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Research article

Vertical tubular flocculator: Alternative technology for the improvement of drinking water treatment processes in rural areas

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ABSTRACT

The guarantee of access to safe drinking water for rural communities is a great challenge due to the increase in contamination and deterioration of water sources. Rural areas face technological, financial, and operational limitations, having poor water quality, generally. The purpose of this study was to evaluate the efficiency of a vertical tubular flocculator (VTF) to be used as part of the purification process in rural areas where small flows are used. An experimental treatment system (ETS) implemented in the field was used. The VTF was implemented using PVC pipes and fittings. Tests were carried out with the same raw water used from a conventional treatment plant with aluminum sulfate as a coagulant. The optimal coagulant dose applied in the ETS was determined by the jar test. In the VTF, the length, turbidity, and flow of the raw water were varied. The hydraulic behaviour of the VTF was evaluated with the analysis of the time distribution curve of concentration of a tracer applying the Wolf-Resnick model. A low residence time VTF was obtained, representing a new efficient flocculation model for the reduction of turbidity and colour. The results showed that the turbidity of the raw water, the residence time, and the degree of agitation are important parameters in the operation and efficiency of a VTF. There was a predominance of plug flow in the reactor. The obtained results were compared with the efficiency of a conventional water treatment plant used in the study site. The results obtained indicated that this ETS that integrates a VTF with settling and filtration can be a useful tool for rural areas. It was recommended to replicate this study with wastewater, other dimensions of the VTF, to establish a specific methodology for the design of the VTF, to evaluate the dosage with dose bombs for improving the results of VTF, and to elaborate a hydraulic model for VTF.

1. Introduction

Urban areas have received drinking water supplied by municipal firms that have conventional purification plants commonly and only some plants with advanced treatments, due to the availability of economic resources, ensuring good drinking water quality (Wu et al., 2019; Valdiviezo et al., 2021). However, in rural areas, the supply of drinking water has several limitations such as: inadequate technology, financial limitations, and deficient operation (Omarova et al., 2019). In rural areas, slow filters are used to treat drinking water commonly (Andreoli and Sabogal-Paz, 2020; Souza et al., 2021); however, the high values of surface water turbidity originated by anthropogenic and climatological factors cause great pressure on the filters, reducing their efficiency (Iqbal et al., 2018; Fujioka et al., 2019).

Conventional purification plants made up of coagulation, flocculation, sedimentation, filtration, and disinfection processes permit to treat very turbid water (Soros et al., 2019). Currently, the implementation of conventional treatment plants in developing communities is difficult due to construction costs, despite the small flows that are necessary to meet the demand of rural populations (Marobhe and Sabai, 2021; García-Ávila et al., 2021). Therefore, research about new efficient and low-cost technologies for treating water in rural areas is necessary (Zinn

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et al., 2018).

Flocculation is one of the most important processes of purification (Sartori et al., 2014), because it allows the agglutination of destabilized colloidal substances in coagulation, thus facilitating their decantation and subsequent filtering. The conventional hydraulic flocculator with baffles accumulates sediment in the corners of the compartments, which reduces the flocculation performance (Cahyana et al., 2021). Mechanical flocculators need an external power source, such as a mechanical stirrer for performing the slow mixing process (Ghawi, 2018). Both hydraulic flocculators with baffles and mechanical flocculators require a high investment for their operation and maintenance, so the implementation of tubular flocculators is an efficient alternative for rural areas (Bratby, 2006).

The tubular flocculators allow the reduction of the residence time and the minimization of load losses, improving the quality of the treated water; in addition, tubular flocculators take up little space and reduce the cost of water production, generating greater social and economic effects (Oliveira and Teixeira, 2017a). Helically wound tube flocculators are considered tubular flocculation units with a low residence time (Vaezi et al., 2011; Sartori et al., 2014; Oliveira and Teixeira, 2017b). The retention times verified in spiral wound tube flocculators are considerably lower than the retention times observed in conventional flocculators such as baffled flocculators (Oliveira and Teixeira, 2017a). Helically wound tubular flocculators have been studied; however, multipass tubular flocculators made up of sections of vertical flow straight pipe had not been evaluated yet, so in this study a vertical tubular flocculator (VTF) was evaluated as an alternative technology for improving treatment processes of drinking water in rural areas.

Tse et al. (2011) used straight and spiral tube flocculators and compared the performance of different flocculation conditions as a function of two properties: settling velocity and post-settling residual turbidity of the flocculated suspensions. Kurbiel et al. (1989) used experimental pilot tubular flocculators with a flow rate of 3–6 $m^3 h^{-1}$ for the treatment of electroplating wastewater, with a 20 m long pipe, but with different diameters and retention times of 12 min, which were built with transparent PVC tubes, which allowed a better follow-up of the experiment. The results reached yields between 90% and 99% in the removal of turbidity and between 88% and 98% in the removal of suspended solids, confirming the high efficiency of the tubular flocculators in the treatment of galvanic wastewater.

The majority of the studies about tubular flocculators has been carried out at the laboratory level for wastewater treatment (Tse et al., 2011; Sartori et al., 2014; Swetland et al., 2014; Oliveira & Teixeira, 2017a, 2019). There is a lack of knowledge about the application of tubular flocculators for drinking water treatment, so the main purpose of this study was to evaluate the main operating parameters and the hydraulic performance of the VTF.

The main operating parameters of the flocculation process are the velocity gradient (G) and the residence time [T] (Oliveira and Teixeira, 2017b; Sun et al., 2019). The optimal values of these parameters are those that together will produce the greatest efficiency (Mcconnachie and Liu, 2000; Cahyana et al., 2021). Through research carried out, it has been determined that the optimal range of velocity gradients for hydraulic deflector flocculators varies between 20 and 75 s^{-1} and that the range of retention times varies between 10 and 30 min, depending on the quality of the water (Haarhoff & Van Der Walt, 2001; Ghawi, 2018). Therefore, the velocity gradient and residence time were analyzed using this type of tubular flocculators in this study, which in turn is related to the efficiency of turbidity and colour removal in purification.

The results of this evaluation allowed to establish that the VTF can be used as an alternative technology to make water drinkable in rural areas. These VTFs built with PVC pipe could be an alternative to replace flocculators with vertical flow deflectors (FVFD), reducing investment costs and physical space and being more affordable for developing communities.

2. Methodology

2.1. Study area

This study was applied in a purification plant located in a rural area of the city of Azogues, Ecuador (Bayas Drinking Water Treatment Plant [BDWTP]), which was administered by the community. The BDWTP is of the conventional type made up of coagulation, flocculation, sedimentation, rapid filtration, and disinfection (García-Avila et al., 2020). It has a design flow of 20 L/s, supplying drinking water to approximately 6000 people.

The BDWTP has a flocculator with horizontal flow deflectors and a flocculator with vertical flow deflectors. The design flow rate for each flocculator is 10 L/s. The BDWTP has 2 high-rate clarifiers and 4 rapid sand filters and a chlorination chamber. The experimental treatment system (ETS) used for this study consisted of a VTF, a settler, and 4 filters, next to the flocculator with vertical flow deflector (FVFD) of the BDWTP, which was carried out to use the same raw water that entered the BDWTP, for comparing the results of turbidity and colour removal of the ETS with the BDWTP removal.

2.2. Implementation of the experimental treatment system

For the coagulation process, a cone-shaped vortex mixer was implemented, into which raw water entered tangentially in the cylindrical part, which generated its rotation around the longitudinal axis of the cone, forming a downward movement towards the lower vertex (Tong, 2012). For the design of the mixing cone, the methodology recommended by Abdulkareem et al. (2014) and Tong (2017) was used.

Considering that there is no defined methodology for the design of tubular flocculators, then the recommended methodology of the design of the FVFD was used for establishing the dimensions of the VTF. Specifically, the design criteria recommended by Haarhoff (1998), Romero (1999), and Crittenden et al. (2012) were used. The main criteria that were taken into account for the design of the VTF were the residence time (between 10 and 60 min) and velocity gradient (between 20 s^{-1} and 70 s^{-1}), recommended for the FVFD (Arboleda, 2000; Crittenden et al., 2012). Likewise, a water velocity between 0.1 m/s and 0.3 m/s was considered (Romero, 1999; Ghawi, 2018).

For the design of the VTF, a design flow rate of 1 L/s, a residence time of 12.5 min, and a velocity of 0.13 m/s were chosen, complying with what was recommended for the design of the FVFD. Applying the methodology of Abdulkareem et al. (2014) and Tong (2017), it was possible to obtain the length of the water path and the area of the flocculator channel with baffles. This obtained length was used for calculating the number of PVC pipes necessary to form the VTF. The run length was divided by 6 for finding the number of PVC pipes, considering that a commercial PVC pipe is 6 m long. Meanwhile, the channel width calculated for a FVFD was approximated to the area of a commercial PVC pipe; in this way, the diameter of the PVC pipe could be determined. The VTF was built with sections of straight pipe arranged vertically. Each section was made up of 3 m tubes (half a tube), in order to control the flocculation process efficiently. A 180° elbow was implemented in the upper part of each tube and a 3 m straight return tube was added to this elbow. This process was repeated until the calculated number of tubes were used. A valve was placed at the bottom of each tube for flocculator cleaning and maintenance. Fig. 1a shows a schema of the VTF.

For the design of the high-rate decanter unit, the methodology recommended by Romero (1999) and Arboleda (2000) was used, who recommended a rate or surface load of 120 $m^3/m^2/d$. The decanter was equipped with honeycomb decantation modules made of acrylonitrile butadiene styrene (ABS). These modules contain cells inclined at 60°, with a cell gap of 7 cm, so that the water rose through the cells with laminar flow. For its design, a flow rate of 1 L/s and a rate of 144 m^3/m^2d were considered. The dimensioning allowed to obtain a clarifier

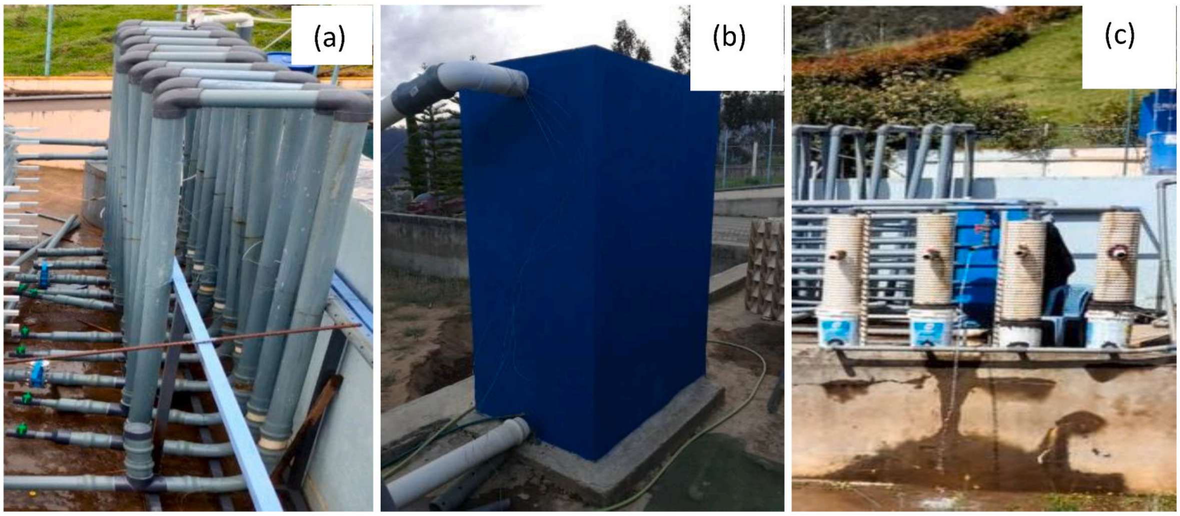

Fig. 1. Experimental system: (a) pilot VTF, (b) decanter, and (c) filter.

with a width, length, and depth of 0.6 m, 1.00 m, and 2.00 m, respectively; additionally, a Reynolds number of 50 was calculated. Fig. 1b shows the high-rate clarifier, which was built of concrete with the collaboration of the BDWTP.

For the removal of the particles that were not removed in the previous processes, granular filtration made up of porous media (gravel and sand) was used. The main criterion for the design of the filtration system was the filtration speed, and due to that a value of 120 $m^3/m^2/d$ was adopted for obtaining a fast filtration. Filters were implemented using PVC pipes of 30 cm diameter. For the sizing of the filtration system, the methodology recommended by Arboleda (2000) and Romero (1999) was used. A sand height of 60 cm, an effective sand size of 0.55 mm, a uniformity coefficient of 1.60, and a porosity of 0.42 were determined. With the collaboration of the BDWTP, it was possible to implement 4 rapid filters using PVC pipes with a diameter of 30 cm and a height of 1.80 m. Each filter treated a flow rate of 0.098 L/s, treating a total flow rate of 0.39 L/s. As tests were carried out with flows of 0.25, 0.5, 0.75, 1.0, and 2.0 L/s, the difference in flow of the settled water was sent to the BDWTP filters. Fig. 1c shows the experimental filtration system.

2.3. *Studies of hydrodynamic flow in vertical tubular flocculation*

2.3.1. *Theoretical residence time*

The theoretical residence time is the period of time that theoretically must elapse for water to pass through a reactor, assuming that all the water moves at a uniform rate. Mathematically, it is equal to the volume of the reactor divided by the flow rate (equation (1)). The volume of the VTF was determined from the length (L) and the radius (r) of the pipe ($V = \pi r^2 L$).

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

The t_o was calculated for all experimental flow rates (0.25, 0.5, 0.75, 1.0, and 2.0 L/s).

2.3.2. *Real residence time*

The real residence time is the time in which the water remains subjected to a treatment process in a given unit. It is not always equal to the theoretical residence time. The tracer technique was used for its determination, for which an instantaneous dose of a NaCl saline solution was applied. This tracer was added to the input of the VTF; meanwhile, the concentration of total dissolved solids (TDS) was measured at the outlet of the VTF, prior to enter into the decanter. For the measurement of TDS, water samples were collected every minute once the tracer was added to the VTF inlet, and the samples were taken every 30 s when a drastic change in the TDS was detected. A digital TDS meter was used for measuring its concentration. Diverse graphs of time vs. concentration were obtained with the measured data of TDS and time. The real residence time (t_r) was determined with the methodology presented by Mastrocicco et al. (2011).

2.3.3. *Flow analysis*

The mathematical model developed by Wolf and Resnick was used for evaluating the hydraulic characteristics of the VTF, which allowed to know the type of flow in the reactor. The piston flow was analyzed, in which all the water particles that enter into the unit remain in it for the same time (Rodríguez et al., 2012).

The particles are discharged in the same sequence in which they were introduced in the plug flow and there is not mixing between the water that enters and the water that is in the VTF. On the other hand, the mixed flow appears when the water that enters the VTF is immediately dispersed within it (Wolf and Resnick, 1963). The concentration of a substance at the outlet of the unit is equal to that existing in the entire reactor in the mixed flow. Likewise, the presence of dead spaces was evaluated, which are those spaces where the fluid remains static. Finally, the existence of short circuits was analyzed, which can happen when part of the volume of the water that enters crosses the VTF so quickly that it leaves instantly, without remaining stored in the reactor (Pérez, 2005). A higher percentage of plug flow increases the efficiency of the tube flocculator system.

The Wolf-Resnick method allowed to quantify the percentage of plug flow (P), the complete mixture (M), and the dead zones (m), which occur in the normal operation of the reactor from parameters such as θ and Tan α (Rodríguez et al., 2012). These percentages were obtained by plotting the subtraction of the unit minus the cumulative function (1-F(t)) on a logarithmic scale against time (t/t_o). Calling F(t) to the volume fraction that leaves the reactor before the theoretical residence time, F(t) is represented by equation (2) (Pérez, 2005).

$$F(t) = 1 - e^{-\frac{1}{(1-p)*(1-m)}\left(\frac{t}{t_o} - p\ (1-m)\right)} \tag{2}$$

equation (3) was obtained rearranging terms and taking the logarithms in both terms.

$$\mathrm{l}[1 - \mathrm{F(t)}] = \frac{-\log(\mathrm{e})}{(1-\mathrm{p})(1-\mathrm{m})}\left[\frac{t}{t_o}p(1-m)\right] \tag{3}$$

A tangent is drawn to the resulting curve of (1-F(t)) in logarithmic scale against normalized time (Fig. 2) for obtaining parameters that are

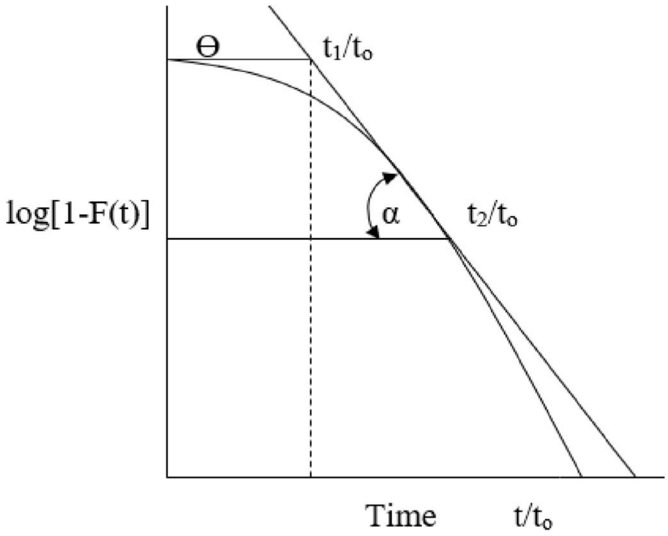

Fig. 2. Curve of the Wolf-Resnick method (Pérez, 2005).

used in the equations to determine the percentages of each flux. The equations used to calculate the percentages were the following:

$$p = \frac{\theta \text{ tag } \alpha}{0.435 + \theta \text{ tag } \alpha} \tag{4}$$

$$\mathrm{M} = (1 - \mathrm{p})(1 - \mathrm{m}) \tag{5}$$

$$m = 1 - \frac{\Theta}{p} \tag{6}$$

$$\text{tag } \alpha = \frac{1}{\frac{t_2}{t_o} + \frac{t_1}{t_o}} \tag{7}$$

$$\Theta = \frac{t_1}{t_o} \tag{8}$$

The values of the unknowns θ and tan α were obtained from the curve in Fig. 2, where t_1 is the first time in which it crosses the line; t_2 is the second time where it cuts the line; t_0 is the initial time where the tracer is detected and α is the inclination angle of the line. Fig. 2 represents the expected curve in the Wolf-Resnick analysis, where the drawn line is tangential to the tracer curve; however, this line may be the curve with the best fit to the curve (Rodríguez et al., 2012; Pérez, 2005).

2.3.4. Velocity gradient

The procedure for determining the intensity of the flocculation or velocity gradient (G) depends on the type of unit. For this tubular hydraulic flocculator, G was calculated using equation (9).

$$G = \sqrt{\frac{\rho * g * h_f}{\mu * t}} \tag{9}$$

where G: mean velocity gradient (s^{-1}); h_f: head loss (m); ρ: water density (Kg/m^3); g: gravity (m/s2); μ: Dynamic viscosity of water (Kg/m/s), t: residence time (s).

The density and dynamic viscosity were determined considering the average temperature of the water measured during the experimental tests. Meanwhile, the Darcy-Weisbach equation (equation (10)) was used to calculate head losses through pipes (Meng et al., 2019). H_f was determined for two different lengths, with the purpose of evaluating the influence of the length on the efficiency of the VTF.

$$h_f = f * \frac{L}{D} * \frac{v^2}{2g} \tag{10}$$

Being f: friction factor (dimensionless); L: pipe length (m); D: Pipe diameter (m); and v: average speed (m/s). For the calculation of the friction factor (f), equation (11) was used (Zeghadnia et al., 2019). A relative roughness of the PVC pipe wall (ϵ) of 3.0 × 10-7 m was considered (Sob, 2021).

$$f = \frac{1}{\left(-2\log\left\{ \frac{\varepsilon}{3.7065D} - \frac{5.0452}{Re}\log\left[\frac{1}{2.8257}\left(\frac{\varepsilon}{D}\right)^{1.1098} + \frac{5.8506}{Re^{0.8981}} \right] \right\} \right)^2} \tag{11}$$

where ε: pipe roughness (m); Re: Reynolds number, which was calculated using equation (12).

$$Re = \frac{\rho * D * v}{\mu} \tag{12}$$

The load loss due to accessories used in the implementation of the VTF was also considered for calculating the total load loss.

2.4. Experimental method and evaluation of the efficiency of the vertical tubular flocculator

2.4.1. Configuration of the experimental tests

For the analysis of the efficiency of the pilot system, a total of 100 experimental trials were carried out between January and December, including duplicate trials to minimize the margin of error. Two pipe lengths were established (L1 = 58 m and L2 = 80 m). For each length (L1 and L2), the inlet flow was varied, considering flows of 0.25, 0.5, 0.75, 1.0, and 2.0 L/s. Likewise, for each length, five ranges of water turbidity were used: <10 NTU, 10–20 NTU, 21–50 NTU, 51–100 NTU, and >100 NTU. Before each test, a sample of raw water entering the BDWTP was taken, which was sent to the laboratory for determining the optimal dose of coagulant (aluminum sulfate) with the jar test.

2.4.2. Treatability study jar test

A jar test treatability study was conducted to determine the optimal dose of coagulant to be used in the experimental system (Ismail et al., 2012). Aluminum sulfate or alum was used as a coagulant, which is used in BDWTP. Jar tests were carried out for the different turbidities of the raw water, so that the previously established ranges of turbidity could be covered. A Phipps & Bird jar test kit was used. The apparatus consisted of six square-based vessels with a capacity of 2 L each one. The jar test procedure was identical for all tests, which included a rapid mix (G = 300 s^{-1}, 60 s) in which different doses of 2.5% alum were injected according to the turbidity of the raw water; followed by slow mixing (G = 41s^{-1}, 12.3 min) for promoting floc aggregation; finally, a sedimentation for 20 min was realized.

A 200 mL water sample was drawn from each beaker at the end of each jar test using a siphon below the water surface, for measuring turbidity and colour. The optimal dose was chosen as the coagulant dose that caused the highest percentage of turbidity removal; that is, the concentration of alum that showed the lowest level of residual turbidity in a sample. It was not necessary to adjust the pH in case of using alum, because the pH was between 6.8 and 7.3, which is the optimal condition (Naceradska et al., 2019). The agitation time applied in the jar tests was 12.3 min, taken from the results of the tracer tests (Fig. 4) for the design flow rate (1 L/s) and a length of 80 m. Meanwhile, the velocity gradient applied in the jar test was 41 s^{-1}, obtained by applying equation (9) (Table 2) for a design flow rate of 1 L/s.

2.4.3. Operation of the experimental system

The raw water inlet flow rate to the ETS was regulated (0.5, 0.5, 0.75, 1.0, and 2.0 L/s), after determining the dose of coagulant by means of a valve. The application of the coagulant was made in such a way that it fell in the centre of the rapid mixing cone. The dosage was carried out with a 2 L plastic bottle, in which an intravenous catheter was adapted to calibrate the dose of coagulant. After the coagulation of the water, it was introduced into the VTF for the formation of the floc.

In the previous process, a dose of flocculant similar to that used in the BDWTP (0.075 mg/L) was added at a point located 12 m away from the beginning of the flocculator. After flocculation, the water entered into the decanter for removing the flocs formed in the VTF. After settling, the water circulated to the sand filters for removing the flocs that were not retained in the settling. Finally, the filtered water entered the BDWTP chlorination chamber. This procedure was repeated for each length of the VTF, combined with a flow rate and turbidity indicated above.

2.4.4. Water quality analysis

Turbidity and colour were analyzed as main quality parameters for evaluating the efficiency of the VTF. For the measurement of turbidity, a HACH brand turbidimeter of model 2100 Q was used. Meanwhile, a HACH brand colorimeter of model DR/890 was used for colour. Three sampling points were defined in the ETS for evaluating the water quality parameters: (1) input of raw water to the mixing cone, before applying the coagulant; (2) exit from the experimental decanter, and (3) exit from the filtration system. While for the BDWTP we chose: (1′) raw water input (BDWTP rectangular weir), (2′) settled water (output of the BDWTP decanter), and (3′) filtered water (output of the BDWTP filters). It should be noted that the sampling was carried out simultaneously in both the ETS and the BDWTP, in order to compare the removal efficiencies, both of turbidity and colour, between the ETS that includes the VTF and the BDWTP that includes the FVFD.

2.4.5. Percentage removal of turbidity and colour

The efficiencies of the different experimental tests were analyzed, for which equation (13) allowed to determine the treatment efficiency when using the VTF + decanter system (D).

$$\mathbf{Removal_{VTF+D}} = \frac{\text{Raw water parameter} - \text{Settled water parameter}}{\text{Raw water parameter}} x100 \quad (13)$$

Equations (13) and (14) were used for determining the percentage removal of turbidity and colour, respectively, for each length of the VTF combined with a given flow rate and turbidity. Likewise, these formulas were used to determine the efficiency in the BDWTP.

2.5. Data analysis

The normalities of the distributions of two data series were analyzed through the Shapiro-Wilk normality test. It was found that the data was not normally distributed, which is why the Spearman correlation coefficient was applied for determining the degree of association between the data series. Considering that the resulting data did not follow a normal distribution, the non-parametric Wilcoxon test was applied for comparing whether there were significant differences in the means of the samples. Multiple linear regression was also applied with the efficiency as the dependent variable and the decimal logarithms of turbidity and length as independent variables at a confidence level of 90%.

2.6. Comparative analysis of costs for the construction of the VTF

The construction of a drinking water treatment plant implies costs that are specfic to the place where it is to be built, as well as to each component of the treatment plant (Sethi and Clark, 1998). The construction cost of a conventional baffle flocculator was calculated using equation (15) (Deb and Richards, 1983). The construction cost of the VTF was calculated by adding the costs of each one of the materials used in the construction.

$$CC = 1553\ (Q_M)^{0.45} \quad (15)$$

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

3. Results and discussion

3.1. Dimensions of the pilot VTF

The design methodology of a hydraulic flocculator with vertical flow deflectors for a design flow rate (Q_di) of 1 L/s allowed to define the length and diameter for the construction of the VTF. The length obtained was 82.6 m; however, a length L_1 = 80 m was considered taking into account the number of pipes, elbows, and other accessories. Additionally, in order to evaluate the influence of length on the efficiency of the VTF, a different length was tested, which was established at approximately 3/4 of L1, obtaining a length of 58 m. For constructive reasons, a L_2 = 58 m was considered. The calculated tube diameter was 4 inches (110 mm); meanwhile, the height of the tubes was determined at 3.0 m (half a tube) and a change in curvature of 0.85 m. Valves were properly installed for changing the length of the VTF from 58 m to 80 m. Said open valves allowed the passage of water directly from L1 and L2 to the decanter.

A 110 mm diameter PVC pipes and accessories were used for building the VTF, forming an up and down circuit (Fig. 3). The VTF was mounted on a metallic structure that served as a support. Additionally, PVC pipes and fittings with elastomeric sealing were used, in order to facilitate the assembly of the VTF. The same Fig. 3 shows the location of the mixing cone, which was made of polyethylene with diameters of 0.2 m and 0.05 m. The high-rate clarifier was made of concrete with a width, length, and depth of 0.6 m, 1.00 m, and 2.00 m, respectively. Likewise, the location of the rapid filters can be observed, which had a height of 1.8 m, with a thickness of sand of 60 cm, with an effective size of 0.55 mm; in addition, the filters were provided with a backwash system.

3.2. Hydrodynamic analysis in vertical tubular flocculation

3.2.1. Theoretical and real residence time of the VTF

The results obtained are in Fig. 4. It can be seen that the values of t_o are close to t_r. Both t_o and t_r decrease as the operational flow rate increases. Residence times were longer at the 80 m length, compared to the 58 m length. Smet and Van Wijk (2002) stated that FVFDs have a residence time between 10 and 20 min. Furthermore, Garland et al. (2017) indicated that the flocculation time should be between 10 and 30 min. For the length of 58 m and flows of 0.25, 0.50 and 0.75 L/s, residence times were obtained in accordance with what was suggested by the literature for hydraulic flocculators. The time was 7.84 min for the design flow rate (1 L/s). Meanwhile, the residence time for the 80 m

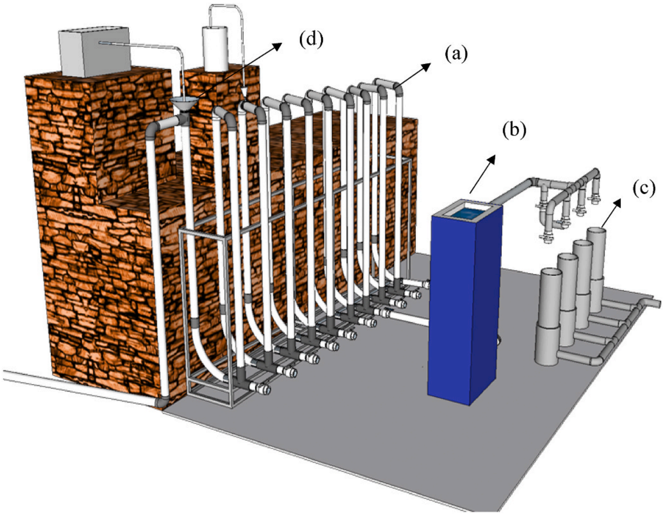

Fig. 3. Experimental drinking water system: (a) Pilot VTF, (b) high rate decanter, (c) sand filter, and (d) fast mixing cone.

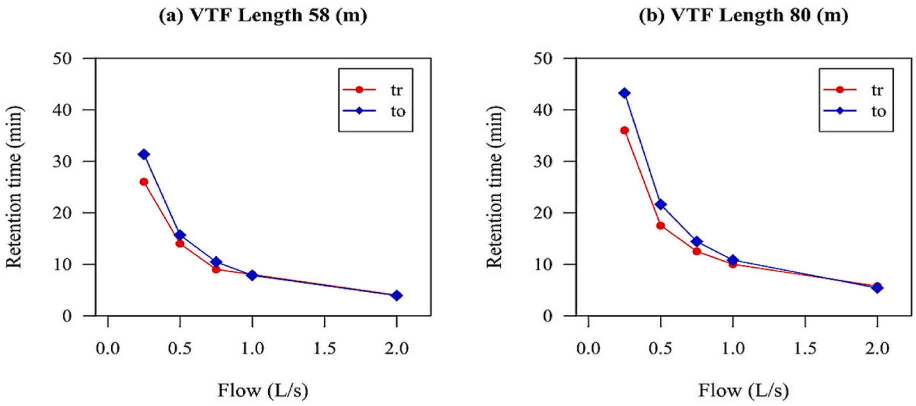

Fig. 4. Retention times: theoretical (t_o) and real (t_r) for lengths of (a) 58 m and (b) 80 m.

length complied with what is recommended by the literature for hydraulic flocculators for flows of 0.25, 0.5, 0.75, and 1.0 L/s. The residence time for the VTFs with lengths of 58 and 80 m and a flow rate of 2 L/s were 3.92 and 5.40 min, respectively. In the latter case, the times were lower than recommended by the literature.

Series of concentration values were obtained by applying tracers to the VTF and analyzing the water samples taken at the outlet, which increased over time until reaching a maximum and then progressively decreased, which originated a curve as indicated in Fig. 5. It can be seen that the real (or experimental) average residence time in the system was close to the calculated theoretical time.

3.2.2. *Hydraulic efficiency applying the wolf resnick method*

After having obtained each resulting curve of (1-F(t)) on a logarithmic scale against normalized time (t/t_o), the curvilinear models were fitted for each flow rate experienced and for each length. Table 1 shows the adjusted models for each experienced flow and for the two lengths 58 m and 80 m, as well as the percentages of piston flow, mixed flow, and dead spaces.

It was found that the percentage of plug flow (%P) in the experimental tests varied from 87.33% to 94.73%. The mixed flow (%M) was between 5.27% and 12.67% and the dead spaces (m) varied from −0.52 to −1.79. Negative values of m indicated that there are no dead zones in the system. The predominance of the piston flow over the mixed flow is notorious, which in turn is related to a greater efficiency in the flocculator. The small percentage of mixed flow may be due to existing 180° turns in the system. While the plug flow operation is closer, the short circuits will be minimized, maximizing the reaction kinetics and the reactor efficiency will increase (Rojas and García, 2010). Therefore, plug flow was mainly produced in the VTF and there were no short circuits or dead spaces that could affect the residence time, making the theoretical and real retention times relatively similar. From the hydraulic point of view, the present reactor is efficient, confirming that hydraulic flocculators do not present short circuits (Mcconnachie and Liu, 2000; Carissimi and Rubio, 2005).

3.2.3. *Velocity gradient evaluation*

The results of the gradient calculated using both the theoretical time and the real time are in Table 2. It can be seen that the real G values are slightly higher than the theoretical G for the two lengths of the VTF and increase in proportion to the flow rate. The minimum value of G registered for the VTF of 60 m was 3.10 s^{-1} for the flow rate of 0.25 L/s; meanwhile, the maximum G was 64.91 s^{-1} for the flow rate of 2 L/s. The minimum value of G recorded for 80 m was 2.98 s^{-1} for a flow rate of 0.25 L/s; while the maximum G was 62.12 s^{-1} for the flow rate of 2 L/s.

Smet and Van Wijk (2002) proposed that for a hydraulic flocculator, G should have typical values from 10 to 100 s^{-1}. Mohammed and Shakir (2018) recommended that G should be between 10 and 75 s^{-1}. Comparing the values of G recommended by the literature with those obtained in the present study, it can be seen that G is fulfilled for flows of 0.5, 0.75, and 1.0 L/s for the two lengths of the VTF.

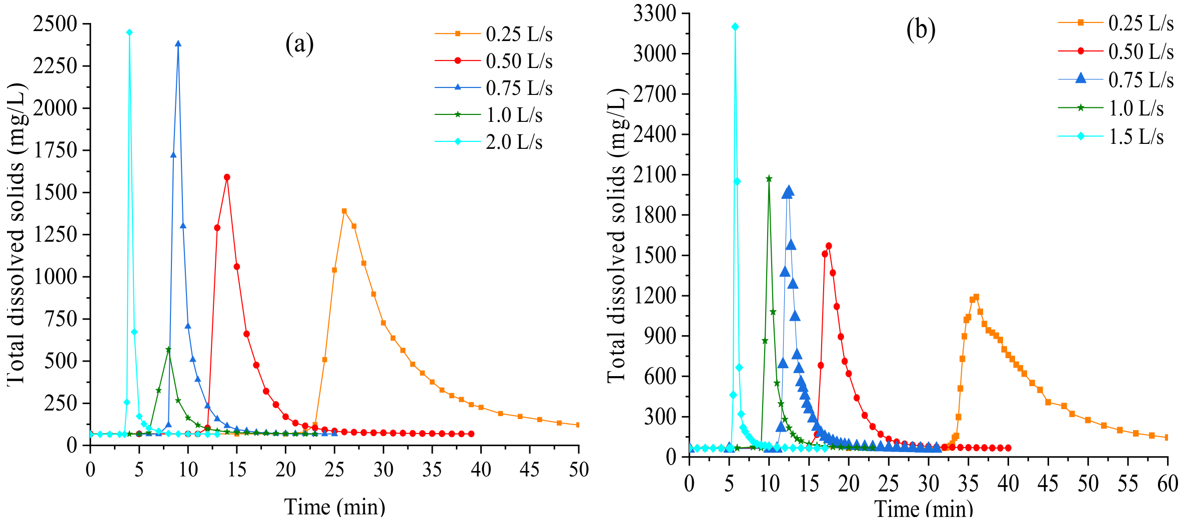

Fig. 5. Tracer distribution curves in the VTF effluent.

Table 1
Percentages of plug flow, mixed flow, and dead spaces in the VTF.

VTF Length (m)	Caudal (L/s)	Equation	R^2 (%)	%P	%M	m
58	0.25	Log (1-F(t)) = 7.96–3.99 × t/to	99.06	88.85%	11.15%	−1.24
	0.50	Log (1-F(t)) = 8.69–4.749 × t/to	99.20	89.69%	10.31%	−1.04
	0.75	Log (1-F(t)) = 10.26–6.75 × t/to	96.92	91.12%	8.88%	−0.67
	1.00	Log (1-F(t)) = 6.89–2.82 × t/to	98.61	87.33%	12.67%	−1.79
	2.00	Log (1-F(t)) = 17.98–12.46 × t/to	98.01	94.73%	5.27%	−0.52
80	0.25	Log (1-F(t)) = 10.17–6.476 × t/to	97.58	91.05%	8.95%	−0.73
	0.50	Log (1-F(t)) = 7.73–4.81 × t/to	71.74	88.56%	11.44%	−0.82
	0.75	Log (1-F(t)) = 12.30–8.45 × t/to	99.18	92.49%	7.51%	−0.57
	1.00	Log (1-F(t)) = 9.48–5.77 × t/to	90.50	90.47%	9.53%	−0.82
	2.00	Log (1-F(t)) = 12.15–7.08 × t/to	94.51	92.40%	7.60%	−0.86

Table 2
Theoretical and real velocity gradient.

VTF Length (m)	Caudal (L/s)	Theoretical G (s^{-1})	Real G (s^{-1})
58	0.25	3.10	3.40
	0.50	8.43	8.92
	0.75	15.25	16.43
	1.00	23.28	23.04
	2.00	64.91	64.24
80	0.25	2.98	3.27
	0.50	8.10	9.00
	0.75	14.63	15.71
	1.00	22.31	23.19
	2.00	62.12	60.23

3.3. *Evaluation of the optimal dosage of aluminum sulfate*

3.3.1. *Jars test*

The optimal doses of the coagulant applied in the ETS for eliminating the different turbidities of the raw water are shown in Fig. 6. Using this curve, it was possible to guarantee the adequate dosage of aluminum sulfate for each turbidity of the raw water that entered into the BDWTP and that also was used for the trials performed at the STE. There was not a linear relationship between the optimal applied dose of coagulant and the turbidity of the raw water, because in the experimental tests results were obtained that if the turbidity of the raw water increases, then the dose of coagulant also increases; but, this dose increase is small at turbidities greater than 100 NTU. The dose increase is proportional to the turbidity at turbidities less than 75 NTU, with a linear trend due to the fact that the suspended particles are few at low turbidities, which makes it difficult for them to collide with one another to form the floc, requiring more addition of coagulant. Meanwhile, the trend was exponential at turbidities greater than 75 NTU.

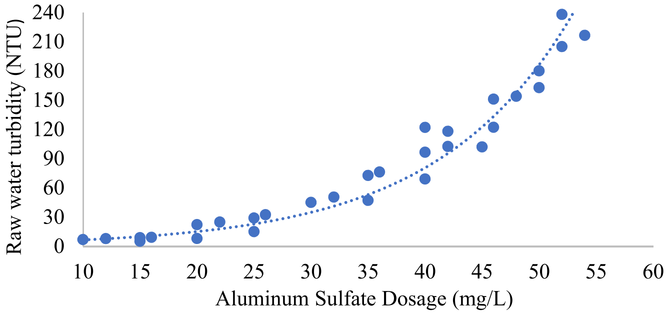

Fig. 6. Aluminum sulfate dosage curve.

León-Luque et al. (2016) used raw water with turbidities ranging between 10 and 180 NTU in their jar test study, for which their optimal doses of aluminum sulfate were between 10 and 35 mg/L, obtaining removals of 29%–94.4%. Zand and Hoveidi (2015) tested water with turbidities between 10 and 100 NTU, obtaining alum doses between 5 and 50 mg/L and a turbidity removal of 95.7%–97.1%. In this study, they tested raw water with turbidities that varied between 9.15 and 226.5 NTU, obtaining optimal doses of aluminum sulfate between 10 and 54 mg/L and removals between 90.9% and 97.6%.

3.3.2. *Dose of coagulant used in the experimental tests*

The dose of alum applied in the ETS had as its starting point the curve of Fig. 6; however, it should be emphasized that as the execution of the experimental tests progressed, the doses obtained in the jar test were reduced. It is due to that in the first tests, a high efficiency of the experimental system was obtained. Therefore, it was decided to reduce the doses in the following tests. In the experimental field tests, a lower dose was used compared to the jar tests for raw water turbidities greater than 50 NTU; in addition, the field doses were equal to or greater than the doses from the jar tests for turbidities less than 50 NTU. When comparing Fig. 6 with Fig. 7, it is evident that a lower dose of aluminum sulfate was applied in the ETS compared to that obtained in the jar test. Fig. 7 shows the dose of aluminum sulfate vs. the turbidity of raw water for the different flows used and for the two lengths of the VTF under study.

For the length of 58 m, the maximum raw water turbidity was 226.5 NTU for a flow rate of 2 L/s and a coagulant dose of 43.75 mg/L, while the lowest turbidity was observed at the flow rate of 1 L/s, corresponding to 9.15 NTU with a dose of 20.83 mg/L of aluminum sulfate. In the 80 m length, the maximum turbidity was 222.0 NTU for a flow rate of 2 L/s with a coagulant dose of 42.95 mg/L, while the lowest turbidity was 9.48 NTU for a flow rate of 0.75 L/s and with a coagulant dose of 23.06 mg/L.

Fig. 8 shows the dosage of coagulant applied in the BDWTP, as well as the dosages applied for the different flow rates of the ETS. It is possible to differentiate a concentration of points at low turbidities, less than 50 NTU, and at doses less than 30 mg/L in Figs. 7 and 8, corroborating that at low turbidities there is less quantity of suspended solids, which makes it difficult for them to collide with each other to form the floc and therefore requires more addition of alum. Fig. 8 plotted the curve of raw water turbidity versus dose of coagulant applied both in the ETS for the different flow rates, as well as for the BDWTP. It can be seen that only for the flow rate of 0.25 L/s (blue curve), a dose higher than the dose of the plant (black curve) was required; meanwhile, the dosage of ETS was lower compared to BDWTP for the other flows.

For achieving greater flocculation efficiency, a dose of 0.075 mg/L of cationic polyelectrolyte (flocculant) was added. This dose was determined in a jar test and corresponds to the dose currently applied in the BDWTP.

Both in Figs. 7 and 8, it can be seen that the alum dose increased as the turbidity of raw water also increased for the flow rate analyzed. The curve of the flow of 0.25 L/s is far from the curves corresponding to the other flows, which indicates that it is not feasible to use a flow of 0.25 L/s in this VTF of 58–80 m length and pipe diameter of 110 mm; but, it is

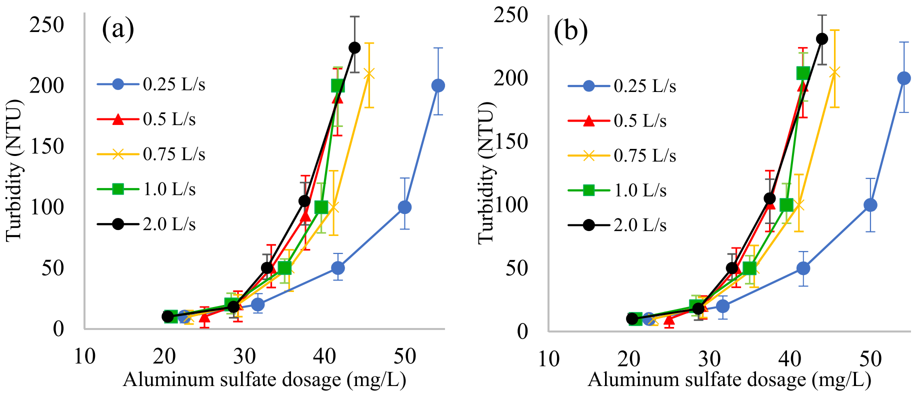

Fig. 7. Dose of coagulant applied when the VTF was used for: (a) 58 m and (b) 80 m.

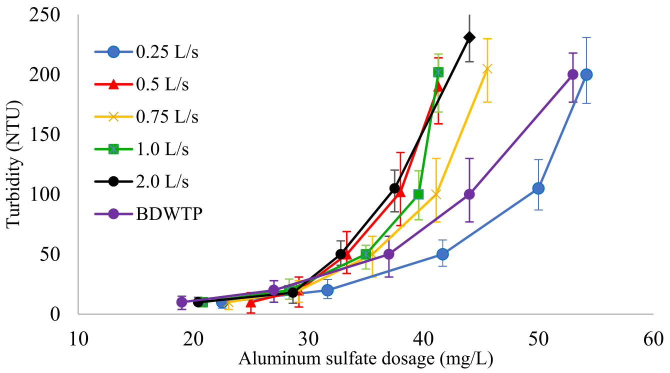

Fig. 8. Dose in the VTF vs. Dose in the Plant.

possible to use any flow between 0.5 and 2 L/s, due to that their doses do not differ significantly even at turbidities lower than 50 NTU. The applied doses were similar in all cases.

For turbidities greater than 50 NTU, the doses for flows of 0.5–2 L/s differ slightly, as shown below: (a) for raw water of 100 NTU with the VTF of 58 m and a flow of 0.5 L/s, a dose of 38.5 mg/L was applied, (b) a dose of 41.1 mg/L was applied for a flow rate of 0.75 L/s, (c) a dose of 39.5 mg/L was applied for a flow rate of 1 L/s, and (d) a dose of 37.5 mg/L was applied for a flow rate of 2 L/s. It can be seen that there was less dosage for a flow rate of 0.5 L/s; however, this lower dose affected the efficiency of the system, due to that the lower average turbidity and colour removals were obtained for this flow; therefore, the dose for the flow rate of 0.5 L/s should have been increased, as explained at the end of subsection 3.4.1.

Despite the aforementioned, it is possible to find an answer to this event by making a hydraulic model (which is outside the scope of this study). This hydraulic model (digital construction of the VTF) would reproduce and predict the behaviour of this pilot system and to determine the pressure at different points of the system, as well as the flow, speed, pressure loss in the pipes, retention times, and determine the problems and define solutions in this way. This virtual model will need to be adjusted in such a way that its operation is similar to the real one; for which, it will be necessary to perform a calibration to the virtual design, in such a way that the information obtained as the final result of the computational analysis is comparable with the real one and it is determined as valid, due to that in this way it will be possible to execute the recommendations obtained through the software in the field work. Software such as Watercad, Epanet, or others that are frequently used for pipe modeling could be used for this model.

3.4. *Evaluation of the efficiency between the experimental system and the BDWTP*

3.4.1. *Turbidity and colour removal in the VTF + decanter system as a function of flow*

Fig. 9 shows the average values of the turbidity removal efficiency in the ETS that includes the VTF with a length of 58 m and the settler; which was in the range between 40.96% and 96.64%; while, the efficiency was between 41.97 and 96.66% when the VTF was used with 80 m length and settler. Meanwhile, the efficiency measured at the outlet of the BDWTP settler (FVFD + settler) had removal values between 62.64% and 98.83%, showing a higher removal percentage in the latter.

The maximum turbidity removal efficiency found in the experimental system (VTF + decanter) using the two lengths of the VTF were similar. It was 96.64% in the VTF_58 m and 96.66% for the VTF_80 m, while the average value was 83.33% using the first length and 79.99% using the second length. Meanwhile, the average value was 91.1% for the BDWTP. It can be seen that the removal efficiency of VTF in the ETS can achieve slightly lower removals than the system that has a FVFD. In all cases, there is removal of turbidity, due to that the residual turbidity was removed in the filters as will be indicated later.

The maximum colour removal efficiency for the ETS using the 58 m and 80 m VTF was 95.55 and 94.62%, respectively. On the other hand, the average removal efficiency in the first configuration presented values of 74.12%, while it was 75.14% in the second configuration. This information can be corroborated in Fig. 10. Although there is no marked trend, it is possible to see that in the VTF_80 m, the removal percentage (72.21) was slightly higher than the efficiency of the VTF_58 m (70.74). However, the results of these two configurations were lower compared to the colour removal efficiency of BDWTP, which had an average value of 92.29%.

In Fig. 9(a), (b), 10(a), and 10(b), it can be seen that the average percentages of turbidity and colour removals obtained for a flow rate of 0.5 L/s were lower than those obtained for other flows; which answers the question presented in Figs. 7 and 8. That is, the applied dose was similar to that used for 1 and 2 L/s for a flow rate of 0.5 L/s, as was observed in Figs. 7 and 8, concluding that the dose applied for 0.5 L/s was lower than necessary; therefore, minor turbidity and colour removals were obtained. If the dose were increased for the flow rate of 0.5 L/s; then, the curve (red colour) in Figs. 7 and 8 would fit between the 0.25 L/s curve (blue colour), and the 0.75 L/s curve (orange colour), and surely the values of turbidity removal and colour would increase, being similar to those obtained for the other flows (Figs. 9 and 10).

3.4.2. *Turbidity and colour removal in the VTF system + decanter + filter as a function of flow*

The turbidity removal efficiency in the ETS using VTF + decanter + filter is presented in Fig. 11. On average, this removal percentage presented maximum values of 99.92% and 99.88% for VTF lengths of 80

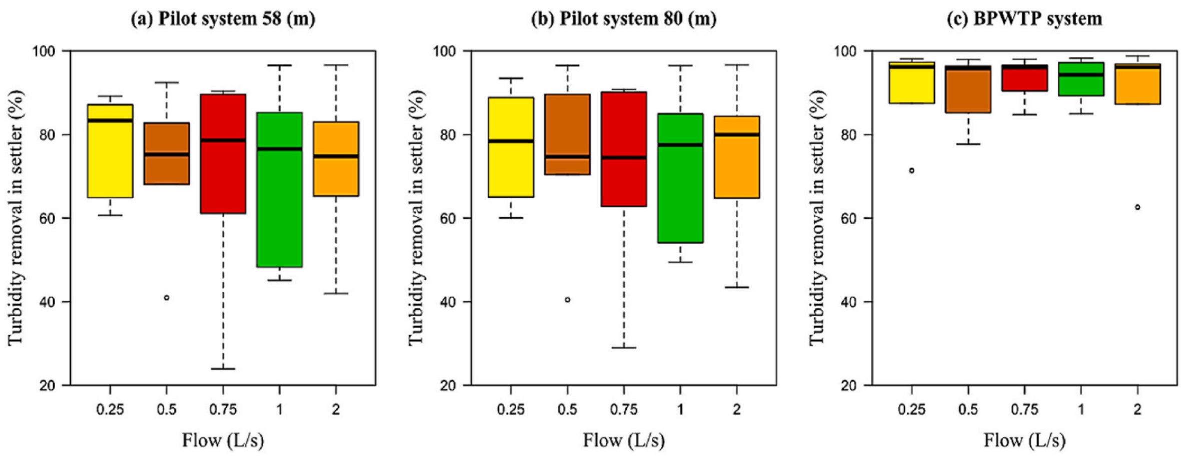

Fig. 9. Turbidity Removal Efficiency in the Experimental System: (a) VTF_58 m + settler, (b) VTF_80 m + settler and (c) VTF + BDWTP settler.

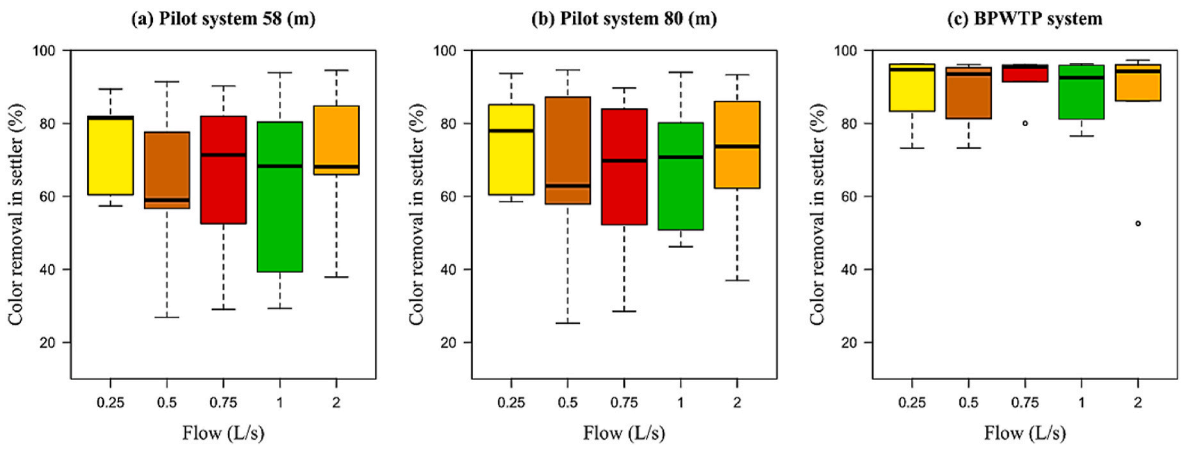

Fig. 10. Efficiency of Colour Removal in the Experimental System: (a) VTF_58 m + settler, (b) VTF_80 m + settler, and (c) VTF + PTAPB settler.

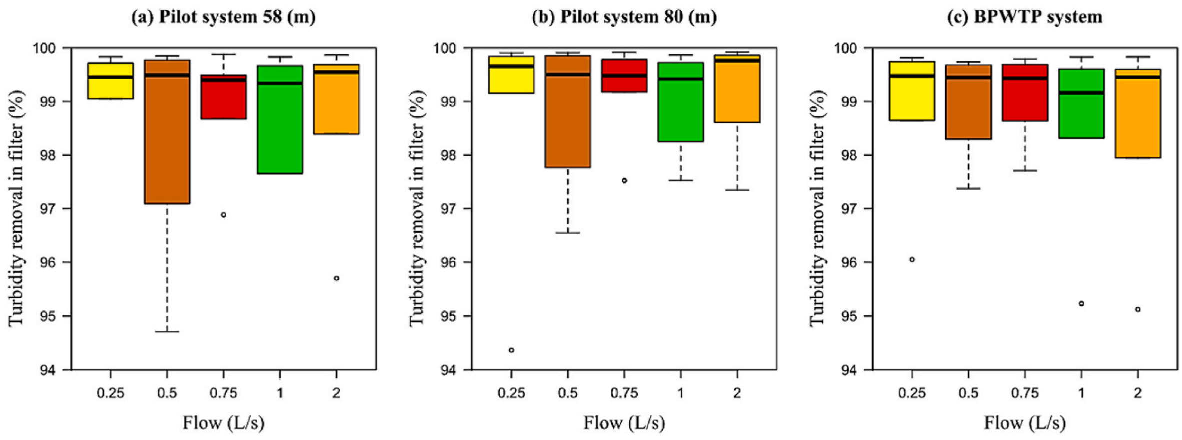

Fig. 11. Efficiency of Turbidity Removal in the Experimental System: (a) VTF_58 m + decanter + filter, (b) VTF_80 m + decanter + filter, and (c) VTF + decanter + BDWTP filter.

and 58 m, respectively, with a minimum difference with respect to the values reported in the BDWTP filters of 99.83%. The values in the ETS for the two lengths of the VTF and for the five flows were similar, except for the flow of 0.5 L/s. It could be due to the fact that there were turbidity fluctuations in the raw water during the days that the tests were carried out with this flow, which could affect the results in the ETS as well as in the results obtained in the BDWTP.

Fig. 12 shows the maximum values of colour removal in the ETS using the two lengths of the VTF, as well as those of the BDWTP, finding a removal of 100% in the two systems. Minimum removal values of 99.08% are observed using VTF_58 m, 99.33% using VTF_80 m, and 99.03% in the BDWTP. Although these variations are minimal, it should be noted that, in all cases, they exceed 99%, demonstrating that a system that uses VTF + decanter + filter can be efficient for the purification

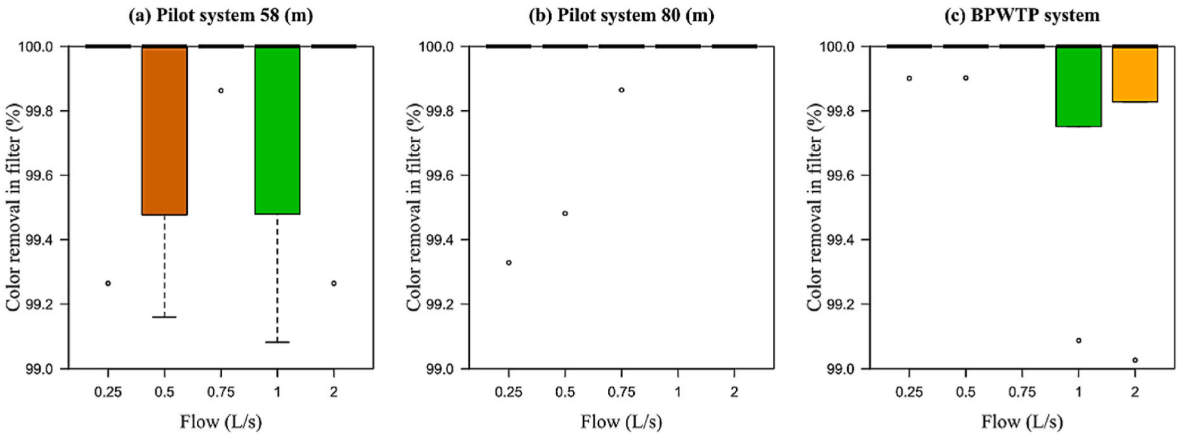

Fig. 12. Efficiency of colour removal in the experimental system: (a) VTF_58 m + decanter + filter, (b) VTF_80 m + decanter + filter, and (c) VTF + decanter + BDWTP filter.

process.

Unlike Figs. 9 and 10, Figs. 11 and 12 do not present a significant difference in the average removal of turbidity and colour, respectively, because the filters work efficiently eliminating the different concentrations of flocs that managed to pass through the filters for each one of the flows experienced in the same way. Precisely, these turbidity values obtained in the filters were what led to the decision about the estimation of the concentrations presented in Figs. 7 and 8.

3.5. Comparative analysis among the experimental system and the BDWTP depending on the length of VTF

3.5.1. Statistical analysis of flocculator + decanter systems

Fig. 13 shows the efficiency of turbidity and colour removal measured at the decanter outlet between the experimental treatment system (STE) and the BDWTP. It is possible to show that the VTF_58 m + clarifier and VTF_80 m + clarifier configurations have lower values compared to the FVFD + clarifier system of the BDWTP. As can be seen, in Fig. 13 there is no greater difference in the ETS removal efficiency when using VTF_58 m or VTF_80 m.

In the turbidity removal efficiency (Table 3), the maximum removal of the two VTF configurations (96.64% and 96.66%) were similar to the mean of the BDWTP (98.83%). The same happens in the colour removal efficiency for these lengths (94.55 and 94.62%) and the mean of the BDWTP (97.35%). The average removal efficiency of ETS turbidity with the VTF_58 m and VTF_80 m was 76.57% and 77.57%, respectively. However, when excluding the flow rate of 2 L/s, the turbidity efficiency increased to 80.24% for the VTF_58 m + decanter system; similarly, the efficiency increased to 82.11% for the VTF_80 m + decanter system.

A tubular flocculator with helical flow (FTHe) was used for turbidity removal with various lengths between 1.89 m and 36.84 m (Oliveira and Teixeira, 2017b). The average removal efficiency in the FTHe + decanter system was greater than 80%, with a maximum removal of 86.2%. It was detected that the best results were given by using lower values of G. Compared with the present study, the removal of the FtHe + decanter system was slightly higher than the experimental system VTF + decanter; however, the maximum removal values obtained using the VTF were higher than the maximum value using FTHe.

There was a notable difference in the removal of turbidity and colour obtained in the ETS compared to the removal obtained in the BDWTP. However, as indicated above, the removals are similar to the removals obtained by Oliveira and Teixeira (2017b) in a helical flocculator. It should be noted that there were not qualified operators in the BDWTP, who apply doses somewhat higher than those obtained in the dosage curve of Fig. 4 (this fact was observed while this work was being carried out). However, as a result of this study, it was recommended to the directors of the BDWTP that the applied doses must be reduced and the curve of Fig. 4 was delivered for its application in said plant.

3.5.2. Statistical analysis of the VTF + decanter + filter system

Fig. 14 shows graphically the turbidity and colour removal efficiencies between the experimental systems and the BDWTP, while Table 4 shows the statistical results obtained for the turbidity and colour removal efficiency. The average turbidity and colour removal efficiency in both the experimental systems and the BDWTP were greater than 98% and 99%, respectively. Therefore, a system made up of VTF + decanter + filter has the same performance as using FTD + decanter + filter. In the ETS with VTF_58 m, there were maximum values of turbidity

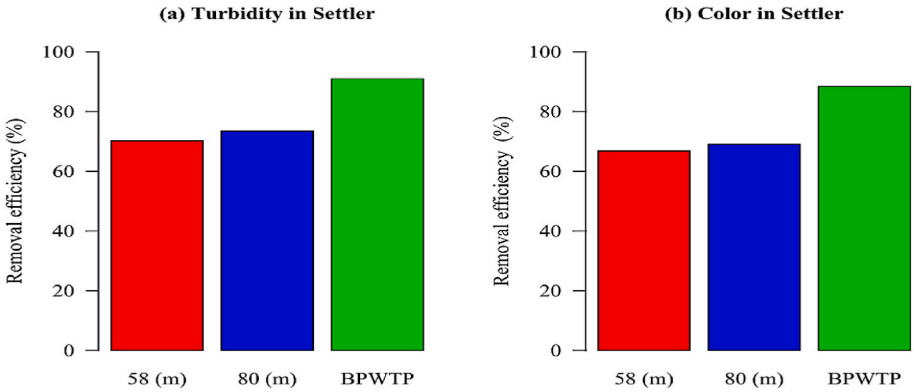

Fig. 13. Removal efficiencies of: (a) turbidity and (b) colour in the VTF_58 m + decanter, VTF_80 m + decanter and FVFD + BDWTP decanter systems.

Table 3
Statistical parameters of the turbidity and colour removal efficiency in the experimental system and the BDWTP.

System	% Turbidity Removal				% Colour Turbidity			
	Mean	Maximum	Minimum	SD	Mean	Maximum	Minimum	SD
VTF_58 m	72.09	96.64	23.97	19.62	66.8	94.55	26.89	21.42
VTF_80 m	73.47	96.66	28.94	19.13	68.88	94.62	25.27	20.77
BDWTP	91.01	98.83	62.64	9.24	88.46	97.35	52.55	10.94

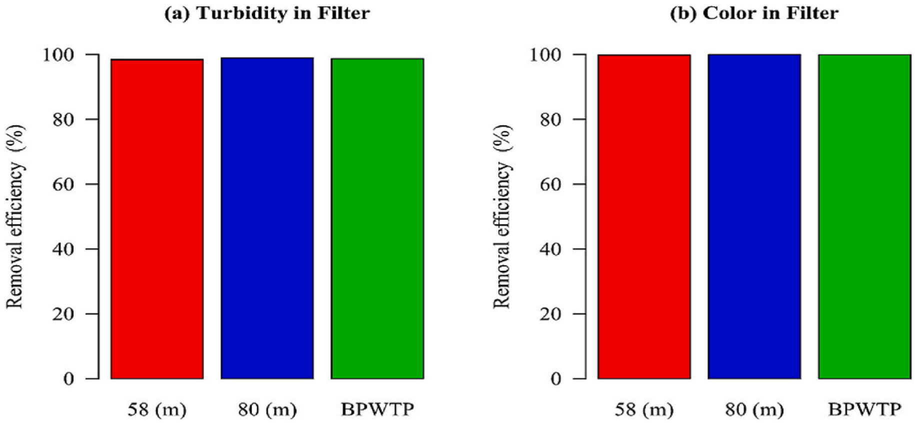

Fig. 14. Removal Efficiencies of: (a) Turbidity and (b) Colour in the VTF_58 m + settler + filter, VTF_80 m + settler + filter and FVFD + settler + BDWTP systems.

Table 4
Statistical parameters of the efficiency of turbidity and colour removal in the experimental system and the BDWTP.

System	% Turbidity Removal				% Colour Turbidity			
	Mean	Maximum	Minimum	SD	Mean	Maximum	Minimum	SD
VTF_58 m	98.39	99.88	93.08	2.04	99.82	100	99.08	0.32
VTF_80 m	98.91	99.92	94.36	1.38	99.95	100	99.33	0.17
BDWTP	98.7	99.83	95.12	1.42	99.9	100	99.03	0.26

removal of 99.88% and minimum values of 93.08%; meanwhile, the maximum turbidity removal was 99.92% and the minimum 94.36% in the VTF_80 m. There was a maximum removal of 99.83% and a minimum of 95.12% for turbidity removal in the BDWTP.

In the ETS with VTF_58 m and VTF_80 m, there were maximum values of colour removal of 100% and minimum values of 99.08% and 99.33%, respectively. There was a maximum removal of 100% and a minimum of 99.03% for colour removal in the BDWTP, showing that there were not significant difference in the removal of turbidity with the uses of the VTF_58 m or the VTF_80 m, in comparison with the removal obtained in the BDWTP.

3.6. Statistical results of hypothesis testing

The Shapiro-Wilk analysis determined that there is no normal distribution in the turbidity removal efficiency data measured at the outlet of the decanter and the filter. For the analysis of the Wilcoxon test regarding the turbidity removal efficiency, the following hypotheses formulations were made: H_o: There were not statistically significant differences in the turbidity removal and H_a: There were statistically significant differences in the removal of turbidity. The results are described in Table 5.

The results showed that there were statistically significant differences in the removal of turbidity between the two lengths of the VTF prior to the decantation process; therefore, it is better to use the longest VTF + decanter for efficient turbidity removal. When evaluating the efficiency of removal in the filters, the alternative hypothesis is accepted, finding that there is a significant difference between the two lengths of the VTF prior to the decantation + filtration process; therefore, the shortest length VTF + decanter + filter can be used for efficient turbidity removal.

There were statistically significant differences in the removal of turbidity between the VTF + decantation system and the FVFD + BDWTP decanter system; but, there were not found differences between the VTF + settling + filter system and the FVFD + settling + filter system of the BDWTP; therefore, an efficiency equal to the efficiency of conventional system made up with a FVFD followed by a settler and filter can be obtained with the VTF followed by a settler and filter.

3.7. Empirical modeling of turbidity removal in the VTF

The influential variables were identified: Reynolds number (Re), retention time (t_r), hydraulic gradient (G), flow rate (Q), raw water turbidity (RWT), and system length (L), for defining the model that allows to determine the efficiency in the pilot system (VTF + settler + filter). As a first step, the normality of each variable was analyzed with the Shapiro Wilk test, finding that no variable had a normal distribution. The results of the correlation through the Spearman test are presented in Table 6.

In general, it can be seen that almost all the variables have a weak and non-significant correlation with efficiency, except for raw water turbidity with a very strong correlation (significant at 99% confidence). The raw water turbidity was the most important factor that influences the efficiency of the VTF. Table 6 also shows that there is a relationship between time, gradient, flow rate, and Reynolds number, because they are linked in their calculation.

Table 7 presents the results after applying the multiple linear regression, where the adjusted R^2 is the determination coefficient

Table 5

Wilcoxon statistical test to determine the difference in removal between the experimental systems and the BDWTP.

H_o	H_a	p-value	Interpretation
There were not significant differences between the VTF_58 m + decanter system and the VTF_80 m + decanter system	There were significant differences between the VTF_80 m + decanter system and the VTF_80 m + decanter system	0.0146	There were significant differences.
There were not significant differences between the VTF_58 m + decanter + filter system and the VTF_80 m + decanter + filter system	There were significant differences between the VTF_58 m + decanter + filter system and the VTF_80 m + decanter + filter system	<0.001	There were significant differences.
There were not significant differences between the VTF_58 m + decanter system and the FVFD + decanter system of the BDWTP	There were significant differences between the VTF_58 m + decanter system and the FVFD + decanter system of the BDWTP	<0.0001	There were significant differences.
There were not significant differences between the VTF_58 m + clarifier + filter system and the FVFD + clarifier + filter system of the BDWTP	There were significant differences between the VTF_58 m + clarifier + filter system and the FVFD + clarifier + BDWTP system	0.9506	There were not significant differences.
There were not significant differences between the VTF_80 m + decanter system and the FVFD + decanter system of the BDWTP	There were significant differences between the VTF_80 m + decanter system and the FVFD system + BDWTP decanter	<0.0001	There were significant differences.
There were not significant differences between the VTF_80 m + clarifier + filter system and the FVFD + clarifier + BDWTP system	There were significant differences between the VTF_80 m + clarifier + filter system and the FVFD + clarifier + BDWTP system	0.0562	There were not significant differences.

adjusted by the number of variables with a value of 0.647. The Durbin-Watson (DW) test had a value of 1.71, which was between 1.5 and 2.5, so it was concluded that there was not autocorrelation. It was determined that the predictive variables of efficiency were the length of the flocculator and the turbidity of the raw water at a confidence level of 90%, because they met the necessary statistical conditions (Smith, 2018). However, logarithms were applied in the model of this research as proposed by Al-Zubaidi et al. (2021). Vaneli and Teixeira (2019) found turbidity removal estimation models for helical flocculators whose R^2 was 0.5. LOGLength is the decimal logarithm of the length and LOGTurbidity is the decimal logarithm of the turbidity.

Considering what is stated in Table 7, at a confidence level of 90%, the following model is obtained:

$$\text{Efficiency} = 86.623 + 3.844\ \text{LOGLength} + 2.982\ \text{LOGTurbidity}.$$

3.8. *Control test*

In the first instance, the experimental system without the VTF was evaluated; for which, the water coagulated with aluminum sulfate was sent directly to the settler and later to the filter. It was done with the purpose of measuring the efficiency between the system composed of VTF + settler + filter and the system composed of settler + filter; in such a way to be able to determine the importance of the incorporation of the tubular flocculator in the purification process. This test was performed in triplicate using the design flow rate (1 L/s) and with an average raw water turbidity of 56.6 NTU and average colour of 548 UC_Pt–Co. The results are presented in Table 8, obtaining an average turbidity and colour removal of 39.9% and 45.1%, respectively. These efficiency values were lower than those obtained when the full pilot system was used. It shows the importance of including the VTF before the settler and filter.

In a second case, the experimental system was evaluated without the dosage of coagulant; for which, the raw water with an average turbidity of 50.5 NTU was fed directly to the VTF + settler + filter system, without adding coagulant. It was done with the purpose of evaluating the importance of coagulating raw water in this type of system. A turbidity and colour removal efficiency was obtained at the outlet of the VTF_58 m + settler + filter system of 14.78% for turbidity and 15.04% for colour, while in the VTF_80 m + settler + filter system, the efficiency was 23.03% and 20.77% for turbidity and colour, respectively (Table 8). The efficiencies were much lower compared to the efficiencies obtained

Table 7

Standardized and non-standardized regression function coefficients for HTF efficiency.

Model	Non standardized coefficient		Standardized coefficient	t	Sig.
	B	Dev. Error	Beta		
(Constant)	86.623	3.891		22.262	<0.001
LOGLength	3.844	2.099	0.156	1.831	0.073
LOGTurbidity	2.982	0.317	0.799	9.41	<0.001

Table 8

Results of the experimental tests without VTF and without coagulant.

Pilot System	Turbidity Removal (%)	Colour Removal (%)
Settler + filter	39.90	45.10
FTH_58 m + Settler + filter (Without coagulant)	14.78	15.04
FTH_80 m + Sedimentador + filtro (Without coagulant)	23.03	20.77

Table 6

Correlation matrix of elements that influence the VTF.

	Efficiency	Re	t_r	G	Q	RWT	L
Efficiency	1.00						
Re	−0.027	1.00					
t_r	0.034	−0.960	1.00				
G	−0.027	0.985**	−0.952**	1.00			
Q	−0.028	1.00**	−0.960**	0.985**	1.00		
RWT	0.943**	0.030	−0.027	0.029	0.030	1.00	
L	0.029	0.000	0.244	−0.035	0.000	−0.107	1.00

Note. Correlations with ** are significant at 99% confidence.

when coagulant was used in all cases. The importance of the use of a coagulant in the purification process is evident.

This study permitted to establish that there is no significant difference in the removal of turbidity and colour between a system made up of a VTF together with a decanter and filter compared to a conventional DWTP made up of a FVFD, a decanter, and a filter. Average ETS efficiencies of 99.65% for turbidity and 99.88% for colour were obtained; while removal efficiencies of 99.70% for turbidity and 99.9% for colour were obtained in the BDWTP.

Table 9 shows that the residence time in the VTF for the design flow (1 L/s) was 10.8 min; meanwhile, it was 23 min in the FVFD. Although the residence time of the VTF was almost half that of the FVFD, the efficiency measured in the pilot settler was somewhat lower than the efficiency measured in the BDWTP settler; meanwhile, the efficiency measured in the pilot filter was the same as the efficiency measured in the BDWTP filter.

The residence time in the BDWTP settler was 25 min; meanwhile, the residence time in the ETS was 12 min for the design flow rate (1 L/s). The residence time of the pilot settler was almost half that of the BDWTP settler, which would be one of the factors that caused the efficiency in the pilot settler to be somewhat lower than the efficiency measured in the BDWTP settler. The removal efficiency of the floc particles depends on the residence time because there was a short residence time for collecting the flocs. The sedimentation rate in the BDWTP settler was 94 m^3/m^2d; meanwhile, it was 144 m^3/m^2d in the experimental settler. The higher sedimentation rate in the pilot settler caused the efficiency to be lower than in the BDWTP settler.

The same filtration rate was used in BDWTP filter and the ETS filter. As can be seen in Table 9, the FVFD has a longer residence time compared with the VTF, the BDWTP settling time was greater than the experimental settler, and the BDWTP settling rate was lower than that of the experimental settler; therefore, the aforementioned data would offer better efficiency for the BDWTP with respect to the pilot system under study. However, the system made up of VTF + settler + filter had efficiencies similar to those of the BDWTP made up of FVFD + settler + filter.

Residence time in a hydraulic baffle flocculator should be between 20 and 25 min for allowing adequate flocculation for the production of low residual turbidity after a subsequent treatment step, such as sedimentation or filtration (McConnachie, 1993). In this study, the time was adequate below that recommended by McConnachie (1993).

This study allowed us to establish that there is no significant difference in the removal of turbidity and colour in a system made up with VTF together with a decanter and filter compared to a conventional DWTP. The results obtained in the system made up with VTF + decanter + filter for a flow rate of 1 L/s, applying a G of 22 s^{-1} and a residence time of 10.8 min reached 99.88% reduction in turbidity. In the conventional treatment plant, it achieved 99.70% reduction in turbidity, applying a flow rate of 10 L/s, G of 40 s^{-1}, and a residence time of 23 min. Most of the tests applied for different flow rates had a turbidity reduction greater than 80% and a colour reduction greater than 90%.

The evaluation of the removal efficiency as a function of G and the turbidity of the raw water showed that high values of G impaired the formation of the flocs, resulting in a lower removal of turbidity and colour. It occurred when flow rates of 2 L/s were used. The gradients applied for the other flows prevented the breakage and disintegration of the already formed flocs, allowing more compact and easily removable flocs in the following processes.

Table 9
Specifications of the pilot system and the conventional PTAP.

Treatment Unit	Residence Time (min)	Surface Load (m^3/m^2d)
Pilot Vertical Tubular Flocculator (VTF)	10.8 min	
Flocculator with Vertical Flow Deflectors (FVFD)	23 min	
BDWTP high rate settler	25 min	94 m^3/m^2d
ETS High Rate Pilot Settler	12 min	144 m^3/m^2d
BDWTP sand filter		120 m^3/m^2d
ETS pilot sand filter		120 m^3/m^2d

Additional control tests were carried out for complementing the evaluation of the efficiency of the VTF. Tests were performed without adding coagulant. These tests with the design flow rate and a raw water turbidity between 48.8 and 52.9 NTU with the VTF_58 m and the decanter allowed a removal of 14.78% for turbidity and 15.04% for colour at the outlet of the decanter, while the removal efficiencies were 23.03% and 20.77% using the VTF_80 m for turbidity and colour, respectively. These removals were much lower compared to the removal when coagulant was used, evidencing the importance of the use of coagulant for eliminating turbidity and colour in raw water using a VTF. Another control test was carried out excluding the VTF, that is, the coagulated water after the mixing cone passed directly to the decanter and later to the filter; during these tests, the turbidity of the raw water was between 55.1 and 58.5 NTU. The turbidity removal in this case was 39.9% and the colour removal was 45.1%. In this second case, the importance of VTF in the purification process could be evidenced, because without flocculation there was not good floc formation, consequently affecting settling and filtration. The removal was low for both turbidity and colour, as in the first control tests.

The results of the control tests permitted to verify that the collision between them occurs efficiently in a VTF, as the particles are destabilized during coagulation, guaranteeing the formation of flocs of good size and weight that are easily retained in the next stage of decantation. Therefore, the use of VTF followed by a settling and filtration treatment is recommended, especially for small towns, due to its easy implementation and low cost for small flows, being an option for communities with low economic resources.

Comparing the efficiency and other characteristics of the VTF used in the present study with other studies that used tubular flocculators, it can be distinguished that the length and diameter of the pipe used in the present study was much greater than those used in previous studies (Cahyana et al., 2021; Oliveira and Teixeira, 2017b; Kurbiel et al., 1989). According to the results of Table 10, it can be seen that it was possible to treat higher flows (3.6 m^3/h) in the ETS than those used by Cahyana et al. (2021) and Oliveira and Teixeira (2017b), who used a flow rate of 0.018 and 0.12 m^3/h, respectively; furthermore, Kurbiel et al. (1989) used flows of 3.5 and 4 m^3/h, similar to the flows of the present study. Regarding the diameter of the pipe used in the studies, Cahyana et al. (2021) used diameters of 12.7 and 15.87 mm; while Oliveira and Teixeira (2017b) used diameters of 9.5 and 16.0 mm. The aforementioned values were lower than the diameters of 71.4 and 86.4 mm that were used by Kurbiel et al. (1989), as well as the diameter of the present study (110 mm). Looking at the gradients in Table 10, Cahyana et al. (2021) applied gradients of 24.7 and 32.4 s^{-1}.

Kurbiel et al. (1989) applied gradients of 33.2 and 52.7 s^{-1}; those that were close to those applied in the present study, which were 42 and 46 s^{-1}, which were between 10 and 100 s^{-1}, which is recommended for hydraulic flocculators; meanwhile, Oliveira and Teixeira (2017b) applied much higher gradients between 160 and 295 s^{-1}. The retention times in the tubular flocculators varied from 22.5 to 56.25 s in the study by Oliveira and Teixeira (2017a). On the other hand, the retention times in the tubular flocculators varied from 82.3 to 105 s in the study by Cahyana et al. (2021), which were lower than the times of 435 and 738 s used in the present study. Meanwhile, Cahyana et al. (2021) applied retention times between 985 and 1335 s, which were quite high compared to the first studies. These times were similar to the recommended times for hydraulic baffle flocculators, which vary between 600 and 1800 s (Romero, 1999). Regarding the efficiencies obtained in these tubular flocculators, the highest efficiencies were 93.6% in the study of Cahyana et al. (2021) and 91.37% in the present study, as well as the efficiency of 86.2% obtained in the study of Oliveira and Teixeira

Table 10
Characteristics and Efficiency of the VTFs used in other Studies and in the Present Study.

Author	Flocculator Length (m)	Pipe diameter (mm)	Gradient G (s^{-1})	Caudal (m^3/h)	Time (s)	Initial Turbidity (NTU)	Efficiency (%)
Cahyana et al. (2021)	50	12.7	32.4	0.018	985	159	91.3
Cahyana et al. (2021)	50	15.87	24.7	0.018	1335	155	93.6
Kurbiel et al. (1989)	20	71.4	52.7	3.5	82.3		68.8
Kurbiel et al. (1989)	20	86.4	33.2	4	105		54.3
Oliveira y Tong (2017)	15.16	16	160	0.12	56.25	50	82.3
Oliveira y Tong (2017)	36.84	9.60	295	0.06	22.5	50	86.2
Current study	58	110	23	3.6	470	226	76.5[a] 98.4 [b]
Current study	80	110	22	3.6	648	222	77.5 [a] 98.9 [b]

[a] Measured at the settler outlet.
[b] Measured at the filter outlet.

(2017b). The last indicated results show that tubular flocculators are highly efficient for the removal of turbidity in drinking water systems.

The increased demand for water treatment systems suitable for rural areas and small towns has allowed experimental field studies of tubular hydraulic flocculators to be carried out. The VTF used in the present study showed high clarification efficiency and short residence time compared to other flocculators commonly used in drinking water facilities. The ETS was a compact clarification system made up with a VTF, a settler, and rapid sand filters. The ETS has a design flow of 86,400 L per day, being able to provide drinking water to a population of approximately 720 inhabitants, considering a demand of 120 L/inhabitant. day.

The VTF is somewhat flexible for varying operating conditions, compared to mechanical flocculators where the speed remains constant and the residence time increases or decreases as the flow rate changes. If the range of velocity gradients is chosen appropriately, then this property can be used in the design of plants that include a VTF within the purification process.

Tubular flocculators are presented as easy cleaning and maintenance systems. Possible material adhered to the walls of the pipe can be released with a backwash. The VTF used in this study was very simple for building and operation, being very efficient when complemented with a high-rate settler and a rapid filter. The theoretical and real residence times were similar, because there were not dead spaces or short circuits. The operation of the VTF is very reliable and economical, because it does not require electrical energy. Due to its great depth, the VTF requires small areas and very compact designs are achieved, being recommended for rural communities that have low resources and need small flows.

In this study, an efficiently proven, easy-to-implement, and low-cost water treatment system has been presented, contributing to the sixth sustainable development goal, allowing small populations to have access to drinking water. The results of this study suggest the continuation with other studies such as experimentation with tubular flocculation, using two or more pipe diameters, a smaller diameter at the beginning and a larger diameter at the end of the flocculation, which will allow to have a greater velocity gradient at the beginning of the flocculator and a lower gradient at the end, which could improve floc formation, as occurs in baffle flocculators (Mcconnachie and Liu, 2000; Haarhoff & Van Der Walt, 2001). Likewise, the height and number of tubes could be varied, other coagulant different to aluminum sulfate could be tested, and a longer length than the one used in this study could be tested.

All the experimental tests were carried out in the field for calculating the efficiency of a vertical flow tubular flocculator, with the same natural raw water used in a purification plant in a rural community. It was necessary to implement a pilot system made up of the VTF, a high-rate decanter, and a sand filter for the experimental tests.

4. Conclusions

A large-scale experimental clarification system was obtained, considering that 3.6 m^3/h could be treated, which is enough to provide drinking water to a population of approximately 720 people. The vertical flow tubular flocculator had a high efficiency in removing turbidity and colour from the raw water used for purification. This flocculator had a low residence time, compared to hydraulic baffle flocculators commonly used for this purpose. The results showed that the VTF must be coupled to a settling and filtration system for an efficient clarification system.

The hydrodynamic analysis of the VTF indicated that the real and theoretical residence times are very similar, considering that the times varied between 7.84 and 10.8 min for the design flow (1 L/s) for the lengths of 58 and 80 m, respectively. Meanwhile, the velocity gradient varied between 22.3 and 23.2 s^{-1} for the same flow rate for lengths of 58 and 80 m, respectively. These data may be useful in the design of the VTF, indicating that this type of flocculator may be promising for use in clarification processes for small flow rates.

Average turbidity removal efficiency was 99.92% using VTF_80 m + decanter + filter, presenting similar results to the VTF_58 m + decanter + filter system, where an efficiency of 99.88% was obtained; meanwhile, the system composed of FVFD + decanter + filter that is traditionally applied had an efficiency of 99.83%. A similar behaviour was verified in the turbidity removal efficiency when using the VTF of 58 and 80 m, which indicates that it is possible to obtain maximum values of turbidity removal efficiency with a flocculator length between 58 and 80 m. The decimal logarithms of length and turbidity also allow to explain the efficiency of the VTF at a confidence level of 90%.

The limitations of the study are the following: (a) the coagulant dosages were manual and (b) continuous monitoring of the filtration race was not done. The coagulant dosages were changing as the coagulant content in the preparation tank decreased; therefore, if continuous doses were maintained by means of dosing pumps; then, the results could improve. Continuous monitoring of the filtration race was not done because the tests were carried out during the day, being able to monitor the filtration race for a maximum of 12 h; therefore, it was not possible to estimate the filtration race for each applied flow.

The results of this study suggest to continue with other studies such as the experiments with tubular flocculation using two or more diameters of pipe, a smaller diameter at the beginning, and a larger diameter at the end of flocculation, which will allow to have a greater velocity gradient at the beginning of the flocculation process, and a lower gradient at the end, which could improve floc formation, as occurs in baffled flocculators (Mcconnachie and Liu, 2000; Haarhoff & Van Der Walt, 2001). Likewise, the height and number of tubes could be varied, a coagulant different from aluminum sulfate could be tested, and a length greater than the used in this study could be tested.

It is recommended to evaluate the application of a flow rate of 1 L/s for obtaining greater efficiency in drinking water using a VTF, for which the VTF should have a diameter of 110 mm, a length between 58 and 80 m, a speed of 13 cm/s, a retention time between 7.8 and 10.8 min, and a velocity gradient between 22 and 23 s^{-1}. Considering that the FVFD design methodology was used in order to dimension the VTF of the present study; therefore, it is still necessary to establish a specific methodology for the design of the VTF. Finally, it is recommended to evaluate the dosage with dose bombs for improving the results of VTF and to elaborate an hydraulic model for VTF, considering that a filtration race is necessary for optimizing its operation.

Author contributions statement

Vertical tubular flocculator: alternative technology for the improvement of drinking water treatment processes in rural áreas, Fernando García Ávila: Conceptualization, Methodology, Writing – original draft, Supervision, Darwin Tenesaca-Pintado: Resources, Validation, Francisco Novoa-Zamora: Resources, Validation, Emigdio Antonio Alfaro Paredes: Data curation, Formal analysis, Alex Avilés Añazco: Reviewing and Editing, Alexandra Guanuchi Quito, Reviewing and Editing, María D. Tonon Ordoñez, Funding acquisition, César Zhindón Arévalo: Investigation.

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.

Data availability

Data will be made available on request.

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References

Abdulkareem, H.A., Abdurrahman, S.B., Umar, I., 2014. Design of a water treatment Mechanical Mixer for a pre- chlorination tank as an effective algae control, aeration, and coagulation processing. International Journal of Engineering Science Invention 3 (11), 25–36.

Al-Zubaidi, H.A.M., Naje, A., Abed Al-Ridah, Z., Chabuck, A., Ali, I.M., 2021. A statistical technique for modelling dissolved oxygen in salt lakes. Cogent Engineering 8 (1). https://doi.org/10.1080/23311916.2021.1875533.

Andreoli, F.C., Sabogal-Paz, L.P., 2020. Household slow sand filter to treat groundwater with microbiological risks in rural communities. Water Res. 186 https://doi.org/10.1016/j.watres.2020.116352.

Arboleda, J., 2000. *Teoría y práctica de la purificación del agua* [Theory and Practice of the Water Purification]. Bogotá, Colombia 1, 390 s.e. http://fing.uncu.edu.ar/catedras/sanitaria/archivos/libros-arboleda-valencia/Teoria y Practica de la Purificacion del H2O - Tomo 1 - Arboleda Valencia.pdf.

Bratby, J., 2006. Coagulation and Flocculation in Water and Wastewater Treatment. IWA Publishing. https://doi.org/10.2166/washdev.2021.253%0ADownloaded.

Cahyana, G., Suwandhi, P., Mulyani, T., 2021. Novel helical or coiled flocculator for turbidity reduction in drinking water treatment: a performance study. IOP Conf. Ser. Earth Environ. Sci. 623, 012009 https://doi.org/10.1088/1755-1315/623/1/012009.

Carissimi, E., Rubio, J., 2005. The floes generator reactor-FGR: a new basis for flocculation and solid-liquid separation. International. Journal of Mineral Processing 75 (3–4), 237–247. https://doi.org/10.1016/j.minpro.2004.08.021.

Crittenden, J., Trussell, R., Hand, D., Howe, K., Tchobanoglous, G., 2012. MWH’s Water Treatment: Principles and Design. John Wiley & Sons, Inc.

Deb, A.K., Richards, W.G., 1983. Evaluating the economics of alternative technology for small water systems. J. Am. Water Works Assoc. 75 (4), 177–183. https://doi.org/10.1002/j.1551-8833.1983.tb05102.x.

Fujioka, T., Ueyama, T., Mingliang, F., Leddy, M., 2019. Online assessment of sand filter performance for bacterial removal in a full-scale drinking water treatment plant. Chemosphere 229, 509–514. https://doi.org/10.1016/j.chemosphere.2019.04.197.

García-Avila, F., Zhindón, C., Álvarez, R., Donoso, S., Tonon, M.D., Flores, L., 2020. Optimization of water use in a rapid filtration system: a case study. Water-Energy Nexus 3 (1), 1–10. https://doi.org/10.1016/j.wen.2020.03.005.

García-Ávila, F., Avilés-Añazco, A., Sánchez-Cordero, E., et al., 2021. The challenge of improving the efficiency of drinking water treatment systems in rural areas facing changes in the raw water quality. S. Afr. J. Chem. Eng. 37, 141–149. https://doi.org/10.1016/j.sajce.2021.05.010.

Garland, C., Weber-Shirk, M., Lion, L.W., 2017. Revisiting hydraulic flocculator design for use in water treatment systems with fluidized floc beds. Environ. Eng. Sci. 34 (2), 122–129. https://doi.org/10.1089/ees.2016.0174.

Ghawi, A.H., 2018. Optimal design parameters for hydraulic vertical flocculation in the package surface water treatment plant. Scientific Review Engineering and Environmental Sciences 27 (4), 438–451. https://doi.org/10.22630/PNIKS.2018.27.4.42.

Haarhoff, J., 1998. Design of around-the-end hydraulic flocculators. J. Water Supply Res. Technol. - Aqua 47 (3), 142–152. https://doi.org/10.2166/aqua.1998.20.

Haarhoff, J., Van Der Walt, J., 2001. Towards optimal design parameters for around-the-end hydraulic flocculators. J. Water Supply Res. Technol. - Aqua 50 (3), 149–159. https://doi.org/10.2166/aqua.2001.0014.

Iqbal, M.M., Shoaib, M., Farid, H.U., Lee, J.L., 2018. Assessment of water quality profile using numerical modeling approach in major climate classes of Asia. Int. J. Environ. Res. Publ. Health 15 (2258). https://doi.org/10.3390/ijerph15102258.

Ismail, I., Fawzy, A., Abdel-Monem, N., Mahmoud, M., El-Halwany, M., 2012. Combined coagulation flocculation pre treatment unit for municipal wastewater. J. Adv. Res. 3 (4), 331–336. https://doi.org/10.1016/j.jare.2011.10.004.

Kurbiel, J., Spulak, A., Schade, H., 1989. Application of pipe flocculator and cross-flow tilted plate settler for effective separation of precipitate from electroplating wastewater. Water Sci. Technol. 21 (1), 539–546. https://doi.org/10.1016/b978-1-4832-8439-2.50055-9.

León-Luque, A.J., Barajas, C.L., Peña-Guzmán, C.A., 2016. Determination of the optimal dosage of aluminum sulfate in the coagulation-flocculation process using an artificial neural network. Int. J. Environ. Sustain Dev. 7 (5) https://doi.org/10.7763/IJESD.2016.V7.797.

Marobhe, N., Sabai, S., 2021. Treatment of drinking water for rural households using Moringa seed and solar disinfection. J. Water, Sanit. Hyg. Dev. 11 (4), 579–590. https://doi.org/10.2166/washdev.2021.253.

Mastrocicco, M., Prommer, H., Pasti, L., Palpacelli, S., Colombani, N., 2011. Evaluation of saline tracer performance during electrical conductivity groundwater monitoring. J. Contam. Hydrol. 123 (3–4), 157–166. https://doi.org/10.1016/j.jconhyd.2011.01.001.

McConnachie, G.L., 1993. Water treatment for developing countries using baffled-channel hydraulic flocculation. Proc. Inst. Civ. Eng.: Water, Maritime and Energy 101, 55–61. https://doi.org/10.1680/iwtme.1993.22992.

Mcconnachie, G., Liu, J., 2000. Design of baffled hydraulic channels for turbulence-induced flocculation. Water Res. 34 (6), 1886–1896.

Meng, F., Van Wie, B.J., Thiessen, D.B., Richards, R.F., 2019. Design and fabrication of very-low-cost engineering experiments via 3-D printing and vacuum forming. Int. J. Mech. Eng. Educ. 47 (3), 246–274. https://doi.org/10.1177/0306419018768091.

Mohammed, T.J., Shakir, E., 2018. Effect of settling time, velocity gradient, and camp number on turbidity removal for oilfield produced water. Egyptian Journal of Petroleum 27 (1), 31–36. https://doi.org/10.1016/j.ejpe.2016.12.006.

Naceradska, J., Pivokonska, L., Pivokonsky, M., 2019. On the importance of pH value in coagulation. J. Water Supply Res. Technol. - Aqua 68 (3), 222–230. https://doi.org/10.2166/aqua.2019.155.

Oliveira, D.S., Teixeira, E.C., 2017a. Experimental evaluation of helically coiled tube flocculators for turbidity removal in drinking water treatment units. WaterSA 43 (3), 378–386. https://doi.org/10.4314/wsa.v43i3.02.

Oliveira, D.S., Teixeira, E.C., 2017b. Hydrodynamic characterization and flocculation process in helically coiled tube flocculators: an evaluation through streamlines. Int. J. Environ. Sci. Technol. 14 (12), 2561–2574. https://doi.org/10.1007/s13762-017-1341-z.

Oliveira, D.S., Teixeira, E.C., 2019. Swirl number in helically coiled tube flocculators: theoretical, experimental, and CFD modeling analysis. Int. J. Environ. Sci. Technol. 16 (7), 3735–3744. https://doi.org/10.1007/s13762-018-2027-x.

Omarova, A., Tussupova, K., Hjorth, P., Kalishev, M., Dosmagambetova, R., 2019. Water supply challenges in rural areas: a case study from Central Kazakhstan. Int. J. Environ. Res. Publ. Health 16 (688). https://doi.org/10.3390/ijerph16050688.

Pérez, J.M., 2005. *Análisis de flujos y factores que determinan los periodos de retención* [Analysis of Flows and Factors that Determine Retention Periods]. CEPIS/OPS. https://xdoc.mx/preview/analisis-de-flujos-y-factores-que-determinan-los-periodos-5ddae47319f3d.

Rodríguez, D., Giácoman, G., Champagne, P., 2012. Assessment of the plug flow and dead volume ratios in a sub-surface horizontal-flow packed-bed reactor as a representative model of a sub-surface horizontal constructed wetland. Ecol. Eng. 40 (1), 18–26. https://doi.org/10.1016/j.ecoleng.2011.10.018.

Rojas, A., García, A., 2010. Análisis de la curva de distribución del tiempo de residencia en un sistema de lixiviación [Analysis of the Residence Time Distribution Curve in a Leaching System]. Tecnol. Quím. 30 (1), 61–68.

Romero, J., 1999. *Potabilización del Agua* [Water Purification]. Alfaomega, 3^{a} ed.

Sartori, M., Oliveira, D.S., Teixeira, E.C., Rauen, W.B., 2014. CFD modelling of helically coiled tube flocculators for velocity gradient assessment. J. Braz. Soc. Mech. Sci. Eng. 37 (1), 187–198. https://doi.org/10.1007/s40430-014-0141-3.

Sethi, V., Clark, R., 1998. Cost estimation models for drinking water treatment unit processes. Indian J. Eng. Mater. Sci. 5 (1), 223–235.

Smet, J., Van Wijk, C.V., 2002. Small Community Water Supplies: Technology, People and Partnership. IRC International Water and Sanitation Centre, Delft (Technical Paper Series 40).

Smith, G., 2018. Step away from stepwise. Journal of Big Data 5 (32). https://doi.org/10.1186/s40537-018-0143-6.

Sob, P.B., 2021. Designing an efficient and stable household Irrigation system. Int. J. Eng. Res. Technol. 14 (5), 456–467.

Soros, A., Amburgey, J., Stauber, C., Sobsey, M., Casanova, L., 2019. Turbidity reduction in drinking water by coagulation-flocculation with chitosan polymers. J. Water Health 17 (2), 204–218. https://doi.org/10.2166/wh.2019.114.

Souza, F., Pizzolatti, B., Sens, M., 2021. Backwash as a simple operational alternative for small-scale slow sand filters: from conception to the current state of the art. J. Water Proc. Eng. 40, 101864 https://doi.org/10.1016/j.jwpe.2020.101864.

Sun, Y., Zhou, S., Chiang, P., Shah, K., 2019. Evaluation and optimization of enhanced coagulation process: water and energy nexus. Water-Energy Nexus 2 (1), 25–36. https://doi.org/10.1016/j.wen.2020.01.001.

Swetland, K., Weber-Shirk, M., Lion, L., 2014. Flocculation-sedimentation performance model for laminar-flow hydraulic flocculation with polyaluminum chloride and aluminum sulfate coagulants. J. Environ. Eng. 140, 04014002 https://doi.org/10.1061/(asce)ee.1943-7870.0000814.

Tong, Z.G., 2012. Study on the technology of vortex coagulation and its application in water plant of DongFeng motor corporation. J. Water Supply Res. Technol. - Aqua 61 (4), 253–261. https://doi.org/10.2166/aqua.2012.095.

Tong, Z., 2017. Application of micro-vortex coagulation process in reconstruction project of liling railway water plant. Biotechnology: An Indian Journal 13 (3), 135.

Tse, I., Swetland, K., Weber-Shirk, M., Lion, L., 2011. Fluid shear influences on the performance of hydraulic flocculation systems. Water Res. 45 (17), 5412–5418. https://doi.org/10.1016/j.watres.2011.07.040.

Vaezi, R., Sanders, R., Masliyah, J., 2011. Flocculation kinetics and aggregate structure of kaolinite mixtures in laminar tube flow. J. Colloid Interface Sci. 355 (1), 96–105. https://doi.org/10.1016/j.jcis.2010.11.068.

Valdiviezo, L.G., García, F.F., Cabello, R.J., Castañeda, C., Alfaro, E.A., 2021. Scientometric study of drinking water treatments technologies: present and future challenges. Cogent Engineering 8 (1), 38. https://doi.org/10.1080/23311916.2021.1929046.

Vaneli, B.P., Teixeira, E.C., 2019. Model improvement for estimating of water turbidity removal efficiency in helical tubular flocculators. Eng. Sanitária Ambient. 24 (4), 773–783. https://doi.org/10.1590/s1413-41522019180405.

Wolf, D., Resnick, W., 1963. Residence time distribution in real systems. Ind. Eng. Chem. Fundam. 2 (4), 287–293. https://doi.org/10.1021/i160008a008.

Wu, J., Cao, M., Tong, D., Finkelstein, Z., Hoek, E., 2019. A critical review of point-of-use drinking water treatment in the United States. Clean. Water(Washingt.) 4 (40). https://doi.org/10.1038/s41545-021-00128-z.

Zand, A.D., Hoveidi, H., 2015. Comparing aluminium sulfate and poly-aluminium chloride (PAC) performance in turbidity removal from synthetic water. Journal of Applied Biotechnology Reports 2 (3), 287–292.

Zeghadnia, L., Robert, J., Achour, B., 2019. Explicit solutions for turbulent flow friction factor: a review, assessment, and approaches classification. Ain Shams Eng. J. 10 (1), 243–252. https://doi.org/10.1016/j.asej.2018.10.007.

Zinn, C., Bailey, R., Barkley, N., Walsh, M., Hynes, A., Coleman, T., Savic, G., Soltis, K., Primm, S., Haque, U., 2018. How are water treatment technologies used in developing countries and which are the most effective? An implication to improve global health. J. Publ. Health Epidemiol. 2 (25) https://doi.org/10.21037/jphe.2018.06.02.