (February 2023)	QM (March 2023)	Colombian Decree 2115/2007
pH	7.33±0.06	6.43±0.12	6.5-9.0
Turbidity (NTU)	15.8±0.66	44.2±1.83	2.0
Alkalinity (mg/L as $CaCO_3$)	40	10	200
Apparent colour (Pt-o)	237±12.8	819±29	15
UV_{254} (1/cm)	0.21±0.02	1.29±0.02	NR
Total hardness (mg/L)	50	50	300
Nitrate (mg/L as NO_3)	25	0.0	10
Iron (mg/L as Fe)	0.0	2.0	0.3
Nickel (mg/L as Ni)	0.0	5.0	0.02

The presence of iron in the surface waters is influenced by the soil composition within the basin as well as the decomposition of organic matter such as leaves, and other plant material (Civardi and Tompeck, 2015). Elevated Fe concentrations in drinking water have been associated with adverse health effects, including hemochromatosis, liver cirrhosis, and chronic fatigue (Chaturvedi et al., 2014). Potentially lower cost alternatives for iron removal may include aeration, chlorination, or hydrogen peroxide, as well as conventional softening, filtration and DAF (Vries et al., 2017; Pacini et al., 2005).

The apparent colour of the CR water was notably high, measuring 237 Pt-Co units, with a characteristic brownish hue attributed to the presence of crop residues and the decomposition of plant material from adjacent forested areas. The nitrate concentration in the raw CR water was 25 mg/L as NO_3^-, a level is considered relatively high and inappropriate for human consumption without prior treatment. This elevated concentration represents a potential health risk for populations using this water without adequate treatment. Nitrate contamination in surface waters is primarily linked to the use of agricultural fertilizers and animal manure. When present at elevated concentrations, nitrates can have significant adverse health effects (Ward et al., 2018) including: (1) infantile methemoglobinemia; (2) increased risk of colorectal, bladder, and breast cancers; (3) thyroid dysfunction; and (4) neural tube defects (Ward et al., 2018; Grout et al., 2023). Water treatments for nitrates removal include membrane filtration and activate carbon adsorption (Li et al., 2024; Zeggar et al., 2023).

As shown in Table 1, the QM water contains nickel (Ni) at a concentration of 5.0 mg/L, which substantially exceeds the maximum permissible limit established by Colombian drinking water regulations (0.02 mg/L as Ni). The presence of Ni in surface waters is often associated with runoff carrying particulate matter, as well as the weathering and dissolution of nickel-bearing rocks and soils (WHO, 2005). Nickel exposure has been associated with various adverse health effects in humans, including gastrointestinal disturbances (nausea, vomiting, and diarrhea), neurological symptoms (such as dizziness, fatigue, and headaches), respiratory problems (shortness of breath), as well as reproductive, developmental, and immunological effects, including allergic contact dermatitis (WHO, 2005). In addition, prolonged exposure to elevated concentrations of nickel, particularly in its sulfidic and oxidic forms, has been associated with an increased risk of lung and nasal cancers (WHO, 2005).

Conventional water treatment processes (C/F/SED), coupled with filtration have been shown to achieve nickel removal efficiencies ranging from 35% to 80% (Maleki et al., 2005). Factors such as elevated pH (>7.0), high turbidity, and substantial concentrations of humic substances have been reported to enhance the Ni removal efficiency (Rosińska and Dąbrowska, 2016).

3.1 Comparison of C/F/DAF and C/F/SED jar test results for turbidity removal

Figures 4(a) and 4(b) present the optimal coagulant doses identified for turbidity removal by C/F/DAF and C/F/SED for the CR and QM waters, respectively. As shown in Figure 4(a), the optimal alum dose for treating CR was 30 mg/L as aluminium, represented by blue squares for SED and red triangles for DAF. At this dosage, the residual turbidity for DAF was 2.10 NTU, corresponding to a removal efficiency of 86%, while for SED, the residual turbidity was 1.30 NTU, yielding a removal efficiency of 93%. An independent t-test comparing the turbidity removal efficiencies between SED and DAF for CR demonstrated that SED (91%) achieved statistically greater removal than DAF (86%) ($p<0.05$). Therefore, for the CR water, SED exhibited superior turbidity removal performance compared to DAF. These results are consistent with the guidance provided by (Edzwald and Haarhoff, 2011), as well as by (Valade et al., 2009). Coagulant doses below 30 mg/L were also evaluated for the treatment of CR in the jar tests, however, due to their poor turbidity removal efficiency, the corresponding results are not presented in this study.

Figure 4(b) shows that the best coagulant dose for QM was 60 mg/L for both SED (blue squares) and DAF (red triangles). After treatment, SED reduced turbidity to 3.30 NTU (93% removal), while DAF reached 4.50 NTU (90% removal). An independent t-test confirmed that the turbidity removal efficiency of SED (93%) was statistically significantly greater than that of DAF (90%) ($p<0.05$), indicating that SED also outperformed DAF for the treatment of QM. Additionally, Figure 4(b) shows that increasing the coagulant dose beyond 60 mg/L did not lead to further improvements in turbidity removal for QM. Coagulant doses below 60 mg/L were also evaluated for the treatment of QM in the jar tests, however, due to their poor turbidity removal efficiency, the results are not presented in this study. It is noteworthy that the optimal coagulant dose for CR (30 mg/L) was substantially lower than that required for QM (60 mg/L). This difference in optimal dosages may be attributed to variations in the raw water characteristics of the two sources, particularly turbidity and pH, as summarized in Table 1. Although SED demonstrated statistically superior performance, the turbidity removals achieved by DAF were only slightly lower. Accordingly, DAF can also be considered a feasible process for treating the high turbidity waters used in this study.

3.2 Coagulant dose impact on the final pH

Figure 5(a) illustrates the effect of the varying coagulant doses on the pH of the coagulated raw water from the CR. For CR, all tested coagulant doses resulted in pHs above 6.5, as indicated by the green shading in Figure 5(a). In contrast, Figure 5(b) shows that for QM, all the tested coagulant doses resulted in a substantial reduction in pH, decreasing from 6.43 to 5.57, as indicated by red shading. This is the result of the higher coagulant dose, the greater alkalinity consumption by the coagulant, and the lower raw water alkalinity. As a result, post-coagulation pH adjustment will be necessary for QM to ensure compliance with the minimum Colombian drinking water quality standards of 6.5 (Table 1).

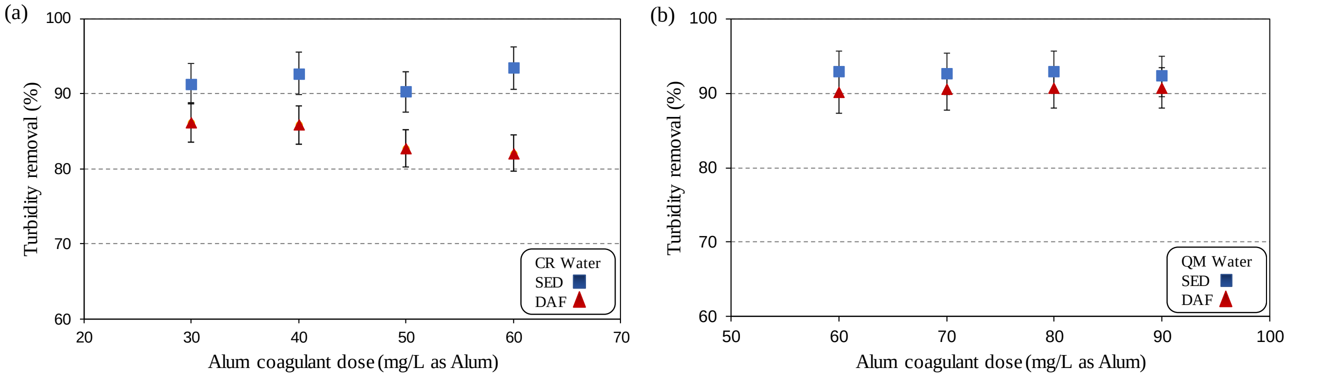

Figure 4. Turbidity removal for the SED and DAF jar test treating: (a) CR; and (b) QM. (error bars indicate one standard deviation) (n=2)

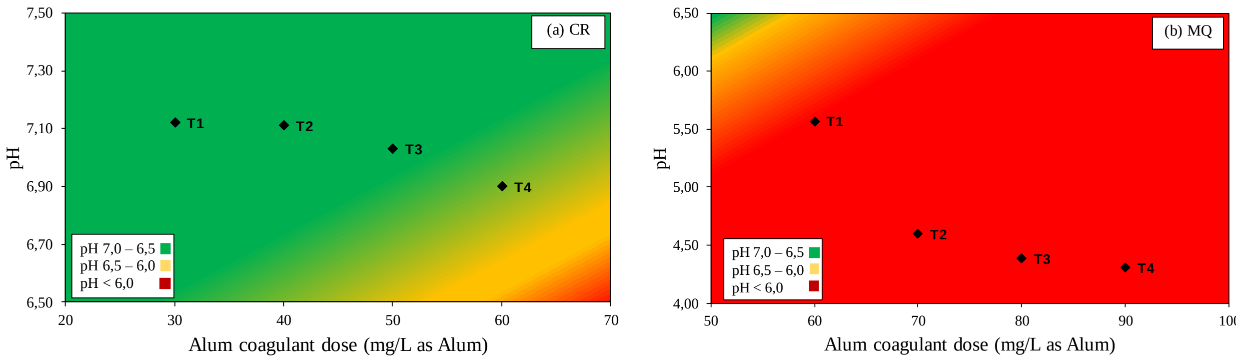

Figure 5. Impact of coagulant dose on treated water pH for: (a) CR; and (b) QM (T indicates the turbidity removal with the optimal coagulant dose)

3.3 Floc settling velocity test

Figure 6(a) presents the concentration of flocs remaining in the jar after various sedimentation times using the optimal coagulant dose of 30 mg/L for the treatment of CR water. The settling velocity of the flocs was indirectly assessed using the residual turbidity measurements. Water samples for turbidity analysis were withdrawn using a 10 mL pipette positioned about 1 cm below the surface of the water in the 1 L beaker. After 10 min of sedimentation, approximately 30% of the flocs remained suspended in the jar, corresponding to a turbidity of 4.84 NTU. For longer sedimentation durations of 15, 20, and 30 min, a gradual settling of very small, low-density floc particles was observed. The corresponding percentages of remaining flocs were 16% (2.63 NTU), 14% (2.21 NTU), and 11% (1.84 NTU), respectively. The final turbidity achieved after 30 min of sedimentation was 1.84 NTU, representing an 89% turbidity removal efficiency. This result is considered satisfactory, as it meets the Colombian regulatory limit of ≤2.0 NTU for treated water (Table 1), even prior to the filtration stage, which is expected to further improve the final turbidity.

A settling velocity test was also conducted using QM water to assess the sedimentation behaviour of the floc particles using the optimal coagulant dose of 60 mg/L (Figure 6(b)). The results in Figure 6(b) show that the flocs formed at this optimal dose settled quickly, presumably because of their high density and compactness. Specifically, 81% of the floc population settled within the first 1.5 min, resulting in a turbidity of 7.52 NTU. After 10 min of sedimentation, the turbidity further decreased to 3.65 NTU, corresponding to a removal efficiency of 91%. This result suggests that a sedimentation time of 10 min was sufficient to achieve turbidity removal comparable to that obtained by DAF (90%), as indicated by the red triangles in Figure 4(b). Sedimentation times of 15 and 30 min yielded only marginal improvements in turbidity reduction, with final turbidity values of 2.48 NTU and 2.43 NTU, respectively, corresponding to a removal efficiency of approximately 94% in both cases.

The formation of large flocs, as observed through visual inspection during the treatment of QM, is likely attributable to sweep flocculation processes. This mechanism likely enhanced by the precipitation of iron and nickel compounds present in the raw water (Tang et al., 2016; Bora and Dutta 2019).

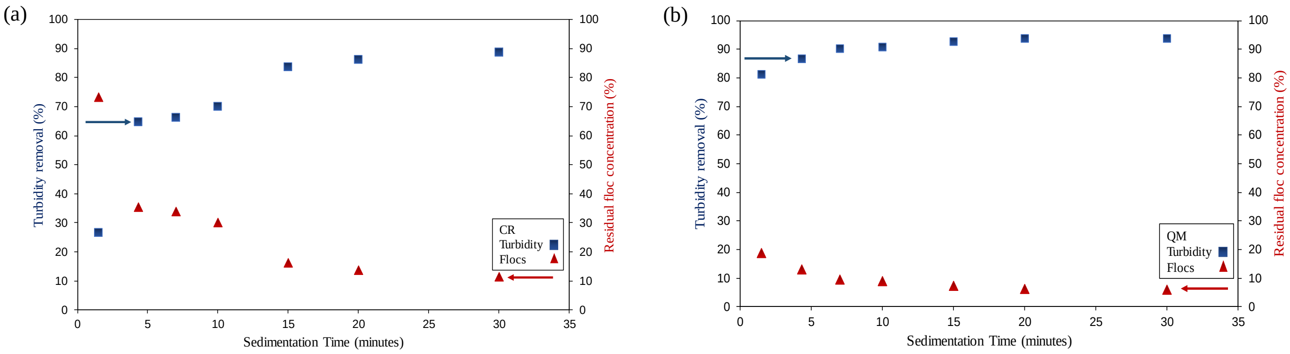

Figure 6. Impact of sedimentation time on residual floc concentration and turbidity removal for: (a) CR; and (b) QM

3.4 Flocculation time impact on turbidity removal

An efficiently conducted clarification process enhances subsequent treatment stages, such as conventional granular filtration or membrane filtration, by extending filtration run times, reducing the frequency of backwashing cycles, and minimizing membrane fouling (Jiao et al., 2017; Malkoske et al., 2020). Accordingly, this study investigated the impact of two different flocculation times on the treatment performance for CR and QM waters. As shown in Figure 7(a), the flocculation time greatly impacted the turbidity removal by SED when treating CR.

Increasing the flocculation time from 10 min to 15 min led to a 6.5% increase in turbidity removal, corresponding to 1.20 NTU. The size and structure of the flocs formed during the coagulation-flocculation process depend on several factors, including raw water characteristics (e.g., turbidity, pH, alkalinity, temperature, and NOM concentration and composition), as well as operational parameters such as coagulant dose and type, velocity gradient, and flocculation time (Wang et al., 2020, González-Galvis et al., 2022). In this case, the flocculation time played a critical role in enhancing the turbidity removal by SED (Figure 7(a) blue bars). The flocculation time also influenced turbidity removal by DAF when treating CR. As shown in Figure 7(a) (red bars), extending the flocculation time from 10 to 15 minutes resulted in a modest improvement of approximately 8% in turbidity removal efficiency during the DAF process. Nevertheless, a flocculation time of 10 minutes can be considered adequate to achieve satisfactory results with the tested conditions.

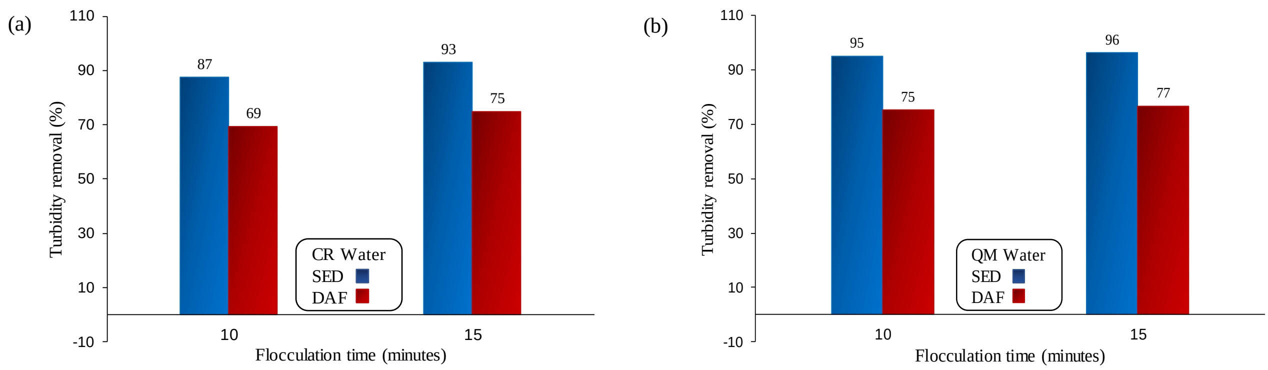

Figure 7. Impact of flocculation on turbidity removal by SED and DAF for: (a) CR; and (b) QM

In DAF systems, the buoyancy force plays a critical role in the interaction between the flocs and bubbles within the separation zone. Smaller flocs experience a proportionally greater buoyancy force than larger flocs, making them more likely to float. These conditions favour high collision efficiency between small flocs and bubbles, in accordance with the principles described by Stokes' law and the

Reynolds turbulence flow conditions (Basařová and Hubička, 2014; Wang et al. 2021). In this study, well-formed flocs observed following a 15-minute flocculation period for the CR water enhanced buoyancy in the DAF jar tests. This suggests that compact flocs, together with their attached bubble aggregates, exhibited greater overall buoyancy, facilitating more efficient flotation. Furthermore, the probability of floc-bubble collisions likely increased due to the terminal settling velocities of the compact flocs in the DAF jar.

An independent t-test comparing turbidity removal by SED and DAF confirmed a statistically significant difference ($p<0.05$) between the two processes, with SED achieving 93% turbidity removal, compared to 75% for DAF at a 15 minutes' flocculation time.

Figure 7(b) illustrates the impact of the flocculation time on the turbidity removal for the QM treatment. The results indicate that the flocculation time had no significant effect on either SED or DAF for QM. The formation of well-structured, dense flocs within 10 min of flocculation as observed in the jar was attributed to the raw water characteristics, including high turbidity (44 NTU), high apparent colour (819 Pt-Co), the presence of heavy metals such as iron and nickel (Table 1), and the high optimum coagulant dose used (60 mg/L as alum). Therefore, for the QM water, a 10-min flocculation time was sufficient to achieve 95% turbidity removal by SED and 75% by DAF. The lower turbidity removal efficiencies by DAF compared to SED for treating the QM water was likely due to the formation of large, heavy flocs with low buoyancy, which yielded poorer separation efficiency of the floc-bubble aggregates in the DAF jar test.

3.5 Sedimentation time impact on turbidity removal

In this study, the impact of three different sedimentation times (10, 20, and 30 min) on turbidity removal was evaluated for the treatment of both CR and QM waters (Figure 8). These time intervals were selected on the basis of recommendations from standard jar test procedures (Pivokonsky, 2022).

Figure 8 illustrates the effect of the sedimentation time on the turbidity removal for CR (red dash pattern bars) and QM (blue pattern bars). For CR water, turbidity removal gradually increased with sedimentation time, reaching 86% removal (2.40 NTU) at 20 minutes. In contrast, the sedimentation time had no significant effect on turbidity removal for the QM, with 10 minutes of sedimentation being sufficient to achieve 95% removal (1.49 NTU).

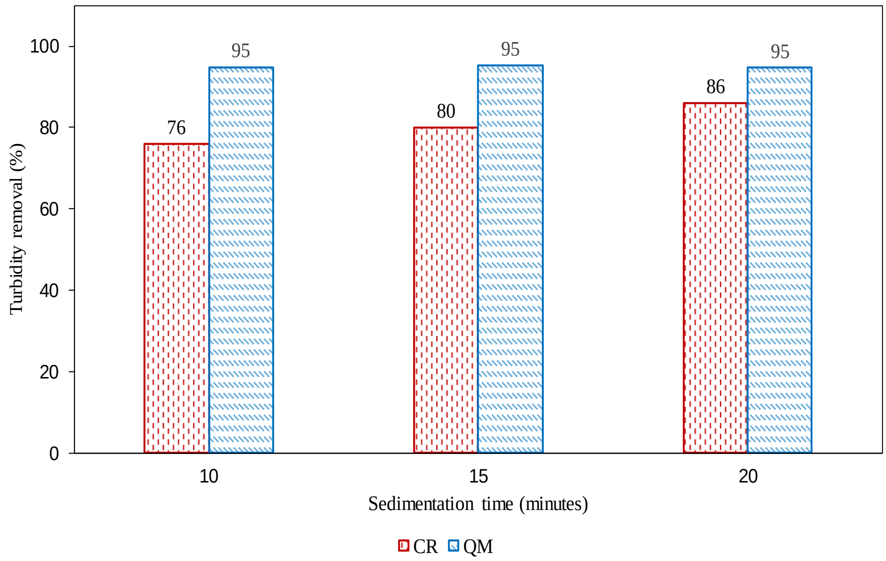

Figure 8. Impact of SED time on turbidity removal for CR and QM waters

The high turbidity removal efficiency observed for QM with just 10 min of sedimentation is likely attributable to the formation of well-structured, compact flocs, (as was visually observed in the jar during the coagulation and flocculation process) which facilitated rapid settling. Moreover, the combination of the applied coagulant dose and the higher raw water turbidity likely resulted in a floc mass in QM at least twice as large, thereby enhancing turbidity removal efficiency through the sweep flocculation mechanism.

3.6 C/F/DAF and C/F/SED jar test results for colour removal

To determine the optimal coagulant dose for apparent colour removal (i.e., unfiltered water samples) in both the CR and QM water sources, C/F/DAF and C/F/SED jar tests were performed (Figure 9(a) and Figure 9(b)).

The optimum coagulant dose for the removal of apparent colour in CR water was found to be the same as the optimum for turbidity removal (i.e., 30 mg/L of aluminium sulphate) for both the SED (blue squares) and DAF (red triangles) treatments (Figure 9(a)). The percent reduction in apparent colour for CR was nearly identical for both clarification strategies, with SED achieving 88% removal and DAF achieving 89%. An independent t-test showed no statistically significant difference between the two treatments ($\rho<0.05$). The final apparent colour after coagulation (SED=29 Pt-Co and DAF=25 Pt-Co) for both treatments still exceeded the Colombian regulatory limit of 15 Pt-Co (Table 1). This indicates that additional treatments, such as activated carbon filtration combined with disinfection or oxidation (i.e., chlorination), would be required to remove the remaining colour-causing substances (Wang et al., 2016).

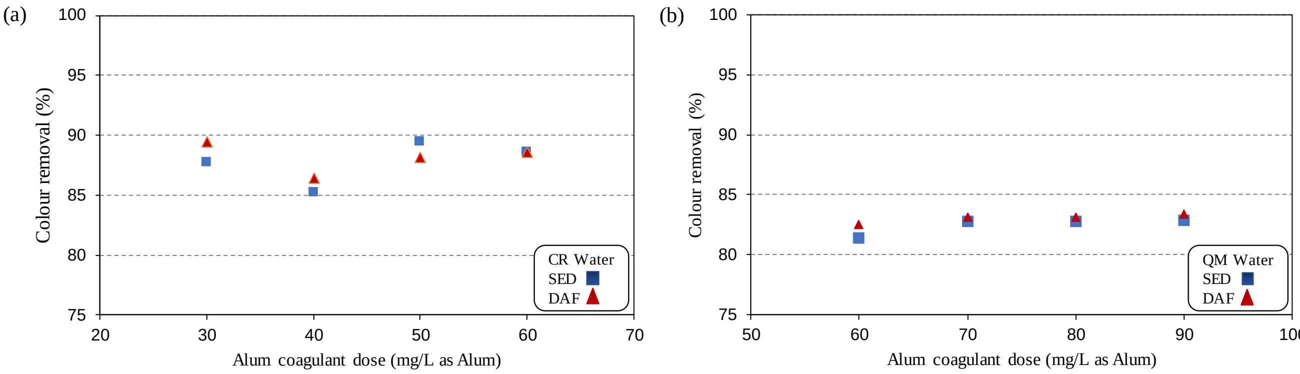

Figure 9. Apparent colour removal for SED and DAF jar test treating: (a) CR; and (b) QM

For QM water, the optimum coagulant dose for the removal of apparent colour was also found to correspond to that for optimum turbidity removal (60 mg/L of aluminium sulphate) for both SED (blue squares) and DAF (red triangles) (Figure 9(b)). The apparent colour removal was relatively similar for both treatments, with SED and DAF achieving an 81% (152 Pt-Co) and 83% (143 Pt-Co) reduction, respectively, at the optimal aluminium coagulant dose. In addition, Fe was completely removed by both the SED and DAF processes. The persistence of high apparent colour in the QM water after coagulation could be associated with residual heavy metals, particularly Ni, that was not fully removed during the treatment process. To further reduce the high apparent colour in surface waters, it is recommended to incorporate chlorine dioxide oxidation and filtration after C/F/SED or C/F/DAF (Civardi and Tompeck, 2015).

3.7 C/F/DAF and C/F/SED jar test results for UV254 removal

Ultraviolet absorbance at a wavelength of 254 nm (UV254) was used as a surrogate measure of the concentration of NOM in both the CR and QM samples. The 254 nm wavelength specifically quantifies the aromatic components of NOM, which can serve as precursors to disinfection by-products (DBPs) (Dong et al., 2023). Figures 10(a) and 10(b) show the removal of UV254 by SED and DAF treatments for CR, while Figures 10(c) and 10(d) illustrate the removal of UV254 by SED and DAF treatments for QM.

Figure 10(a) shows that the UV254 removal with the optimal coagulant dose (i.e., 30 mg/L) for treating CR was 62% for SED and 59% for DAF. Additionally, Figures 10(a) and 10(b) demonstrate that UV254 removal increased gradually with higher aluminium coagulant doses for both treatments.

However, beyond 50 mg/L, there was only limited improvement in UV254 removal. This could be attributed to the low variability in pH across the tested coagulant doses (Matilainen et al., 2010). A one-way ANOVA conducted for the different coagulant doses used to treat CR water showed no statistically significant difference between UV254 removal by SED and DAF (ρ<0.05). Thus, the results indicate that UV254 removal for CR water depends mainly on the aluminium coagulant dose rather than on the type of solid-liquid separation process used (Malkoske et al., 2023).

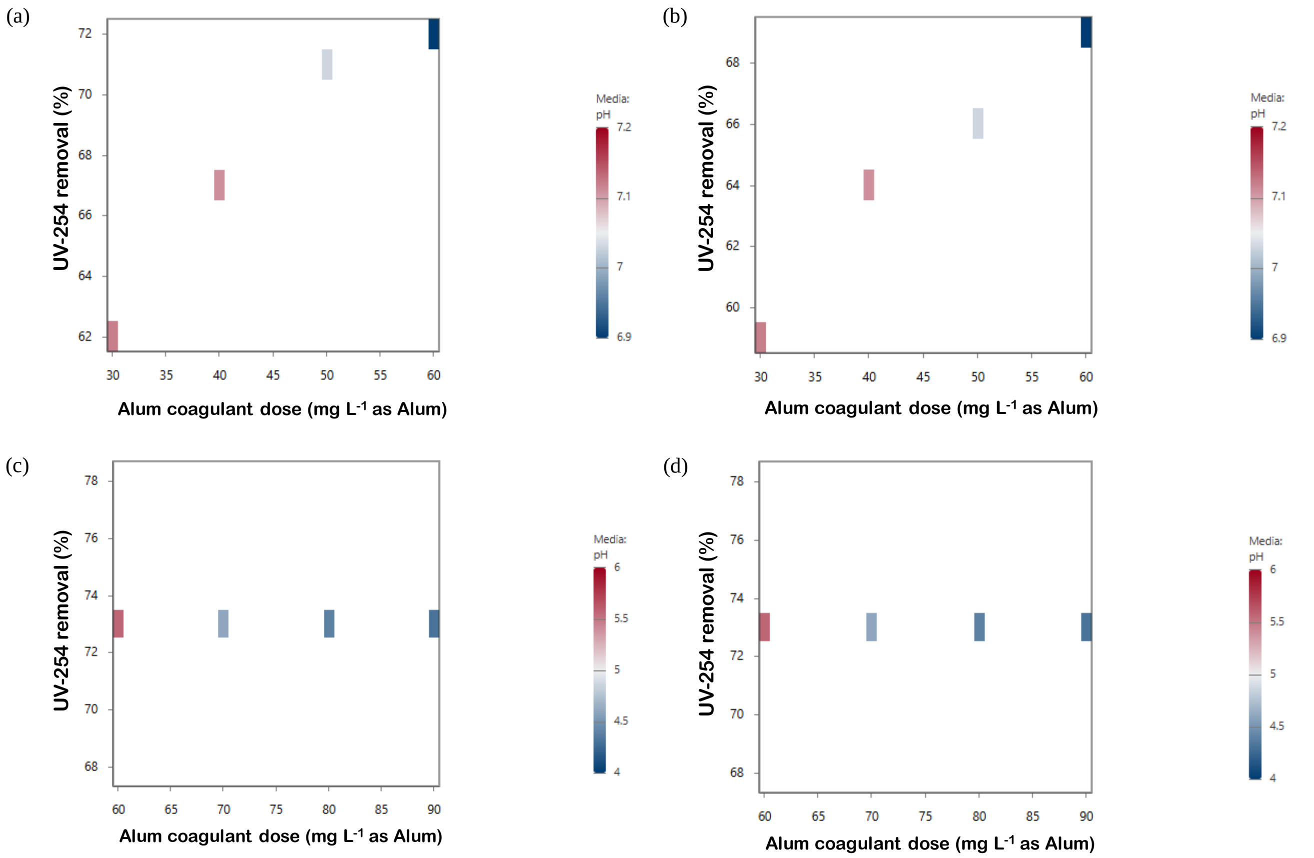

Figure 10. Removal of UV254 absorbance for: (a) SED-CR; (b) DAF-CR; (c) SED-QM; and (d) DAF-QM (Minitab®).

When the QM water was considered, there were also no differences in UV254 removal observed between SED and DAF treatment at the optimal coagulant dose (Figures 10(c) and 10(d)). The high UV254 removal percentage for QM is likely due to the high coagulant dose that created effective sweep floc conditions and contained more aluminium flocs, facilitating removal by adsorption (Matilainen et al., 2010). Reducing the amount of aromatic substances in water is important because it can help reduce the concentration of disinfection by-products (DBPs), such as trihalomethanes (THMs), in drinking water distribution systems (Mustereț et al., 2021). In Colombia, total trihalomethanes (THMs) must not exceed a concentration of 200 µg/L at the extremes of the distribution system.

4. CONCLUSION

This study presents the first comparative assessment of SED and DAF for the clarification of two surface water sources with high turbidity in Colombia specifically, the CR and QM. While both treatment alternatives achieved high turbidity removals, SED was found to consistently outperform DAF, yielding greater turbidity reduction and lower residual turbidities. The flocculation time significantly impacted the turbidity removal for CR. Compared to a 10-minute flocculation period, fifteen minutes of flocculation improved turbidity removal by 6.4% in SED and 8% in DAF. However, for QM water, the flocculation time was found to have minimal impact on turbidity reduction. This is likely due to higher feed turbidity and much higher optimal coagulant dose.

When the impact of sedimentation time was assessed using the CR water, turbidity removal improved with increasing sedimentation time, reaching 86% after 20 minutes. In contrast, for the QM water, the maximum turbidity removal of 95% was achieved after only 10 minutes, indicating that extended sedimentation was unnecessary for this source. The final colour values for all combinations of water and treatment types were found to exceed the Colombian regulatory limits, indicating that the water requires additional treatment, including filtration and chlorination for oxidation (e.g., chlorine dioxide). Future work should explore combined treatment strategies (e.g., advanced oxidation processes, activated carbon filtration) to address the persistent colour and NOM challenges, especially for QM. The UV254 absorbance showed similar removal rates for both SED and DAF. The UV254 removal efficiency was primarily a function of the source water and the coagulant dose rather than the separation method. These findings underline the necessity of integrating additional treatment processes (e.g., oxidation or adsorption) tailored to each source's contaminant profile. Since the optimal coagulant dose for treating QM produced a post-coagulation pH below the Colombian regulatory limit of 6.5, it is recommended to perform a pH adjustment after treatment to ensure compliance with drinking water quality standards and reduce corrosion in the distribution system. In summary, sedimentation demonstrated slightly superior turbidity removal and matched DAF in colour and UV254 reduction. Given its lower operational complexity and comparable efficiency, SED may represent a more robust and context-appropriate clarification method for high-turbidity surface waters where there is unlikely to be space constraints requiring a more compact separation process.

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AUTHOR CONTRIBUTIONS

J. P. González-Galvis participated in the sampling campaigns, conducted the experiments, conceptualized the study, wrote, reviewed, and edited the manuscript. A. M. Jaramillo and B. Pacheco participated in the sampling campaigns and reviewed and edited the manuscript.

DECLARATION OF CONFLICT OF INTEREST

The author declares no competing financial interest.

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