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Research article

Experimental approach and analysis of the effectiveness of a tubular helical flow flocculator for water supply in developing communities

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ABSTRACT

The main objective of this study was to evaluate the impact of the length and retention time of a tubular helical flow flocculator (THFF) on the elimination of turbidity and color from raw water, to obtain quality treated water for consumption in areas rural. For this, a large-scale field experimental system was used, the THFF was built with 4-inch diameter polyethylene hose and coupled to a sedimentation and filtration process. For the different experimental tests, aluminum sulfate was chosen as the coagulant. To find the optimal dose of coagulant, jar tests were previously carried out. For the tests the length of the THFF was varied (50 m and 75 m), flow rates of 0.25, 0.5, 0.75, 1 and 2 L/s and turbidity ranges of <10, 10–20, 21–50, 51–100 and > 100 NTU of raw water were tested. An evaluation of the hydraulic behavior of the THFF was carried out through an analysis of the temporal distribution curve of the concentration of a tracer, applying the Wolf-Resnick model. The average results revealed a haze and color removal efficiency of 98.07 % and 98.50 %, respectively. The residence time and velocity gradient exhibited variations in a range of 2.25–35.0 min and 3.64 to 56.94 s^{-1}, respectively. It was evident that the operation and effectiveness of THFF are directly influenced by the turbidity of the raw water, the residence time and the velocity gradient. These findings indicate that THFF could play a valuable role as a flocculation unit in a purification system, mainly the existence of a plug-type flow was observed. The findings indicate that THFF, complemented by settling and filtration processes, could be a valuable tool for implementation in rural areas.

1. Introduction

Access to quality water has been a problem in communities far from cities and that are developing, because they do not have a mechanism to provide adequate treatment of accessible sources for consumption [1,2]. The unfavorable geographical and

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environmental conditions present in the various communities, as well as climate change, have further increased the problem in obtaining the optimal vital liquid for consumption [3,4].

Conventional water treatment plants are essential to provide an efficient service of quality liquid to the population; However, the costs, knowledge and adaptation of spaces necessary for their operation have been the aggravating factors so that in developing communities there is no possibility of implementing them [5,6]. Therefore, the use of new treatment techniques is required to generate accessible, quality drinking water that integrates optimal processes from its intake to its distribution in homes [7,8]. Within the treatment process of a conventional purification plant (CPP) there are two essential processes and the subsequent processes depend on their efficiency, these are coagulation and flocculation, in the first it is necessary to incorporate a chemical coagulant and in the second a flocculant or coagulation aid [9,10]. These stages stand out within the entire process of obtaining drinking water because, based on the efficiency with which these are carried out, subsequent processes such as sedimentation, filtration and disinfection will have their respective effectiveness index [11].

Hydraulic flocculators generally consist of baffles, which, to treat large flows, require civil infrastructure [12]. On the other hand, mechanical flocculators require external energy sources to move agitators in tanks, which represents high economic costs [13]. Currently, it is necessary to promote research and implementation of low-cost flocculators that generate acceptable drinking water quality and in turn compliance among those who benefit [14]. Presenting tubular flocculators as a more viable alternative to implement in developing communities [15]. Oliveira and Donadel (2024) indicate that the helical tube flocculator offers notable advantages such as high process efficiency, short detention time and cost-effectiveness compared to conventional hydraulic units. Al-Kathili, F. A., and Doaa hameed khalaf (2022) indicate that the use of spiral tubes as a coagulation-flocculation reactor is an efficient, fast and low-cost clarification system.

Within the tubular flocculators, helical flow tubular flocculators are presented as a novel and accessible design for communities that require efficient treatment of their water resources [16]. The tubular helical flow flocculators (THFF) are made up of structures and materials that are removable, which facilitates their transportation, in addition to there being a decrease in the forcing of the liquid flow generated during the change of direction that occurs in conventional hydraulic flocculators [16,17].

THFFs are developed with a longitudinal dimensioning of the path so that they comply with corresponding chemical and physical processes [18]. THFFs have a very particular design; they require a flexible material for their operation, as well as a fixed base to wrap around [19]. This author defines the THFF as a plug flow reactor. Carissimi [20] worked with a THFF experimentally, generating a tubular flocculator under controlled laboratory conditions. This type of flocculators aim to provisionally improve the deficiencies presented in hydraulic and mechanical flocculators [21,22].

The aspects to consider in the application of these systems lie especially in the number of turns, their speed gradient, retention time and more hydrodynamic aspects [23]. Being tubular, they require less periodic maintenance and in the same way prevents the existence of dead mixing zones [24]. Through modifications in its design and layout, the aim is to generate the lowest possible pressure losses [16]. A case focused on helical tubular flocculation was presented at the University of Montpellier, France, in which a helical design was implemented using transparent hose coiled in a 10 cm diameter PVC cylinder, with sections of 2.4 and 16 m in length this is how he explains it Elmaleh and Jabbouri [24]. The flow rate was 1 cm^3/s; A pump with a power of 200–300 rpm was used to generate mechanical flocculation of a synthetic bentonite suspension. Ferric chloride was injected at a dose of 150 mg/L after being determined in jar tests. The results obtained by Elmaleh and Jabbouri [24] They appeared to be graphically successful due to the optimization of the velocity gradient in the system.

Carissimi [20] presented in his study a compact linear flocculation system, whose name was established as FGR (Floc Generating Reactor) that integrated 5 models, with a helical model standing out. To do this, they used ferric chloride as a coagulant along with cationic polymers. The flocculation system consisted of a transparent polyurethane hose with an internal diameter of 1.25 cm that was wound around a PVC pipe with a radius of 5 cm. The results showed a prediction in floc generation due to its low retention time, a plug flow with the absence of dead zones and short circuits. The helical model with 12 m in length and 1.2 L in volume presented better results in the formation of flocs, since the other 4 models did not allow or broke the formation of flocculated particles.

The study carried out by Oliveira [23] proposed models to predict the functionality of a THFF. A controlled flocculation system was generated, following the methodology proposed by Oliveira [19] that transported pumped water with a turbidity of 50 NTU through a vertically and horizontally wound system. Aspects such as dosage and measurement of losses were regulated through equipment; It was designed with 84 configurations. Computational modeling with CFD software to analyze the operation of the system facilitated a better study since it was complemented with the use of design and drawing software, as well as for data analysis. To characterize the hydrodynamic model, Oliveira [23] used computational models, which turned out to be successful since low Reynolds numbers were obtained, as well as a numerical mesh capable of predicting its behavior.

The studies presented by Oliveira and Teixeira [25] and Oliveira and Donadel [15] presented a theoretical and mathematical modeling respectively of a THFF. They included a previous experimental phase, where each one integrated the analysis of efficiency and removal of turbidity and color along with their experimental modeling. In the first study, we sought to generate a CFD (computational fluid dynamics) modeling for hydrodynamic data, SN values (Reynolds number) and a physical experimentation TRE (turbidity removal efficiency) in order to improve the hydraulic and geometric characteristics deficient. For this, a compact system was used with synthetic water (50 NTU) that passed through a horizontally arranged helical flocculator with 48 configurations and with an experimental flow rate of 0.033 L/s. Meanwhile, for the second case study, a more practical system of 24 configurations was included with flow rates of 1–2 L/min for the first configurations (1–16) and another flow rate of 2–4 L/min for the configurations (17–24) remaining. The length with which the system worked varied from a minimum recorded of 1.89 m to the maximum that corresponds to 36.84 m, in order to record low retention times. The other parameters follow the previous methodology presented by Oliveira and Teixeira [24] focused on the same objective. The results for the study by Oliveira and Teixeira [15] highlight the importance of flocculation time, since a longer time favors the formation of flocs.

Cahyana et al. [26] presented their study carried out at the University of Kebangsaan, India about the performance of a helical flocculator that sought to meet 2 objectives, the first regarding optimal dosage and the second focused on efficiency. It worked with flow rates of 5–45 ml/s, with ½ inch (1.27 cm) and 0.625 inch (1.59 cm) pipes with a coil diameter of 40 and 80 cm. Aluminum sulfate was used as a coagulant for the tests using test jar. Based on the research objectives, the results presented by Cahyana et al. [26] showed that for the optimal dosage with a turbidity greater than 150 NTU, the dose was 220 mg/L aluminum sulfate. On the other hand, the evaluated efficiency presented gradients of 64.9–69.6 s^{-1}, retention times of between 7.3 and 10.2 min that generated an average turbidity removal of 72 and 74 %.

Therefore, the main objective of this study was to evaluate the impact of the length and retention time of a tubular helical flow flocculator on the elimination of turbidity and color from raw water, to obtain quality drinking water for consumption in rural areas, allowing to obtain a sustainable and effective alternative in improving the quality of water intended for human consumption. The research focuses on examining the performance of THFF in removing specific contaminants, as well as evaluating its technical and economic feasibility for applications in smaller-scale community settings. These results can offer valuable insights for the implementation of accessible and efficient water management solutions in community contexts.

2. Materials and methods

2.1. Description of the conventional water treatment plant

The CPP where this study was carried out combines the processes of coagulation, flocculation, sedimentation, filtration and disinfection. This CPP is supplied with raw surface water, operates under gravity and provides drinking water service to a population of approximately 6000 people [27]. The CPP is located in the Bayas parish, city of Azogues, Republic of Ecuador at coordinates 740,740 east and 9699964 north, at an elevation of 2800 m above sea level. This CPP uses aluminum sulfate as a coagulant, which is added in a rectangular landfill that works as a quick mixer. Additionally, the CPP has two hydraulic flocculators that operate in parallel, a horizontal flow baffle flocculator that treats 10 L/s and a vertical flow baffle flocculator that treats 10 L/s, giving a total flow rate of 20 L/s. High-rate sedimentation, rapid filtration and disinfection processes complement CPP.

2.2. Description of the experimental purification plant

To evaluate the tubular flocculation process, a THFF was implemented on a cylindrical metal structure where polyethylene hose was wound, thus forming the helical flow tubular flocculation system. This system was connected to the rapid mixing system used by the CPP, for which PVC pipes were implemented and the flow rate necessary for the different THFF tests was regulated using valves. After the flocculation stage with the THFF, a high-rate decanter was implemented and finally a rapid sand filter was connected. A schematic of the experimental flocculation system is presented in Fig. 1.

Successful operation and development in each stage of the experimental process was essential for the development of the tests and the generation of information for subsequent comparison with the CPP. This system was complemented with valves that allowed controlling the inlet flow and the different lengths of the THFF used during the experimental tests.

2.2.1. Helical flow tubular flocculator

Since there is no established methodology for the design of tubular flocculators, the recommended methodology for the design of a hydraulic baffle flocculator was used, following the criteria proposed by Haarhoff (1998), Romero (1999) and Crittenden et al. (2012). Factors such as residence time (between 10 and 60 min) were taken into account (Arboleda, 2000; Crittenden et al., 2012) and water

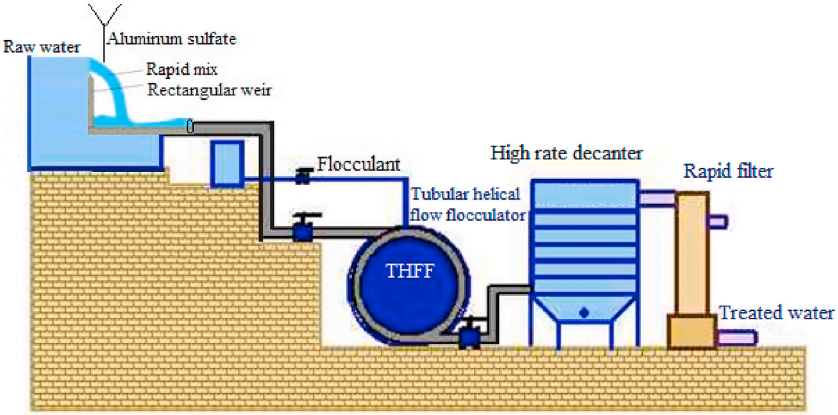

Fig. 1. Side view of the helical tubular flocculator and the system in general (THFF).

speed (0.1 m/s to 0.3 m/s) (Romero, 1999; Ghawi, 2018). For the design of the FTHF, a design flow rate of 1 L/s, a residence time of 10 min and a speed of 0.12 m/s was selected, complying with the recommendations for the design of the hydraulic baffle flocculator. Applying the baffled flocculator design methodology of Abdulkareem et al. (2014) and Tong (2017), a length of 75 m was determined to maintain a retention time of 10 min and a speed of 0.12 m/s. Likewise, considering the flow rate (1L/s) and the mentioned speed (0.12 m/s), a diameter of 0.1 m (equivalent to 4 inches) was obtained. 10 min of retention was considered since the bibliographic references regarding FTHF indicate that this system has short retention times; For this reason, a shorter retention time was also chosen (6.75 min), which in turn corresponds to a length of 50 m for the same diameter of 0.1 m. In an FTHF, the construction material is crucial to allow the necessary turns. For this reason, a flexible material such as polyethylene was used, which meets these requirements. In addition to its flexibility, polyethylene ensures durability and corrosion resistance, its ability to withstand adverse weather conditions also makes it a robust option for outdoor environments.

It must be noted that the entire experimental system worked under gravity. The THFF being a system that relies on helical flow and tubular geometry to promote coagulation-flocculation, this flocculator worked effectively without the need for electrical energy.

2.2.2. High-rate decanter

A high-speed decanter was required to retain the flocculent particles generated in the THFF. The design and construction of this system was based on the methodology recommended by Romero Rojas [28] and Arboleda [29] for a flow rate of 1 L/s and a surface load of 120 m^3/m^2day. The decanter was provided with honeycomb-shaped decanting modules made of Acrylonitrile Butadiene Styrene material. These modules have cells inclined at 60°, with a cell spacing of 5 cm, allowing water to flow upward through the cells with a laminar flow. Fig. 2 illustrates the location of the high-velocity settler, constructed of galvanized brass. In the decanter, it was necessary to implement a valve in the upper part for the entry of flocculated water, a valve in the lower part that served for the evacuation of sludge and maintenance through washing. Likewise, at the upper outlet part it was provided with a connection with PVC pipe that transported the water to the filters as seen in Fig. 2.

2.2.3. Rapid sand filter system

In order to capture the particles that were not retained in the settler, a set of 4 rapid filters was installed that operated with a surface load of 5 $m^3/m^2/h$, the outlet of the filters was connected to each other. Valves were installed on the top of the filters to facilitate the evacuation of water during the backwash process.

The filter bed of the rapid filters was made up of sand and gravel, a diagram of these filters is seen in Fig. 2. These filters were built using 300 mm diameter PVC pipe. Each filter was provided with gravel of different granulometry in its lower part, completing a height of 30 cm; Meanwhile, the height of the sand was 60 cm with an effective size of 0.7 mm according to what was specified by Romero Rojas [28]. The optimal operating flow rate was 0.1 L/s per unit, giving a total of 0.4 L/s filtered water. The 0.6 L/s that left the decanter and did not enter the experimental filtration system was sent to the CPP filtration process. To backwash the filters, an elevated tank of treated water located at a higher height than the filters was used, in order to take advantage of gravity.

2.3. Hydraulic analysis of the helical flow tubular flocculation system

2.3.1. Residence time calculation

Equation 1 was used to determine the theoretical residence time (to) in the THFF, where V is the volume of the flocculator, and Q is the water flow rate used in the tests. To calculate the volume of the THFF, formula $V = \pi r^2 L$ was used, where L is the length and r is the radius of the flocculator pipe.

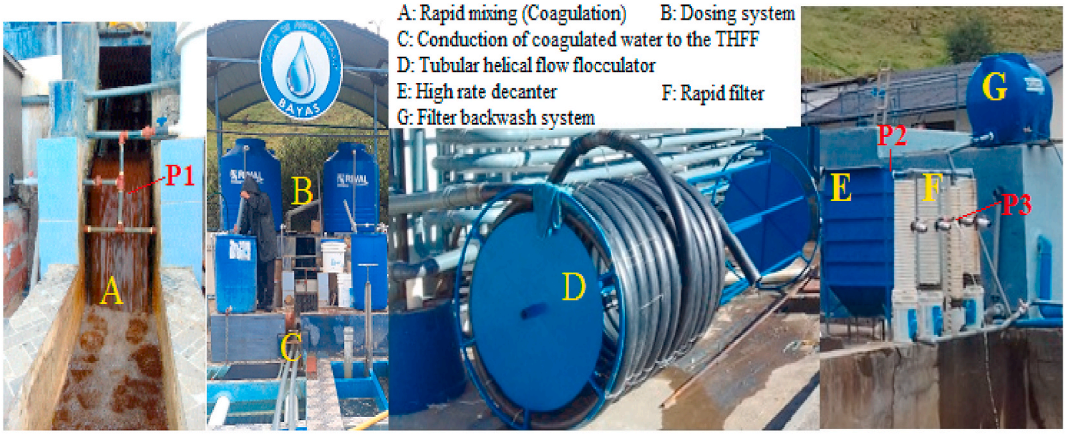

Fig. 2. Experimental system consisting of rapid mixing, tubular helical flow flocculation, high-rate decantation and rapid filter.

$$to = \frac{V}{Q} \tag{1}$$

The tracer technique was used to calculate the real residence time (t_m) [30], for which, an instant dose of a sodium chloride solution was added. The tracer was introduced at the inlet of the THFF, to immediately measure the content of total dissolved solids (TDS) at the outlet of the THFF, just before entering the settler. The TDS content was measured every 30 s using a digital dissolved solids meter; Subsequently, time versus SDT was plotted with the collected data; Finally, the actual residence time was calculated by applying equation (2), where "tm" represents the actual residence time, "Co" denotes the initial concentration of SDT, and "Ci" indicates the concentration of SDT at a specific time "ti" [27].

$$t_m = \frac{\sum_{i=0}^{n} t_i * (C_i - C_o)}{\sum_{i=0}^{n} (C_i - C_o)} \tag{2}$$

2.3.2. Hydraulic characteristics of the FTH

With the tracer concentration data obtained, the flux distribution functions and curves were obtained, being able to obtain the values of F(t) and 1-F(t), and their respective distribution functions. These distribution functions were used to evaluate the flow type of the THFF using the Wolf and Resnick model. Fig. 3 denotes the characteristics of the simplified model of Wolf-Resnick [31], the ordinate axis represents the relationship of the concentrations obtained through experimentation with tracers and that are linked to the time of retention present on the abscissa axis [32]. By calculating the unknown α, the type of flow (P, M, m) present in the THFF can be characterized. Through this model, the percentage of piston flow (P), complete mixture (M), and dead zones (m) could be quantified [27]. The resulting information on the proportion of each type of flow, especially the presence of dead zones, is revealed as a crucial factor for making decisions based on the optimization and efficiency of the process. This detailed analysis not only contributes to understanding the internal dynamics of the THFF, but also facilitates the identification of areas for improvement and the implementation of strategies to maximize system performance. For a further analysis of the Wolf and Resnick model, it is recommended to consult the literature indicated in Perez [31] and Rodríguez [32].

2.3.3. Velocity gradient calculation

The velocity gradient (G) is a parameter that provides crucial information about the intensity of mixing in a system. In the THFF the calculation of the velocity gradient was done taking into account the total head loss along the pipe, and equation (3) has been the most used to evaluate the value of G in a flocculation system [28], where G is the velocity gradient (s^{-1}); ρ is the density of water (kg/m^3); g is gravity (m/s^2); h_f is the head loss (m); μ is the dynamic viscosity of water (kg/m.s); t is the residence time (s). A theoretical velocity gradient (Go) and real velocity gradient (Gr) were calculated using the theoretical residence time and real residence time respectively.

$$G = \sqrt{\frac{\rho * g * h_f}{\mu * t}} \tag{3}$$

Darcy-Weisbach equation (4) was used to calculate the head losses in the THFF pipes [33]. Head losses were evaluated for lengths of 50 m and 75 m. Where f is the friction factor (dimensionalless), L is the pipe length (m), D is the pipe diameter (m) and v is the average velocity (m/s).

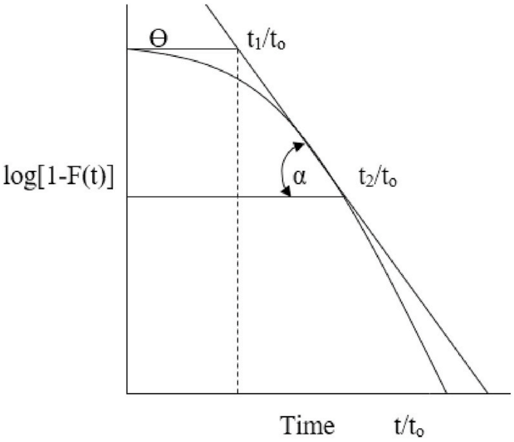

Fig. 3. Characteristics of the Wolf-Resnick simplified model for the evaluation of THFF.

$$h_f = f * \frac{L}{D} * \frac{v^2}{2g} \tag{4}$$

The friction factor (f) was calculated by Chen's expression according to equation (5) [34]. For which, the roughness of PVC pipe was taken into account with a value of 3.0 × 10 $^{-7}$ m [35]. Being ε: Pipe roughness (m); Re: Reynolds number.

$$f = \frac{1}{\left(-2\log\left\{ \frac{\varepsilon}{3.7065D} - \frac{5.0452}{Re}\log\left[\frac{1}{2.8257}\left(\frac{\varepsilon}{D}\right)^{1.1098} + \frac{5.8506}{Re^{0.8981}} \right] \right\} \right)^2} \tag{5}$$

The pressure loss due to the accessories (h_{fa}) present in the THFF were calculated by equation (6); for which, the kinetic load coefficient (K) was considered, which depends on the type of accessory [36].

$$h_{fa} = k\frac{v^2}{2g} \tag{6}$$

where h_{fa}: head loss due to accessories (m); k: kinetic charge coefficient (dimensionalless).

2.4. Experimental analysis of the effectiveness of the tubular helical flow flocculator

2.4.1. Detail of the experiments developed

Fifty experiments were carried out over a year to evaluate the effectiveness of the THFF, each test was carried out in duplicates to reduce possible errors, ultimately obtaining 100 experiments. Two lengths of the THFF were tested, L1 = 50 m and L2 = 75 m. Each length was tested with five raw water flow rates, Q1 = 0.25, Q2 = 0.5, Q3 = 0.75, Q4 = 1.0 and Q5 = 2.0 L/s. Likewise, five levels of turbidity of raw water were considered for each length combined with the aforementioned flow rates, T1 < 10 NTU, T2: 10–20 NTU, T3: 21–50 NTU, T4: 51–100 NTU and T5 > 100 NTU. Before each experiment, a jar test was carried out to determine the optimal dose of coagulant (aluminum sulfate), this in order to guarantee an efficient raw water treatment process.

2.4.2. Laboratory tests to determine the optimal dose of coagulant

Before starting each test at the THFF, the optimal dose of the coagulant necessary for coagulation was determined in the laboratory. For which, the jar test was applied using aluminum sulfate at a concentration of 2 % as a coagulant. Based on the turbidity of the raw water, the exact amount of aluminum sulfate solution that needed to be added to the foot of the rectangular weir was determined to achieve efficient coagulation. The results of these tests made it possible to improve the effectiveness of the coagulation process, optimizing the use of the coagulant and guaranteeing the quality of the water treated in the plant. It should be noted that the rectangular landfill used for rapid mixing was common to both the experimental system that the THFF had and the conventional plant where the study was carried out. Once the raw water was coagulated using a PVC pipe, the coagulated water was transported to the THFF. Polyelectrolyte was then added at a point located one-fifth of the length of the THFF. Subsequently, the flocculated water entered the high-rate decanter and finally, the settled water was directed to the rapid filters.

2.4.3. Operation of the experimental system by modifying the lengths of the THFF, the flow rates and the turbidities of the raw water

THFF (50 m and 75 m) were evaluated in order to analyze the relationship between the length and the efficiency of the THF. For this, a valve was implemented at exactly 50 m with a direct bypass to the settler. When closing this valve, it allowed the direct passage of flocculated water to the settler; Meanwhile, when this valve was opened, the water entered the last section of the flocculator, traveling a total of 75 m. Although both the THFF and the high-rate settler of the pilot plant were designed for a flow rate of 1 l/s, different flow rates were used to analyze the performance of the system based on these operating conditions. To achieve the different flow rates, a regulating valve located at the inlet of the THFF was used. This valve allowed 5 different flow rates to be adjusted (0.25; 0.5; 0.75; 1 and 2 L/s). To complete the experimental test, five ranges of turbidity of raw water were evaluated with the objective of covering turbidity in both the summer and winter seasons. For which, turbidities T1 < 10 NTU, T2: 10–20 NTU, T3: 21–50 NTU, T4: 51–100 NTU and T5 > 100 NTU were grouped. To achieve these turbidity variations, a raw water sample was taken daily, and its turbidity was measured; Based on the value obtained, it was classified in one of the ranges mentioned above. In case of obtaining a turbidity already evaluated previously, wait the next day to obtain a different value and proceed in this way until all the established turbidity ranges are completed.

In summary, 50 tests were carried out combining 2 lengths, 5 flow rates and 5 turbidity ranges, each test was replicated, totaling 100 experiments carried out from January to December 2022 in order to obtain reliable data on the elimination of the analyzed parameters.

2.4.4. Parameters evaluated

The efficiency of THFF was evaluated through the analysis of turbidity and color as key parameters of raw water treatment. A HACH turbidimeter, model 2100 Q, was used to measure turbidity. Meanwhile, a HACH brand colorimeter, model DR 900, is used to measure the color. For the collection of samples, three points are identified to evaluate the water quality parameters: the first point P1 at the entrance of the conventional plant, where raw water was collected, the second point P2 at the exit of the experimental decanter; finally, the third point P3 at the outlet of the filtration system (Fig. 2). The turbidity and color values obtained in the previous points were compared with the values of these same parameters but measured in the conventional water treatment plant. For this, three points are also selected in the CPP: the first point (P1), which is common with the experimental system at the entrance of the conventional plant, where the raw water was collected, the second point at the exit of the decanter of the CPP; Finally, the third point on the output of the filters of the CPP.

2.4.5. THFF efficiency based on turbidity and color removal

The effectiveness of each of the experimental tests was evaluated by applying equation (7) [27], which made it possible to calculate the turbidity and color removal efficiency using the THFF + decanter (D) system.

$$\text{Removal}_{\text{THFF+D}} = \frac{\text{Raw water parameter} - \text{settled water parameter}}{\text{Raw water parameter}} x100 \tag{7}$$

The turbidity and color removal efficiency by combining the THFF system + settler (D) + filter (F) was calculated using equation (8) [16].

$$\text{Removal}_{\text{THFF+D+F}} = \frac{\text{Raw water parameter} - \text{Filtered water parameter}}{\text{Raw water parameter}} x\ 100 \tag{8}$$

2.5. Data analysis

The sample distribution of the data addressed in this study is examined by performing normality tests. In order to evaluate the normality of the data, statistical tests were carried out, specifically the Kolmogorov-Smirnov (KS) and Shapiro-Wilk (SW) tests, using a significance level set at 0.05. In the context of these tests, the null hypothesis (H_0) assumes that the distribution is normal, and this hypothesis is rejected if the p value is less than 0.05 [37]. After examining the distribution of the data, we proceeded to analyze the relationship between the variables that affect treatment and efficiency. In this process, an evaluation matrix was used that includes the evaluation coefficients and their significance levels. To develop an equation that enables the evaluation of turbidity removal efficiency, the multiple regression analysis methodology was applied [38].

The Wilcoxon test was used to analyze possible significant differences between the efficiency levels obtained when using THFF with lengths of 50 m and 75 m. This choice of non-parametric analysis was based on the lack of normality in the data, after performing the Shapiro-Wilk normality test, as noted by Freidlin et al. [39]. For this, the null hypothesis was proposed: There are no differences in turbidity removal when using the system with THFF_50 m and the system with THFF_75 m. A significance level (α) of 0.05 was developed for this study. The null hypothesis (Ho) was considered valid unless there was sufficient evidence for its rejection, indicated by a p value < 0.05, which would denote a statistically significant difference [40]. Ultimately, the effectiveness of removing turbidity and color at each length of the THFF implemented in the pilot system was evaluated compared to a conventional plant baffle flocculator. In this case, the null hypothesis was raised: There are no differences in turbidity removal when using the experimental system with THFF and the conventional water treatment plant with a flocculator with baffles. This approach strengthened the evaluation of THFF performance under various operating conditions, allowing comparison with an established benchmark.

2.6. Cost analysis for the implementation of the THFF

The construction of a water treatment plant involves expenses that may vary depending on the specific location of the project and the different components that make up the facility [41]. The construction cost of a conventional baffle flocculator was determined by applying equation (9), according to Deb and Richards [42]. In the case of the THFF, the construction cost was calculated by adding the expenses associated with each of the materials used in its construction.

$$CC = 1553\ (F_M)^{0.45} \tag{9}$$

Being CC, the construction cost in USD and F_M, the maximum daily flow in m^3/d.

Table 1
Theoretical and average detention times of the THFF with 50 m and 75 m length.

THFF length (m)	Flow (L/s)	Theoretical residence time (min)	Real residence time (min)
50	0.25	23.13	28.5
	0.5	11.56	11.5
	0.75	7.71	8.0
	1	5.78	6.15
	2	2.89	2.25
75	0.25	34.69	35
	0.5	17.34	18
	0.75	11.56	13.5
	1	8.67	9.0
	2	4.33	5.25

3. Results and discussions

3.1. Residence time evaluation

The results of the theoretical residence times (to) calculated for the two lengths (50 m and 75 m) and their respective flow rates (0.25, 0.5, 0.75, 1 and 2 L/s) are presented in Table 1.

Residence periods were found to be longer at the 75 m length compared to the 50 m length. According to Smet and van Wijk [43], deflector flocculators typically have a residence time of 10–20 min. Other studies, such as that of Garland et al. [44] indicated that the flocculation time should be between 10 and 30 min. For the case of the length of 50 m and flow rates of 0.25 and 0.50 L/s, residence times were observed in accordance with the literature recommendations for hydraulic flocculators; meanwhile, for the flow rate of 0.75, 1.0 and 2.0 L/s, the time was less than 10 min; therefore, less than what is described in the literature for this type of systems. On the other hand, in the length of 75 m, the residence time met the recommended guidelines for hydraulic flocculators at flow rates of 0.25, 0.5 and 0.75 L/s; meanwhile, for the flow rate of 1.0 and 2.0 L/s, the time was less than 10 min, being less than what is described in the bibliographic recommendations.

For a 50 m length of THFF, the theoretical and actual retention times for all flow rates except 0.25 L/s are similar, indicating that the THFF maintains notable consistency in water retention throughout the process. This uniformity in retention times suggests a constant capacity for treatment in the THFF, regardless of variations in flow rates, which is essential to ensure constant efficiency in turbidity and color removal. For a length of 75 m of the THFF, the actual retention times are slightly longer than the theoretical times for all flow rates, which suggests that the system has an effective water retention capacity during the flocculation process. This small discrepancy could be attributed to factors such as the presence of non-ideal flow paths or small fluctuations in operating conditions, resulting in longer retention compared to theoretical estimates.

In order to know the residence times obtained in various study cases that also analyzed helical tubular flocculators, Table 2 is presented. In the present study, detention times were obtained that varied between 2.89 min to an average time of 35 min for the lengths of 50 and 75 combined with flow rates of 2 L/s and 0.25 L/s respectively. Comparing the times presented in Table 1 with those presented in Table 2, the times obtained in our study for the two lengths are within those obtained by Carissimi [20], Oliveira [19] and Oliveira and Teixeira [15], a exception of flow rates of 1 and 2 L/s. While the values obtained by Cahyana et al. [26] are like those obtained for the two lengths of the THFF and flow rates of 0.75 and 1.0 L/s. These findings reinforce the validity and consistency of the results obtained in this study, largely aligning with previous research and providing a more complete perspective on the effectiveness of THFF lengths under different operating conditions and flow rates.

3.2. Hydraulic performance analysis of helical flow hydraulic tubular flocculator

3.2.1. Analysis of plug flow, mixed flow and dead spaces

Using the tracer distribution curve, the type of flow and other characteristics of the THFF were analyzed. In this case the analysis was carried out with the two distributions of the tracer for the two lengths and five flow rates used in the tests. Table 3 shows that, for the two lengths of the THFF, the range of piston flow percentage (P) is between 86 % and 93.45 %; Meanwhile, the mixture flow (M) was between 6.54 and 13.99 % and the dead zones (m) represented losses of less than 0.48 %. Indicating a predominance of plug flow in the THFF. Considering that the THFF hose has a smooth interior surface with a constant twist a throughout its winding length, it allows that, during its operation, the dead zones (m) can be interpreted insignificantly compared to other types of flow.

This efficient design of the flocculator, with its constant rotation and minimal dead zones, contributes to maintaining a predominant piston flow during its operation, which highlights the effectiveness and optimization of the device in the agglomeration and flocculation of particles suspended in the treated fluid. Analyzing the data in Table 3, it can be seen that there are dead zones in a minimum percentage, these occur in the areas of union and presence of valves that cause a minimum part of the fluid to remain immobile. On the other hand, the helical design of the flocculation system allows the fluid to be maintained with a mixed flow regime; since, as indicated by Oliveira and Teixeira [16] in their modeling, the areas far from the radius of gyration move more irregularly than those that are closer to the radius of gyration. It should also be considered that the plug flow present in the THFF is predominant with respect to the mixed flow, because the material used, polyethylene hose, having a limited number of accessories necessary for its operation allows the fluid flow to be constant during the entire system path. For both the 50 m and 75 m length of the THFF, there is no significant difference in the percentage of plug flow that was determined for each of the flow rates.

3.2.2. Velocity gradient analysis

The results indicate that there is a directly proportional relationship between the hydraulic gradient (G) and the flow, since the

Table 2
Residence times obtained in THFFs used in other studies.

Author	Residence time (min)
Carissimi [20]	10–40
Oliveira [19]	11.25–45
Oliveira and Teixeira [15]	Average of 11.2
Cahyana et al. [26]	7.3–10.2

Table 3
Different flow patterns of THFF obtained with the Wolf Resnick model.

Flow L/s	50 m			75 m		
	%P	%M	m	%P	%M	m
2	89.61	10.38	0.11	93.45	6.54	0.16
1	86	13.99	0.48	88.13	11.86	0.33
0.75	88.75	11.24	0.39	89.40	10.59	0.41
0.50	89.66	10.33	0.39	88.67	11.32	0.38
0.25	88.34	11.14	0.50	92.99	7.00	0.33

gradient increases as the flow is greater, as seen in Table 4. In this table the gradient was calculated using the theoretical residence time called the theoretical gradient (G_o) and was also calculated using the real residence time called the real gradient (G_r). It is observed that G_o does not differ mostly with G_r, especially for flow rates less than 1 L/s. Meanwhile, there is a slight difference between real and theoretical gradient for the flow rate of 2 L/s for both working lengths (50 and 75 m). The gradients have a direct relationship with the flow; Meanwhile, for the same flow rate for both the length of 50 m and 75 m, the gradients are similar, indicating that the variation in the length from 50 m to 75 m does not significantly affect the velocity gradients of the floccular. Therefore, the efficiency of the floc in transporting the fluid appears to remain consistent over these specific distances.

The direct relationship between velocity gradients and flow highlights the importance of properly controlling and adjusting the flow of water through the system. Precise flow management will help maintain optimal velocity gradients for efficient flocculation. This finding supports the stability and robustness of the floccular design, which is crucial in applications where consistency in treated water quality is essential.

Mohammed and Shakir [45] used different coagulants and flocculants than the present case study, but highlighted the importance and efficiency generated with 45 and 55 rpm corresponding to average gradients of 66 s^{-1} for turbidity removal. Their study highlights a range of gradients, where gradient values less than 10 s^{-1} and those greater than 75 s^{-1} were inefficient.

According to the results obtained in the present study, for flow rates of 0.75, 1 and 2 L/s, the gradient was within the effective gradient recommended for hydraulic flocculators by the literature. However, it must be emphasized that despite obtaining gradients lower than those recommended for flow rates of 0.25 and 0.5 L/s, the efficiencies were acceptable, as will be mentioned later.

According to the study carried out by Smet and van Wijk (2002) [43], they suggest that, for a hydraulic flocculator the values of G should typically range between 10 and 100 s^{-1}. On the other hand, Mohammed and Shakir [45] indicate that G should be in the range of 10–75 s^{-1}. When comparing the G values recommended by the literature with those obtained in the present study, it is observed that the G values are met for flow rates of 0.75, 1.0 and 2.0 L/s in both lengths of the THFF. Although for flow rates of 0.5 L/s, the G values are slightly less than 10 s^{-1}.

According to Souza [46] the gradient values obtained in the present study are within an effective range. As can be seen in Fig. 4, for flow rates greater than 0.75 l/s an optimal gradient is shown, in addition to that, the gradients calculated with the times (t) and (t_m) do not have different values from each other for each flow. However, for flow rates of 0.5 L/s, gradients of 9 s^{-1} were obtained' which does not differ greatly from 10 s^{-1}, which is the minimum gradient recommended for baffle flocculators. Being able to only discard the flow rate of 0.25 L/s, because it would not generate optimal performance in both lengths worked.

3.3. Determination of the coagulant dose applied in coagulation

3.3.1. Jug test results

In order to ensure adequate coagulant dosage for different turbidity levels of raw water, the jar test was carried out. The results of this test are represented in Fig. 5. For the flocculation process in the jar tests, a time of 9.0 min was used, based on the results of the tracer tests (see Table 1) for the design flow of 1 L/s and a length of 75 m. Furthermore, the velocity gradient applied in the jar test was 27 s^{-1}, obtained from Table 4, corresponding to the flow rate of 1 L/s and a 75 m length of the THFF.

Using this curve, it was possible to ensure an appropriate dosage of the coagulant (aluminum sulfate) for the different ranges of turbidity of the raw water that entered the conventional Plant. According to the results of the jar test, it will be found that there is no clear linear relationship between the optimal dose of aluminum sulfate applied and the turbidity of the raw water. As the turbidity of the raw water increases, the coagulant dose also increases, but this increase is most significant at turbidities less than 60 NTU. Thus, at turbidities below 60 NTU, the increase in dose follows a direct proportion with turbidity, showing a linear trend. This is explained by

Table 4
Theoretical speed gradient Go and real Gr.

THFF	50 m length		75 m length	
Flow rate (l/s)	Go (s^{-1})	Gr (s^{-1})	Go (s^{-1})	Gr (s^{-1})
2	58.10	67.36	62.64	56.95
1	22.40	20.72	24.16	26.89
0.75	15.10	14.82	16.28	15.07
0.50	8.68	8.71	9.36	9.19
0.25	3.39	3.06	3.66	3.64

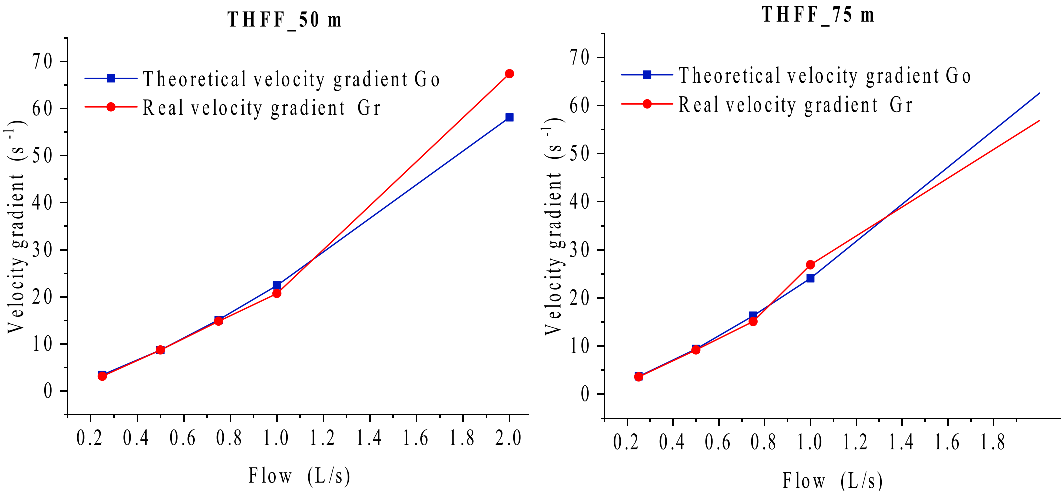

Fig. 4. Velocity gradients calculated with times (t) and (t_m) as a function of the flows and the 50 and 75 m length of the THFF.

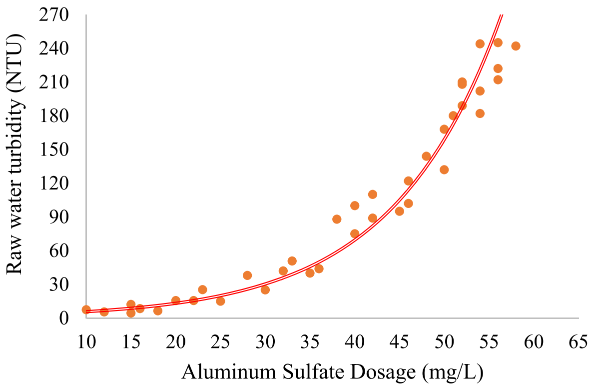

Fig. 5. Aluminum sulfate dosing curve for different raw water turbidities.

Table 5

Turbidity and color removal efficiencies of the THFF + decanter of the experimental system compared to baffle flocculator + decanter of the conventional plant.

Flow (L/s)	Descriptive measures	THFF_50 m + decanter experimental system		THFF_75 m + decanter experimental system		Baffle flocculator + conventional plant decanter	
		Turbidity removal (%)	Color removal (%)	Turbidity Removal (%)	Color removal (%)	Turbidity removal (%)	Color removal (%)
0.25	Average	77.79	79.97	84.04	85.61	86.09	86.87
	Min	7.14	61.39	46.08	58.65	63.22	66.34
	Max	97.24	93.24	96.82	97.57	97.70	98.23
0.5	Average	80.57	77.08	82.25	80.36	89.97	87.29
	Min	45.62	24.39	57.72	17.12	70.38	70.00
	Max	93.63	91.51	89.13	86.19	98.22	97.61
0.75	Average	77.11	71.41	81.40	79.02	89.37	86.62
	Min	69.62	53.45	24.30	48.65	78.38	66.75
	Max	95.95	98.52	91.23	83.03	97.89	95.79
1	Average	82.44	64.23	80.11	73.86	92.92	86.28
	Min	11.63	42.83	44.05	42.06	85.96	67.67
	Max	99.02	98.52	96.74	94.72	99.23	98.92
2	Average	59.83	50.80	78.50	62.09	83.19	74.03
	Min	15.82	31.83	6.78	26.72	51.90	35.65
	Max	96.29	92.67	86.83	89.34	99.44	98.64

the fact that, in the presence of low turbidities, the amount of suspended particles is reduced, which makes the collisions necessary to form the floc difficult, requiring a greater addition of coagulant. On the other hand, at turbidities greater than 60 NTU, an exponential trend is observed. This phenomenon is attributed to the fact that, at higher levels of turbidity, the relationship between coagulant dose and turbidity becomes more pronounced, indicating greater complexity in the coagulation process. These findings reinforce the importance of adjusting coagulant dosage based on specific raw water turbidity characteristics to optimize in-plant treatment effectiveness.

3.4. *Comparative analysis of the effectiveness between the system in the experimental phase and the conventional treatment plant*

3.4.1. *Evaluation of turbidity and color removal in the experimental system (THFF + decanter) compared to the conventional purification plant*

Table 5 presents the statistical values of the turbidity and color removal efficiency; It can be distinguished that the configuration of the experimental system consisting of THFF + decanter has a lower efficiency, compared to the removal of the system consisting of baffle flocculator + decanter from the conventional water treatment plant.

Comparing the average turbidity removal values for the same experimental system made up of THFF_50 m + settler and THFF_75 m + decanter, it can be observed that the average turbidity removal decreases as the flow rate increases. Thus, for the THFF_50 m + decanter system, removal was 67.79 % for a flow rate of 0.25 L/s, then it decreased as the flow rate increased, reaching 50.80 % removal for a flow rate of 2 L/s. Meanwhile, for the THFF_75 m + decanter system, the average turbidity removal was 80.04 % for a flow rate of 0.25 L/s, then it decreased as the flow rate increased, reaching 60.5 % removal for a flow rate of 0.25 L/s 2 L/s. As mentioned above, there is greater turbidity removal for the 75 m length compared to the 50 m length of the THFF. Importantly, despite the decrease in efficiency at higher flow rates, both experimental systems (THFF_50 m + decanter and THFF_75 m + decanter) still achieve significant levels of turbidity removal compared to untreated water. These results suggest that the length of the THFF plays a crucial role in the system's ability to remove turbidity, with THFF_75 m being more effective in this regard than THFF_50 m. Regarding the average color removal, the behavior was like the average turbidity removal, which decreased as the flow rate increased; Likewise, there was greater color removal with the THFF_75 m system compared to the THFF_50 m.

The average turbidity removal values obtained in the decanter of the CPP were in the range of 86.09 and 92.92 %, this efficiency being higher than that obtained in the experimental system. However, it must be noted that the longest retention time tested in the THFF was 9 min for a length of 75 m and a flow rate of 1 L/s, which was the design flow rate. Meanwhile, the residence time of the baffle flocculator in the conventional plant was 21 min, which improves the removal of turbidity and color. In any case, the efficiency values showed that the THFF + decanter with flow rates close to the design is capable of generating the same efficiency as a hydraulic baffle flocculator.

In Fig. 6 the turbidity removal efficiencies for the experimental system comprised of THFF + decanter, as well as the efficiencies of the conventional purification plant composed of the baffle flocculator and the decanter, are represented by box diagrams. By observing the boxes corresponding to each system, the consistency and variability of removal efficiencies can be evaluated, allowing direct comparisons between the THFF + decanter system and the conventional water treatment plant.

In Fig. 7 The color removal efficiencies for the experimental system comprised of THFF + decanter, as well as the efficiencies of the conventional purification plant composed of the baffle flocculator and the decanter, are represented by box diagrams. That is, Figs. 6 and 7 present efficiency values for the removal of turbidity and color at the end of the sedimentation process. At first glance, it can be

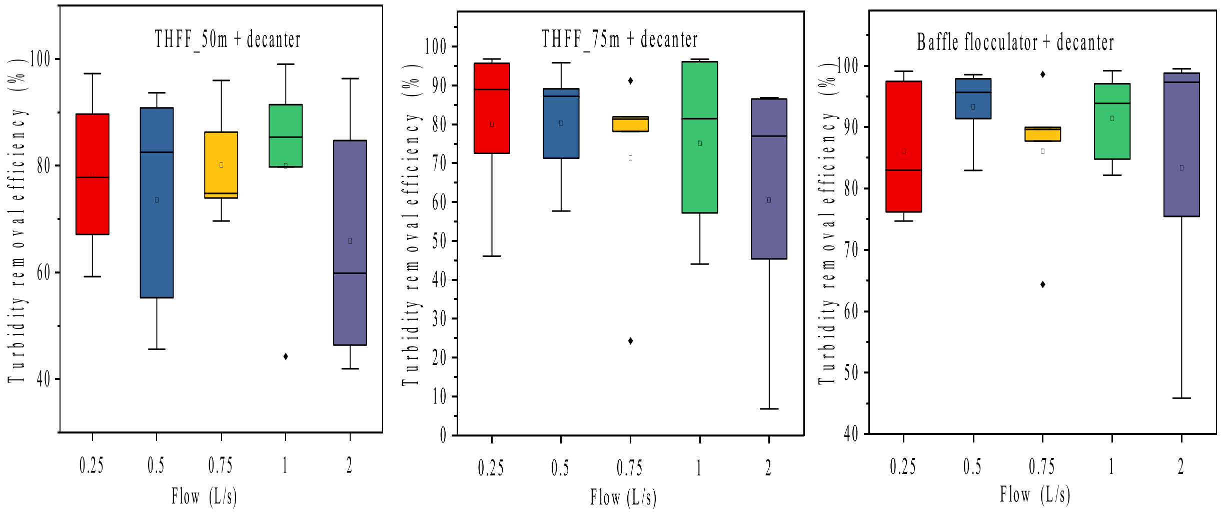

Fig. 6. Turbidity removal efficiency of the experimental systems THFF_50 m + decanter and THFF_75 m + decanter; as well as the baffle flocculator + decanter of the CPP.

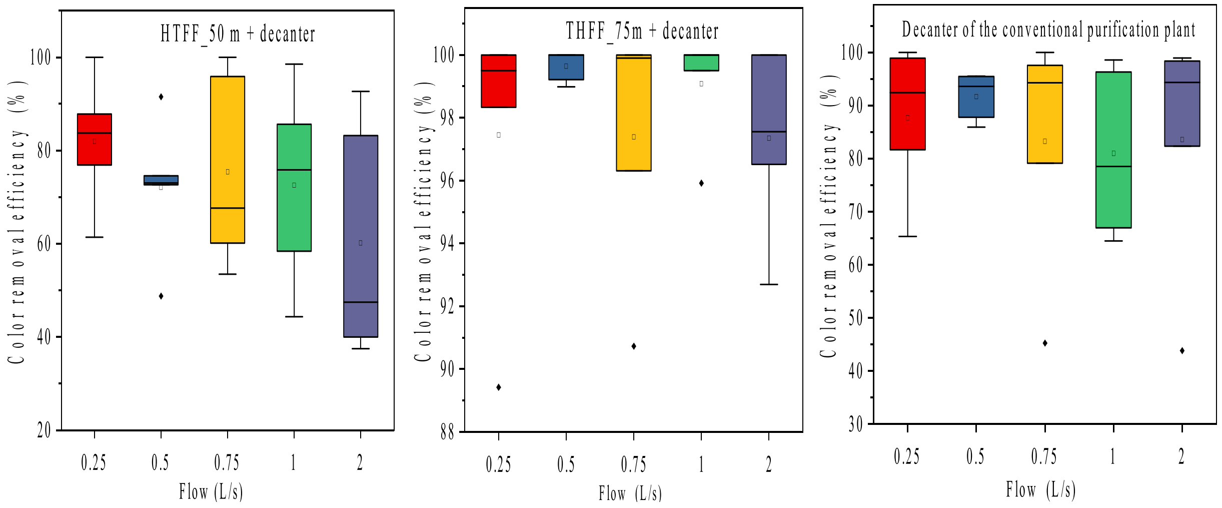

Fig. 7. Color removal efficiency of the experimental systems THFF_50 m + decanter and THFF_75 m + decanter; as well as the deflector flocculator + decanter of the CPP.

seen that the efficiency for flow rates of 2 L/s is lower compared to the other flow rates tested.

The average color removal efficiency percentages for the baffle flocculator + decanter system of the conventional plant is on average 88 %. Meanwhile, the efficiency presented by the THFF + decanter with 50 and 75 m show a very varied efficiency that fluctuates between 75 % and 80 %. Therefore, it is understood that the color and turbidity elimination process in the THFF + decanter system decreases accordingly with increasing flow. On the other hand, for the flow rate of 1 L/s, conditions and removal values similar to those of the conventional purification plant were presented, since it has an average efficiency of 80–82 % compared to 88 %. of the conventional plant. The values of turbidity removal efficiency and final color obtained in the experimental system made up only of the THFF + decanter Most of them present acceptable values considering that there are only two stages of the treatment, which is why better efficiency is expected with the next stage, the filtration stage.

In many of the case studies the color parameter goes unnoticed by the different authors, Nkurunziza et al. [47] in their study emphasize the premise that color removal is achieved simultaneously with turbidity removal efficiency. The removal of turbidity and color presented in the study by Carissimi [20] is influenced by factors such as the size, density, sedimentation times of the flocs in addition to the use of caugalant and flocculant. They have a removal efficiency between 79 and 82 %. It can be interpreted as a directly proportional relationship between measured turbidity and present color in reference to its elimination efficiency. This suggests a directly proportional relationship between the turbidity measurement and the color present in terms of removal efficiency.

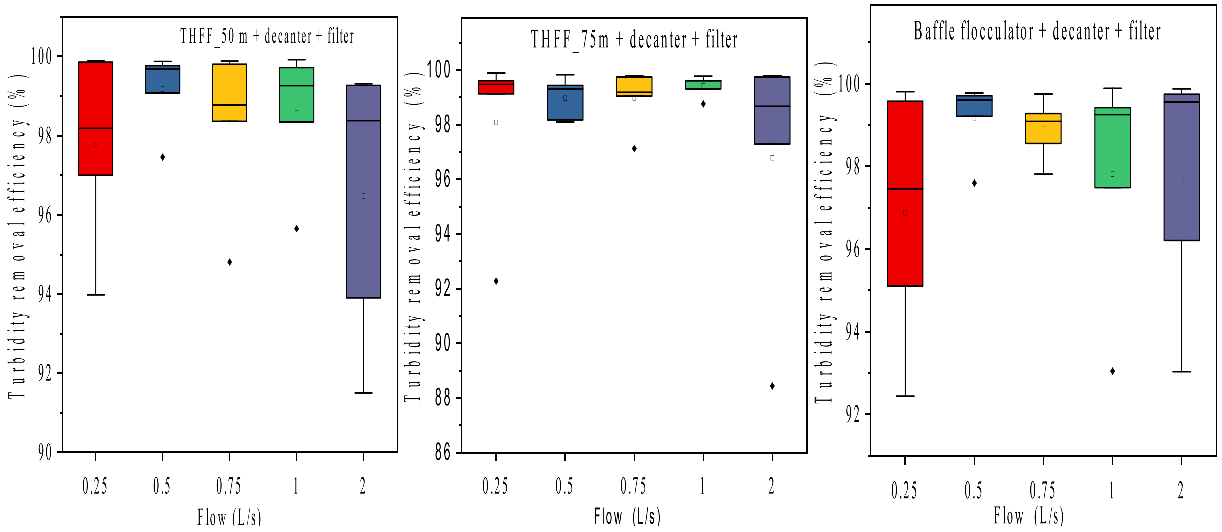

Fig. 8. Turbidity removal efficiency of the experimental systems THFF_50 m + decanter + filter and THFF_75 m + decanter + filter; as well as of baffle flocculator + decanter + filter of the CPP.

3.4.2. Evaluation of turbidity and color removal in the experimental system (THFF + decanter + filter) in comparison with the conventional purification plant

The turbidity removal efficiencies in the experimental system made up of THFF + decanter + filter is similar to the efficiency of the conventional plant made up of baffle flocculator + decanter + filter, as shown in Fig. 8. Turbidity removal reached values close to 100 %; Therefore, at the filter outlet the average turbidity values were 0.36 NTU, which complied with the regulations of 5 NTU for turbidity.

In the THFF_50 m + decanter + filter configuration, the average turbidity removal values were greater than 98 %, achieving a removal of 99.3 % for a flow rate of 1 L/s. Meanwhile, in the THFF_75 m + decanter + filter configuration the average turbidity removal values were greater than 99 %, achieving a removal of 99.6 % for a flow rate of 1 L/s. On the other hand, the system made up of the baffle flocculator + decanter + filter of the conventional plant had average turbidity removals greater than 98 %. As can be seen in Fig. 8, the THFF_75 m + decanter + filter configuration presented values more similar to those obtained in the conventional plant, even for some experimental flow rates the removal was greater than that of the conventional plant. For the experimental flow rate of 2 L/s, the efficiency decreases slightly compared to the other flow rates, however the turbidity obtained was less than 1 NTU, complying with the regulations for human consumption, which confirms the system's ability to meet the quality standards. of drinking water. These findings support the feasibility and efficiency of THFF as part of a purification system, offering promising perspectives for its implementation in real drinking water supply systems.

Fig. 9 indicates the color removal, reaching removals of up to 100 %; therefore, at the output of the filter of the experimental system, the average color values between 0 and 1 UC Pt_Co were obtained, which complied with the regulations that are and 15 UC Pt_Co. For the THFF_50 m + decanter + filter system, only when a flow rate of 2 L/s was used, 100 % color removal was not achieved. In the conventional plant, 100 % color removals were also obtained; There is no difference in the elimination of color in the experimental system compared to the conventional plant.

It is important to consider that a good flocculation pretreatment greatly influences the subsequent filtration process. Oliveira [19] presents average removal efficiency values of 85 %, which are influenced by raw water input quality parameters, hydraulic and geometric parameters of the helical flocculator design and coagulant dosages. Considering the study and its results, it is necessary to carry out more frequent controls in order to avoid data influenced by factors described above.

3.5. Evaluation through statistical analysis

3.5.1. Correlation analysis in the THFF evaluation

The effectiveness of THFFs is crucial in water treatment for the removal of suspended particles; For this reason, an evaluation analysis was carried out to examine the relationship between various variables and the results obtained in the THFF evaluation. This analysis allowed us to identify possible factors that influence the performance of the flocculator and contribute to the optimization of its design and operation.

Table 6 shows the parameters that were correlated, such as operating flow, real residence time, Reynolds number (Re), hydraulic velocity gradient (G), operating flow, raw water turbidity and length of the THFF. experimental. The correlation analysis revealed significant patterns between the variables evaluated. It is necessary to remember that the levels of significance are between the ranges of 1 to −1, values close to these indicate that there is a strong correlation. In this case, a very strong correlation was obtained between

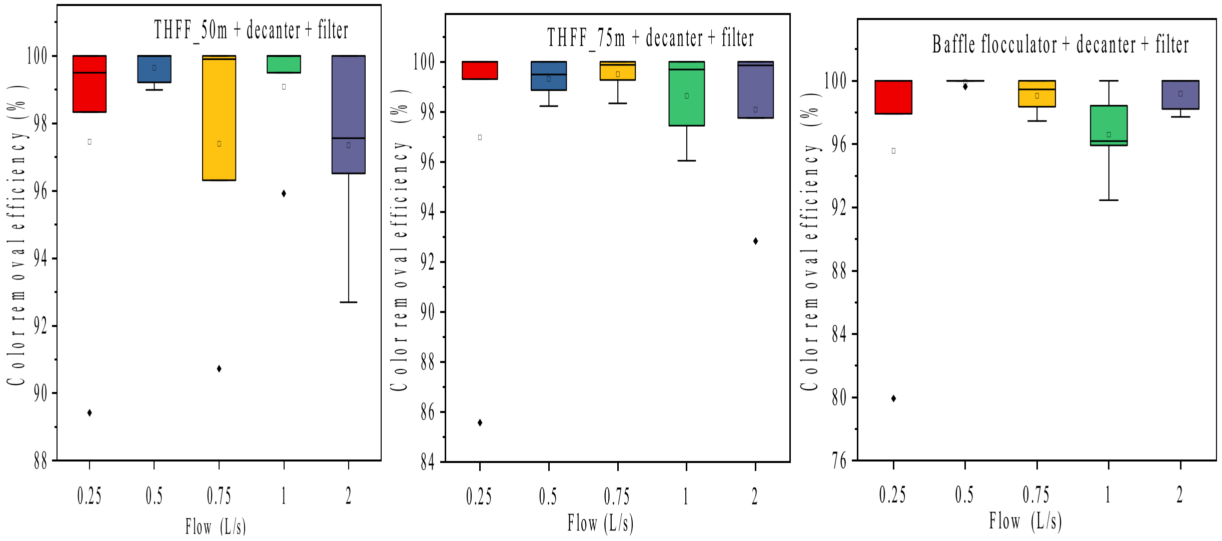

Fig. 9. Color removal efficiency of the experimental systems THFF_50 m + decanter + filter and THFF_75 m + decanter + filter; as well as the deflector flocculator + decanter + filter of the CPP.

Table 6
Correlation matrix of factors in turbidity removal in the THFF.

	Efficiency	Reynolds	Residence time	Gradient	Flow	Turbidity water raw
Efficiency		–	–	–	–	–
Reynolds	−0.224		–	–	–	–
Residence time	0.048	−0.770		–	–	–
Gradient	−0.241	0.985	−0.702		–	–
Flow	−0.244	1	−0.764	0.986		–
Turbidity water raw	0.370	0.077	−0.121	0.065	0.076	
Length	0.095	0	0.216	−0.014	0	0.003

the Reynolds number and the velocity gradient; meanwhile, Reynolds has a strong inverse correlation with the actual residence time. Likewise, the real residence time is linked to the velocity and flow gradient. And finally there is also a correlation between the values of the velocity gradient and the flow rate used. It can be seen that efficiency has a very slight positive relationship with the turbidity of the raw water and a slight negative relationship with the gradient and flow. On the other hand, the factors that are not related are located with very low values or close to zero, such as: the Reynolds number with turbidity and length; In the same way, these last two factors indicated above do not have a direct relationship with the flow rate used in the THFF.

3.5.2. THFF efficiency model using linear regression

Within the framework of research on THFF intended for water supply in developing communities, a turbidity removal efficiency model was found to evaluate the performance of THFF through an empirical mathematical description. Linear regression was used as the main tool to model the relationship between the predictor variables and flocculator efficiency. The linear regression equation obtained from the experimental data was essential to understand the influence of the independent variables on the effectiveness of the flocculator (equation (9)). Analyzing the residual statistics of the regression models using the six variables in Table 6, it was possible to infer that the model that had the best fit was the one that used only the variables water turbidity and velocity gradient; Therefore, only these two parameters were used to obtain the equation. It could well be considered that these two variables cover the processes that influence quality.

The regression coefficients for the final equation provide key information about the relationship between the predictor variables (raw water turbidity and velocity gradient) and the response measured in terms of tubular flocculator efficiency. These coefficients are essential to understand the magnitude and direction of the influence of each variable on the effectiveness of the system. Turbidity, as a determining factor, shows a positive coefficient ($\beta 1 = 0.00882$ in the regression equation, indicating that as turbidity increases, the efficiency of the flocculator also tends to increase. This result suggests a direct stimulation between the presence of particles in suspension and the retention capacity of said particles by the flocculation system. As for the gradient, the associated coefficient ($\beta 2 = -0.0314$ reveals its contribution to the efficiency of the flocculator. The negative coefficient indicates that as the gradient increases, the efficiency of the flocculator tends to decrease. This result suggests that for design optimization and system operation, specific environmental conditions must be taken into account, using the gradient as an adjustable parameter to maximize the efficiency of the helical flow tubular flocculator. The regression equation and its coefficients provide a solid analytical basis for understanding and quantifying the influence of key variables on the effectiveness of tubular helical flow flocculator, paving the way for significant improvements in water supply systems in developing communities.

$$Efficiency = 98.13 + 0.00882 * Turbidity - 0.0314G * gradient \tag{10}$$

3.5.3. Wilcoxon test

After carrying out the Shapiro-Wilk normality test, it was found that the data do not follow a normal distribution, therefore, the Wilcoxon test was applied, applying this test it was determined that there is no significant difference between the turbidity values obtained in the THFF_50 m + decanter and THFF_75 m + decanter system. A p value > 0.05 was obtained; Therefore, the null hypothesis stated above is validated and therefore it was concluded that there is no significant difference in the turbidity removal efficiencies when using the THFF with the two different lengths and followed by a decanter. The values found by the Wilcoxon test are presented in Table 7.

In Table 8 it can be seen that p value is < 0.05 when the turbidity and color removal efficiency is compared between the THFF_50 m + decanter system and the baffle flocculator system + decanter of the conventional purification plant, in the same way when

Table 7
p value to determine the significant difference in the removal of turbidity and color in the THFF + decanter system, as well as in the THFF + decanter + filter system depending on the length of 50 m and 75 m.

Observation 1	Observation 2	Average Difference	Deviation standard	p value	Z
Turbidity removal efficiency of the system THFF_50 m + decanter	Turbidity removal efficiency of the system THFF_75 m + decanter	−0.88	9.86	0.191	1.332
Turbidity removal efficiency of the system THFF _50 m + decanter + filter	Turbidity removal efficiency of the system THFF_75 m + decanter + filter	0.003	1.22	0.399	−0.857

Table 8
p value to determine the significant difference in turbidity and color removal in the THFF + decanter + filter system and THFF + decanter + filter system compared to the conventional plant.

Observation 1	Observation 2	Average Difference	Deviation standard	p value	Z
Removal efficiency THFF_ 50 + decanter	Removal efficiency of the baffle flocculator + decanter of the PPC	0.149	4.043	<0.001	−4.197
Removal efficiency THFF_50+decanter + filter	Removal efficiency of the baffle flocculator + decanter + filter of the PPC	0.125	0.289	0.753	0.329
Removal efficiency THFF_75+ decanter	Removal efficiency of the baffle flocculator + decanter of the PPC	0.225	3.457	<0.001	−4.023
Removal efficiency THFF_75+decanter + filter	Removal efficiency of the baffle flocculator + decanter + filter of the PPC	0.229	0.407	0.399	0.857

comparing the turbidity and color removal efficiency of the THFF_75 m + decanter system with the baffle flocculator + decanter system of the conventional water treatment plant; establishing that there is a significant difference in the efficiency measured in the decanter when a THFF was previously used compared to the efficiency of the decanter that has previously used a hydraulic baffle flocculator.

Meanwhile, it can be seen that p value is > 0.05, when the turbidity and color removal efficiency is compared between the THFF _50 m + decanter + filter system and the baffle flocculator + decant + filter system of the conventional purification plant; as well as, when the removal efficiency of the THFF_75 m + decanter + filter system and the baffle flocculator + decant + filter system of the conventional purification plant are compared; establishing that there is no significant difference in the turbidity measured in the filter when a THFF has previously been used and the turbidity value obtained in the filter when a hydraulic baffle flocculator has been used. To achieve optimal treatment performance, it is preferable to complement the system with a filter rather than relying solely on a decanter, regardless of the type of hydraulic flocculator used. This finding supports the importance of integrating a post-THFF settling and filtration process to improve the quality of the treated water.

3.6. Control test

A first control test was carried out to evaluate the performance of the experimental system without the THFF. In this first scenario, the water coagulated with alumina in the landfill was directed directly to the decanter and then to the filter. The objective was to compare the efficiency to remove turbidity and color between the complete experimental system consisting of THFF + decanter + filter and the system (control test) consisting of only decanter + filter. This allowed determining the relevance of the inclusion of THFF in the purification process; For which, tests were carried out in triplicate using the design flow of the experimetal system (1 L/s), an average turbidity of the raw water of 67.7 NTU and an average color of 658 UC_Pt -Co were used. The results are detailed in Table 8, revealing an average turbidity and color removal of 42.20 % and 40.71 %, respectively. These efficiencies were lower than those obtained with the complete pilot system (Table 5), thus underlining the importance of incorporating the THFF before the decanter and filter.

In a second scenario, the complete experimental system was evaluated, but without the addition of coagulant. In this case, raw water with an average turbidity of 60.1 NTU was used and was introduced directly into the THFF + decanter + filter system, without adding alumina. The purpose of this second control test was to analyze the importance of coagulation in this type of system. In this second case, a turbidity and color removal efficiency were obtained at the output of the THFF_50 m + decanter + filter system of 20.17 % and 18.44 %, respectively. While in the THFF_75 m + decanter + filter system, the efficiency was 25.51 % and 22.24 % for turbidity and color, respectively (Table 9). According to the aforementioned results, the turbidity and color removal efficiencies were notably lower compared to the results obtained in the tests that used a coagulant (Table 5), underlining the importance of using a coagulant in the purification process.

3.7. THFF implementation costs

The most notable expenses during the implementation of the THFF were mainly associated with the acquisition of the 4-inch high-density polyethylene hose and the corresponding valves. Table 10 details the total quantities and costs required for the successful installation of a THFF. It is important to note that the hose coils have a length of 25 m each, so 2 coils were used to achieve a length of 50 m and three coils were needed to obtain a total length of 75 m. In addition, the acquisition of valves and other essential accessories was considered to guarantee its optimal operation.

Table 9
Results of experimental tests without THFF and without coagulant.

Pilot system	Turbidity removal (%)	Color removal (%)
Sedimentator + filter	42.20	40.71
THFF_50 m + decanter + filter (without coagulant)	20.17	18.44
THFF_75 m + decanter + filter (Without coagulant)	25.51	22.24

Table 10
Expenses associated with materials used for construction from THFF.

Nº	Item	Price by unit (USD)	Units	Cost (USD)
1	Polyethylene hose	212.59	3	637.77
2	PVC elbow of 4 inch	16	3	48.00
3	PVC Tee	51	1	51.00
4	Wafer valve 110	128.5	1	128.50
5	PVC ball valve	52	2	104.00
6	Structure metal support	295	1	295.00
7	PVC pipe	29.60	2	59.20
	Total			1323.47

The costs related to the materials used in the construction of the THFF represent an essential part of the investment in this project. The quality and suitability of these materials were fundamental to ensure the efficiency and durability of the structure, making them key factors for the effective performance of the THFF in terms of water management and its environmental impact. In this way, not only the functionality of the THFF is guaranteed, but also the long-term sustainability and effectiveness of this water management infrastructure. According to Table 10, the construction cost of the THFF for a flow rate of 1 L/s implemented in this study was $1323.47.

Equation (9) described above was used to calculate the costs of the implementation of the conventional baffle flocculator, the values detailed in Table 11 were obtained, the cost calculation was carried out for each of the five flow rates used in the present study. It can be seen that the cost of implementing the THFF was lower than the potential costs of implementing the conventional baffle flocculator presented in Table 11. This finding highlights the economic viability of the THFF compared to conventional alternatives, consolidating its position as an option. cost-efficient for water treatment.

3.8. Comparison with previous studies

When comparing certain characteristics of the THFF, such as length, diameter, velocity gradient, treated flow, residence time, turbidity and efficiency, with other previous investigations that also used tubular flocculators, it was observed that the dimensions of the pipe used for The THFF construct in the present study were considerably larger in length and diameter compared to studies by Cahyana et al. [26], Oliveira and Teixeira [16], and Kurbiel et al. [48]. Table 12 shows that the length of the THFF used in the study by Cahyana et al. [26] was 50 m, Kurbiel et al. [48] use a length of 20 m. Meanwhile, Oliveira and Teixeira [16] used lengths of 15.16 and 36.84 m, the lengths of the aforementioned studies were less than the length of 75 m used in the present study; even the length of 50 m used in the present study was longer than the lengths used by Kurbiel et al. [48] and Oliveira and Teixeira [16]. In relation to the pipe diameters used for the construction of the THFF, Cahyana et al. [26] and Oliveira and Teixeira [16] used diameters between 12.7 - 1587 mm and 9.6–16 mm respectively, which were considerably smaller compared to the diameters used by Kurbiel et al. [48] and the present study which were 714–86.4 mm and 110 mm respectively.

Regarding the treated flows, the results in Table 12 indicate that the THFF of the present study demonstrated a capacity to treat flows of 3.6 m^3/h; meanwhile, Cahyana et al. [26] and Oliveira and Teixeira [16] experimented with flow rates of 0.018 and 0.12 m^3/h, respectively. On the other hand, the flow rates used in the study by Kurbiel [48] were similar to the flow rates of the present study, standing at 3.5 and 4 m^3/h. When analyzing the velocity gradients in Table 11, it is highlighted that the values applied in the present study were within the recommended range for hydraulic flocculators (10–100 s^{-1}), being similar to those of Cahyana et al. [26] and Kurbiel [48], but significantly lower than those applied by Oliveira and Teixeira [16], who used gradients that varied between 160 and 295 s^{-1}.

Regarding the residence times, it is evident that the values used in the present study were substantially higher compared to the times applied by Cahyana et al. [26] and Oliveira and Teixeira [16]. However, the residence times of these studies were lower than those applied by Cahyana [26], which were in the recommended range for hydraulic baffle flocculators. In terms of efficiency, the results indicate in this study that efficiencies greater than 98 % were achieved, measured at the outlet of the system made up of the THFF + decanter + filter. These efficiencies are comparable and even higher than those obtained in previous studies, such as the one carried out by Cahyana [26] with efficiencies of 93.6 %, and Oliveira and Teixeira [16] with an efficiency of 86.2 %. These findings highlight the high efficiency of tubular flocculators for turbidity removal in water treatment systems. Table 12 provides a detailed overview of the characteristics and efficiencies of the THFFs used in the different studies, highlighting the key differences between them.

The growing need for water treatment systems adapted to rural areas and small communities has led to the need to conduct field research on tubular hydraulic flocculators. In the present study, the THFF used exhibited outstanding clarification efficiency and a reduced residence time compared to other flocculators with baffles that are commonly used in drinking water supply facilities. The design of the experimental system consisted of a compact clarification system composed of a THFF, a decanter and rapid sand filters. With a design flow of 86,400 L per day, this experimental system has the capacity to provide drinking water for an approximate population of 576 inhabitants, considering an estimated demand of 150 L per inhabitant per day. These findings highlight the effectiveness and feasibility of THFF in size- and demand-constrained environments, showing its potential to address specific water supply needs in rural areas and small communities.

In contrast to mechanical flocculators, which maintain a constant speed while the residence time varies with changes in flow rate, the THFF shows notable flexibility in the face of variations in operating conditions. This property becomes a significant advantage in

Table 11
Cost of a hydraulic baffle flocculator.

Flow rate (L/s)	Cost (USD)
0.25	6189.24
0.50	8454.95
0.75	10147.44
1	11550.54
2	15777.97

Table 12
Characteristics and performance of the THFFs used in previous research and in the present study.

Author	Length flocculator (m)	Pipe diameter (mm)	Velocity gradient (s^{-1})	Flow rate (m^3/h)	Residence time (s)	Turbidity initial (NTU)	Efficiency (%)
Cahyana [26]	50	12.7	32.4	0.018	985	159	91.3
Cahyana [26]	50	15.87	24.7	0.018	1335	155	93.6
(Kurbiel et al. [48]	20	71.4	52.7	3.5	82.3		68.8
(Kurbiel et al. [48]	20	86.4	33.2	4	105		54.3
Oliveira and Teixeira [16]	15.16	16	160	0.12	56.25	50	82.3
Oliveira and Teixeira [16]	36.84	9.60	295	0.06	22.5	50	86.2
Present study	50	110	20.72	3.6	369	218	82.44[a] 98.58[b]
Present study	75	110	26.88	3.6	540	240	80.11[a] 99.41[b]

[a] Measured at the outlet of the decanter.
[b] Measured at the filter outlet.

the planning of facilities that incorporate a THFF in the purification process, especially when an appropriate range of velocity gradients is selected. Cleaning and maintenance of tubular flocculators is simple, since clean water fed in countercurrent allows material accumulated on the walls of the pipe to be released. In the context of this study, the THFF proved to be simple in construction and operation, showing high efficiency when integrated with a high-rate decanter and a fast filter. The residence times, both theoretical and real, were consistent, without presenting dead spaces or short circuits. The reliability and economy of operation of the THFF are notable, as it does not require electrical power for its operation. Additionally, it is presented as a compact installation, making it especially appropriate for rural communities with limited resources and low flow treatment needs. At THFF it is presented as an efficient, reliable and economically viable solution in contexts where operational simplicity and effectiveness in the treatment of water for human consumption are valued, which directly contributes to the achievement of the sixth goal of Sustainable Development, by facilitating access. to drinking water in small communities.

The results obtained in this research suggest the continuity of additional studies, such as the exploration of tubular flocculation applying a decreasing velocity gradient through the use of two or more pipe diameters. The possibility of implementing a THFF with a smaller pipe diameter at the beginning and a larger diameter at the end of flocculation is proposed, which would allow generating a greater velocity gradient at the beginning of the flocculator and a smaller one at the end. This modification could improve floc formation, emulating the behavior observed in baffle flocculators, as documented by Mcconnachie and Liu [49] and Haarhoff and Van Der Walt [50]. In addition, it is proposed to explore adjustments in the passage humerus, that is, to test a different number of tubes. The possibility of testing other inorganic coagulants other than aluminum sulfate is also proposed, as well as experimenting with natural coagulants. Likewise, it is suggested to evaluate lengths greater than those used in this study, in order to examine how these changes, affect the efficiency and capacity of the system.

The impact of variations in the speed and angle of the helical flow on the flocculation process still needs to be investigated, considering the accumulation of sediments in the lower gyres. Likewise, the adaptability of the tubular flocculator to different climatic and seasonal conditions must still be investigated, considering changes in the temperature and quality of the raw water. The possibility of combining different pipe materials to improve durability and efficiency is also an area to investigate. It is necessary to carry out a qualitative study on community acceptance and adoption of technology, considering cultural and social factors, promoting community participation and appropriation of the project. These additional research approaches would improve the understanding of the variables that affect the performance of the tubular flocculation system, providing valuable information to optimize its design and applicability in various conditions. This continuous research effort would contribute to the evolution and improvement of accessible technologies for water treatment in communities with limited resources.

4. Conclusions

A large-scale experimental approach allowed THFF to be built using a polyethylene hose and coupled to a sedimentation and filtration process. The results obtained from the experimental tests offer valuable conclusions about the effectiveness and feasibility of this technology in comparison with conventional purification methods. The findings show that THFF achieved outstanding efficiency in removing turbidity and color, with average percentages of 98.07 % and 98.50 %, respectively. It was observed that the flocculator with a 75 m length showed greater efficiency in removing turbidity and color compared to the 50 m length. Despite a decrease in efficiency at higher flow rates, both lengths achieved significant levels of turbidity removal. Longer residence times, such as those observed with the 75 m THFF, tend to improve efficiency compared to the shorter times of the 50 m THFF. This suggests that a longer residence time may contribute to better water purification in the flocculation process. These results indicate that THFF can provide high-quality treated water for consumption, which is essential in rural settings where access to drinking water is often limited. Optimizing coagulant dosage using jar tests; as well as the variation of the length of the THFF, turbidity levels and raw water flow rates in experimental tests demonstrate the flexibility and adaptability of the system to different conditions. Furthermore, hydraulic analysis using the Wolf-Resnick model revealed significant variations in the residence time and velocity gradient, highlighting the direct influence of these parameters on the operation and effectiveness of the THFF. Raw water turbidity, residence time and velocity gradient were observed to be key factors affecting the effectiveness of THFF. Comparison of the efficiency of THFF with conventional water treatment plant shows that THFF, complemented by settling and filtration processes, can be a valuable tool to improve water quality in rural areas. The existence of a plug-type flow in THFF suggests its ability to play a crucial role as a flocculation unit in water treatment systems. These findings open the door to future successful implementations of this technology, thus contributing to improving water quality and sustainability in rural communities.

CRediT authorship contribution statement

Fernando Garcia-Avila: Conceptualization, Investigation, Methodology, Writing – original draft. **Jaime Cadme-Tandazo:** Data curation, Formal analysis. **Alex Aviles-Anazco:** Resources, Supervision, Validation. **Lorgio Valdiviezo-Gonzales:** Software, Validation, Writing – review & editing. **Rita Cabello-Torres:** Funding acquisition, Software, Visualization. **Manuel Cadme-Galabay:** Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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