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Treatment of washrack wastewater with water recycling by advanced flocculation–column flotation

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ABSTRACT

A new technique for flocculation and flotation (aerated flocs), called flocculation–column flotation (FCF) was evaluated for the treatment of vehicle (bus) washrack wastewater and water reuse. The system is composed of a compact flocculation–flotation unit, utilizing an in-line flocculator device, a centrifugal multiphase pump which generates microbubbles (Sauter mean diameter, 75 μm), and a column flotation for solid/liquid separation. Design and operating parameters were studied and the efficiency of the FCF was evaluated based on the chemical and physio-chemical quality of the treated water. A tannin derivative was employed as a flocculant and aerated flocs (0.8–1.6 mm diameter; 45–150 m h^{-1} rise rates) were rapidly formed (10 s, residence time). Due to the rapid formation of these very light flocs, the FCF system was able to handle a high hydraulic-load capacity (>18 m h^{-1}), using a reduced foot print (compact unit), and reduced energy consumption. The data shows that this rapid FCF system appears to have a high potential to treat oily (or non-oily) voluminous wastewater at high flow-rates.

Keywords: Flotation; Flocculation; Water reuse; Aerated flocs

1. Introduction

Flocculation and flotation processes were originally designed (in the mining and metallurgical areas) to separate one particle type from another whose density is lower or has been made lower than the suspending liquid. Recently, there has been a rapid development of devices and techniques for flocculation and these techniques have been applied in drinking water plants and many process wastewaters [1].

Buses, trucks, big and small vehicles, and equipment washing processes use large amounts of water. For instance in Brazil, more than 4 million cubic meters of water are used for this activity every month, which is equal to the water consumption of a city with 600,000 inhabitants [1]. Moreover, the wastewater from this activity produces elevated toxicity [2] and causes water pollution. Fortunately this scenario has already started to change, due to the pressure of constant water shortages, increasing water prices and environmental laws.

The following stages describe a typical vehicle washrack operation. Each stage produces a different wastewater stream. These different streams are then combined to form a composite wastewater. The first stage is pre-soak (automated nozzle or hand held

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spray), followed by bodywork washing (with high pressure sprays or brushes with or without detergent); rocker panel/undercarriage washing (brushes or high pressure sprays on the sides and underneath of vehicles); first rinse (a high pressure rinse); wax and sealers (a surface finish which is sprayed on the vehicle); and final rinse (a low pressure rinse). Brown [3] has written a report for the International Car Wash Association regarding water conservation in the professional car wash industry. According to this author, reclaimed water can be used in all stages of a professional car wash, except the final rinse, where fresh or spot free water (Total Dissolved Solids (TDS) lower than 350 – water treated with RO) is recommended.

Water quality for reuse varies depending on the industry. The main issues facing reuse for vehicle washracks are the fouling of washing equipment, increased chemical consumption (degreasers, etc. associated with decreased water quality), and exposure of the operators to microbiological contamination. With respect to health and safety, Hamada and Miyazaki [4] showed that there was no presence of hazardous bacteria or *Escherichia coli* in car wash recycling systems.

With regard to vehicles' wash water recycling techniques many technologies have been proposed and tested such as reverse osmosis and nanofiltration [3]; ultrafiltration [5]; ultrafiltration-activated coal adsorption [6]; biological treatment; biological treatment-flotation; and flocculation-sedimentation and flocculation-dissolved air flotation (DAF). Nevertheless, some of these processes are expensive (investment, operation and maintenance) and/or demonstrate poor efficiency, and often require a large foot-print.

Rubio et al. [7] reviewed flocculation–flotation techniques and their applications and in a recent work, Rubio et al. [1] demonstrated the application of the flocculation–flotation in the vehicle washrack wastewater treatment for water recycling. Advantages found were: low maintenance and operational costs (low reagent cost and only a single unskilled operator required), moderate investment costs; reduced footprint area; and high water clarification (more than 85% turbidity reduction). According to the authors, up until 2007, the process had recycled up to 400,000 m^3 of water from more than 20 units operating in Brazil. The first scheme, named ETAR, consisted of flocculation in two stages (an in-line hydraulic flocculator (FF) for rapid mixing and an agitated tank for slow mixing) followed by flotation in a DAF cell (hydraulic-load is 9 m h^{-1}).

FF and flocs generation reactor (FGR®) are in-line facilities which use flux kinetic energy and plug-flow mixing for flocs generation. Carissimi and Rubio [8] described the FGR® development studies and Rosa and Rubio [9] presented the FF flocculator. These authors believe that these devices can work as bubble/particle contactors creating the so-called aerated flocs.

Aerated floc formation mechanisms are not yet well understood and their characterization (size, rise rates, strength, and fractal dimension) as well as the entrapped bubbles diameter and air volume must be fully studied to assist in understanding the flocculation–flotation process, control and design.

Column flotation is broadening its applications in the environmental area, such as in the treatment of oil and grease, metallic ions, de-inking, and suspended solids removal [10–12]. Its high throughput and flux pattern (plug flow) are the main advantages.

This work is a continuation of a series of papers on development, basic principles, and application of advanced flocculation followed by flotation. The aim of this work was to apply and evaluate a new flocculation–flotation unit for washrack wastewater treatment and reuse, named flocculation–column flotation (FCF). Another aim was to provide some data on the rapid formation and characterization of aerated flocs.

2. Materials and methods

The experimental work was carried out at Metropolitan Transportation Bus Company (a 250 bus fleet site), located in Porto Alegre, in southern Brazil. The company installed a flocculation–flotation unit (ETAR) followed by a sand filter in 2004 for the treatment and recycling of the fleet washrack wastewater.

2.1. Description of wastewater and reagents

The wastewater which was studied passed through an API oil separator and was collected via gutters at the bus wash site. The buses had their chasses, bodywork, wheels, and mechanical components washed. Wastewater characteristics showed some variations during the experimental investigation, which posed some problems (separation efficiency), but this is typical of practical real systems (Table 1). Table 1 shows the wastewater characteristics, which were close to those found in wash wastewaters from metallurgical, petrochemical, and petroleum industries.

The reagents employed were Tanfloc SL (a tannin based low molecular weight polymer) at a concentration of 200–700 mg L^{-1} (depending on the effluent characteristics) and Na(OH) for pH adjustment.

Table 1
Wash water composition, main parameters. Number of samples: 30

Parameter	Mean value*
pH	7 ± 0,2
Turbidity (NTU)	139 ± 45
Color (Hz)	217 ± 35
Hardness (mg L^{-1} $CaCO_3$)	168
Surface tension (mN m)	31 ± 1
Conductivity (μS cma^{-1})	446 ± 55
Total solids (mg L^{-1})	543 ± 25
Dissolved solids (mg L^{-1})	452 ± 30
Suspended solids (mg L^{-1})	112 ± 21
Oils and grease (mg L^{-1})	12 ± 6
COD (mg L^{-1})	259 ± 40
TC (mg L^{-1})	45 ± 3
TOC (mg L^{-1})	20 ± 5

* Mean = ±1/2SD.

2.2. Aerated flocs characterization

Aerated flocs characterization was made in-line. According to Owen et al. [13], mechanically stirred vessels and off-line measurements present several problems for floc analyses.

The flux exiting an in-line pilot-scale flocculation and microbubbles generation unit fed a bench scale column flotation device, whereby a graduated cell connected at the top allowed for individual view of the aerated floc. Therefore, the measurement of the flocs rise rate (more than 50 flocs were evaluated) was possible and their equivalent air bubble diameters were estimated using Stokes law [8,14]. Digital images were captured, and the aerated floc equivalent diameter, fractal dimension, and theoretical strength were estimated.

The Boulingand–Minkowski or Minkowski dimension (Eq. (1)) is a method of determining the fractal dimension which creates a relation between the expanded area (A) of an image and the radius (r) of the circumference used to expand this image. The method gives a two dimensional fractal dimension (D_2) [15]. Each floc (around 10 flocs) image had its area expanded with three different radius circumferences (0.5, 1, and 2 pixels).

$$D_2 = 2 - \lim r_{\to 0} \frac{\ln(A(r))}{\ln(r)} \tag{1}$$

Jarvis et al. [16] and Li et al. [17] present the theoretical method for floc strength calculation (Eq. (2)) as a function of flux dissipation energy (ε), fluid characteristics (viscosity (υ), specific weight (ρ) and flocs average diameter (d)). The average strength per unit area at the plane of floc rupture is defined as σ (N/m^2).

$$\sigma = 2.31 \frac{\rho.\varepsilon^{3/4}.d}{\nu^{1/4}} \tag{2}$$

2.3. Microbubble characterization

A multiphase (water/air) pump was employed for bubble generation. The pump receives the air at the inlet (suction), and then shears it within the impeller. Thus, an efficient and fast air-in-water dispersion and dissolution was achieved in the pump outlet, rapidly reaching solution saturation, with the microbubbles being formed after passing by a nozzle (needle-valve).

The microbubbles generated in the recycling current (FCF treated bus washrack wastewater) were measured (in the laboratory) using the LTM-BSizer device [18]. The Sauter mean diameter (D_{32}) of the distribution was employed as the main size parameter.

2.4. FCF studies

An FCF pilot-scale (1 m^3 h^{-1}) unit (Fig. 1) was installed in parallel with the Bus Company water recycling equipment (ETAR). The FCF equipment had its flocculation unit characteristics varied, i.e., reactor geometry, retention time, and mixing intensity (Table 2 shows their hydraulic characteristics).

FGR® [8], the flocs generator reactor and, FF [9], the flocculation–flotation process were developed at our laboratory. The main characteristics and advantages of these in-line mixing facilities instead of agitated tanks are: no need for moving parts; plug flow (less short circuits and dead zones); low volume/retention times (Camp-number – Ca), and small foot-print area [19,20].

The column flotation was evaluated in terms of hydraulic-load capacity and height required. The column flotation constituent modules were each 0.24 m in diameter and 0.6 m high and were made of acrylic. Column hydraulic connections were made of PVC and their fixtures were made of stainless steel.

Feed was placed at approximately two-thirds of the column height using a 100 mm inner diameter PVC tube with its open end turned up. No contact zone (bubbles/flocs) was included within the column.

The operational characteristics of the microbubble generation unit were maintained at a constant rate (recycle rate = 30%, air flow rate = 900 mL min^{-1} and saturation pressure = 4.5 Kgf cm^{-2}).

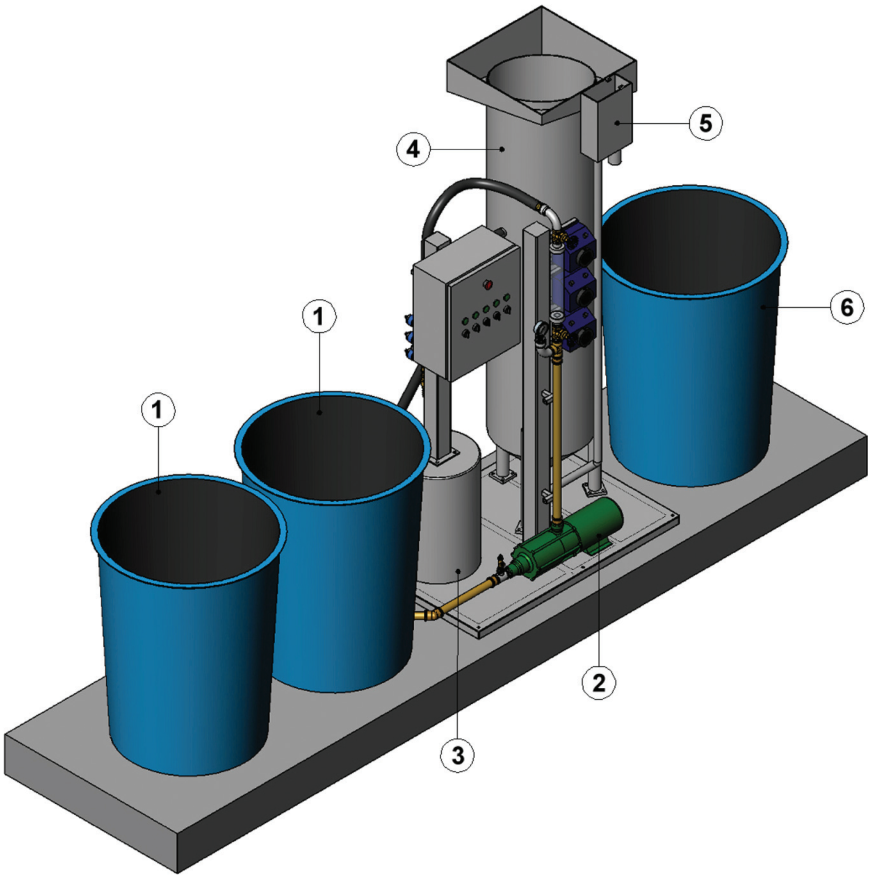

Fig. 1. The FCF unit. 1, wastewater equalization tank; 2, multiphase centrifugal pump; 3, FGR® – flocs generator reactor; 4, column flotation; 5, level control; and 6, treated water tank.

The experiments lasted 2 h, during which time aliquots of the treated wastewater were sampled every 15 min. The experiments were duplicated over several days. Treated water samples had their turbidity, color, conductivity, and surface tension analyzed and the results were statistically treated according to the ANOVA one-way methodology described in Montgomery [21].

FCF validation runs were carried out. These runs lasted 4 h and 30 min, and samples were taken every 30 min, in duplicate. A comparison between the FCF (validation runs results) and the ETAR systems results were performed (water samples from the ETAR system were collected before sand filtration). The water sample qualities were evaluated by analyzing solids (total, dissolved, and suspended), TC, TOC, COD, turbidity,

Table 2
Hydraulic and hydrodynamic characteristics of in-line hydraulic flocculators

Reactor		Rapid mixing (RM)		Slow mixing (LM)		Camp number
RM	LM	[a]R_t (s)	[b]G (s^{-1})	R_t (s)	G (s^{-1})	
FGR®	–	17	1350	–	–	22,650
FF 1	–	10	1025	–	–	10,250
FF 1	FGR®	10	1025	17	1350	32,900
FF 1	FF 2	10	1025	180	50	19,250

[a] R_t, retention time;
[b] G, velocity gradient.

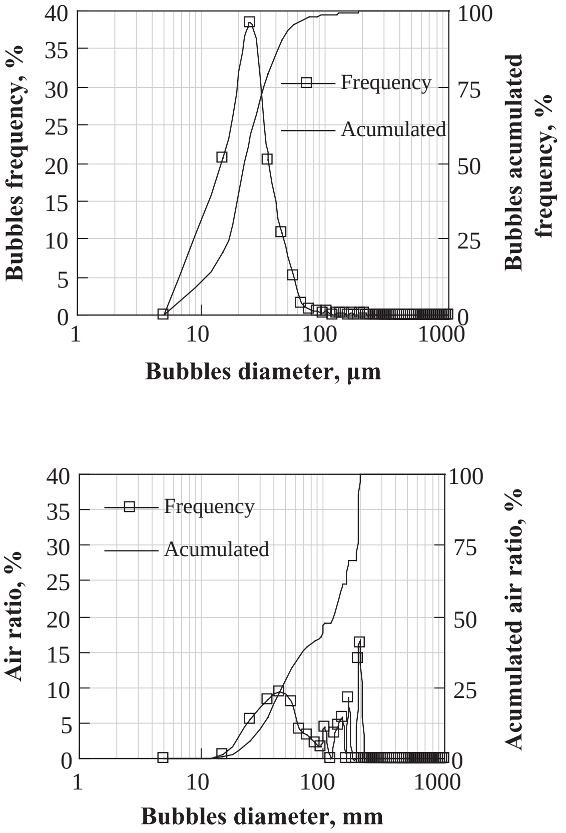

Fig. 2. Bubbles size distribution. Conditions: FCF treated water; water surface tension = 50 mN m; water feed rate = 4 L min^{-1}; air flow rate = 100 mL min^{-1}; saturation pressure = 4 Kgf cm^{-2}.

and color. All water analyses followed the Standard Methods for the Examination of Water and Wastewater [22].

3. Results and discussion

3.1. Microbubbles characterization

The bubbles show a diameter of up to 250 μm (Fig. 2), which characterizes them as microbubbles. The bubble population mean Sauter diameter (D_{32}), is about 75 μm (a rise rate of 11 m h^{-1}), which was somewhat higher than the microbubbles generated from the pressure vessel D_{32} = 60 μm in the DAF [14]. Yet, the bubble population average (arithmetic) diameter is about 30 μm (a rise rate of 2 m h^{-1}). According to Kracht et al. [23], this Sauter mean diameter, a statistical diameter which represents the bubble size distribution (in volume and surface area), is the most important parameter employed to evaluate gas dispersion (surface flux – Sb, for example) in flotation (mineral particles) devices.

Table 3
Aerated flocs characterization. Floc strength and diameter, as a function of flocculant concentration

Flocculant concentration (mg L^{-1})	300	700
Average diameter (μm)	857	1603
σ (Nm^{-2})	49	92

3.2. Aerated flocs characterization

The equivalent average diameter and theoretical strength of the flocs formed in two different reagent concentrations are shown in Table 3. An increase in reagent concentration allows for significant floc growth, and results are in agreement with other studies [16,17]. The explanation is that, the higher the flocculent concentration, the larger the number of polymer bridges.

Li et al. [17] show a theoretic floc strength of σ = 0.24 N m^{-2} for kaolin/aluminum sulfate coagula and Yeung and Pelton [24] show a σ = 1.000 N m^{-2} for calcium carbonate/high molecular weight flocs. Herein, flocculation was assisted by the utilization of a low molecular polymer (tannin base). Therefore, it was expected that the formation of flocs would be stronger than aluminum sulfate coagula, but weaker than those formed in the presence of a high molecular polymer.

The aerated flocs formation mechanisms are not fully defined, but according to [9], aerated flocs are formed only in the presence of a high molecular polymer. Fig. 3 shows the (average >90 m h^{-1}) flocs rise rate, which suggests that several bubbles are inside the flocs. Thus, for any particular flocs velocity, an equivalent bubble diameter has to exist to attain such a rate. In all cases, these ''equivalent'' diameters are higher than

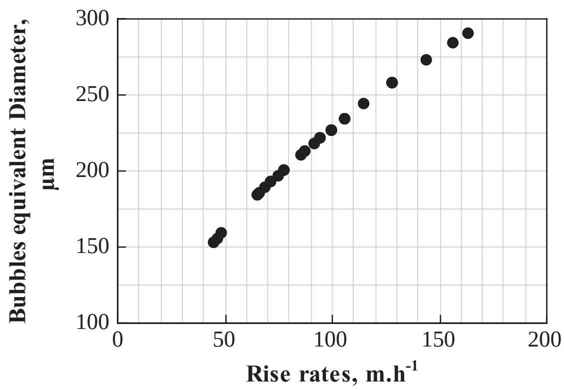

Fig. 3. Bubbles equivalent diameter as a function of aerated floc rise rates.

Table 4
FCF treated water quality as a function of different in-line flocculators. Conditions: [Tanfloc SL] = 300–700 mg L^{-1}; pH = 7 ± 0.1; hydraulic-load = 25 m h^{-1}; column flotation height = 3.6 m

Flocculators	Turbidity		Color		Surface tension	
	Reduction (%)	NTU	Reduction (%)	Hz	Increase (%)	mN m
Bus wash wastewater	–	44–96	–	135–217	–	28–36
FF 1	91	6	73	43	31	40
FGR®	85	8	71	48	36	41
FF1 + FGR®	86	6	68	60	30	42
FF1 + FF 2	92	8	81	42	29	37

those of the microbubbles and this can only be explained by the entrapment and entrainment phenomena [7–9,14].

The flocs average fractal dimension (D_2) was found to be approximately 1.64. Therefore, the flocs are considered to be compact and spherical [25]. Otherwise, high D_2 can be related to flocs that had experienced superficial erosion (breakage) during their formation [24,26]. An important consideration is that floc superficial erosion may occur irreversibly, to some extent, decreasing flocculation efficiency [16,13,27].

3.3. FCF studies

FCF in-line flocculation studies (Table 4) show that despite changes in wastewater characteristics and various mixing devices employed, a clear reduction of the solution turbidity and color can be observed using FCF. This conclusion is based on more than 12 months of study. Surfactant substances removal was not so pronounced, and treated water surface tension remains below 45 mN m. Yet, this low surface tension facilitates microbubble generation [28] and can diminish the use of soap. The FF 1 alone was selected as the best, because it has the lowest volume/retention time and Camp number, and therefore requires less energy transfer. Furthermore, its treatment efficiency is equal to or higher than other devices.

Column flotation hydraulic-load studies (Table 5) have shown that turbidity reduction was found to be clearly dependent on process hydraulic-load and when the flux mean superficial velocity inside the column was greater than 25 m h^{-1}, flocs were dragged toward the clarified current. The highest turbidity reduction was observed at the loading capacity of 18 m h^{-1} (Table 5).

FCF column flotation height studies (Table 6) show that the decrease in the column height from 3.6 to 1.8 m improves the FCF treatment efficiency. This result may be due to the better flocs-bubbles contact after decreasing the height/diameter ratio while keeping the superficial air velocity constant.

3.4. FCF and ETAR system comparison

The ETAR plus sand filtration system has been in use for more than 3 years in the Metropolitan Transportation Company without any operational difficulties (even without a final rinse with fresh water).

Table 5
FCF treated water quality as a function of different hydraulic-load. Conditions: [Tanfloc SL] = 300–700 mg L^{-1}; pH = 7 ± 0.1; flocculator = FF1; column flotation height = 3.6 m

Hydraulic-load	Turbidity		Color		Surface tension	
	Reduction (%)	NTU	Reduction (%)	Hz	Increase (%)	mN m
Bus wash wastewater	–	68–80	–	150–220	–	27–35
9	92	6	79	60	25	41
18	94	6	76	61	27	41
25	88	7	70	65	30	38
33	–	302	10	200	–	–

Table 6
FCF treated water quality as a function of different column height. Conditions: [Tanfloc SL] = 300–700 mg L^{-1}; pH = 7 ± 0.1; flocculator = FF1; hydraulic-load = 25 m h^{-1}

Column height (m)	Turbidity		Color		Surface tension	
	Reduction (%)	NTU	Reduction (%)	Hz	Increase (%)	mN m
Bus wash wastewater	–	60–95	–	30–190	–	32–28
3.6	87	6	59	60	50	41
3.0	88	6	40	61	32	41
2.4	90	7	33	65	32	38
1.8	93	302	42	200	40	–

Therefore, it might be stated that ETAR treated water quality suits the bus wash purpose. The sand filter works as a barrier against no floatable flocs (generated by incrustations of hydraulic flocculators and/or column flotation release), which may appear during system stops.

Comparative results between the ETAR system and the FCF system are shown in Table 7. The main advantages of the FCF are higher loading capacity and most of the water quality parameters, considering their fluctuations, are much closer.

Finally, other advantages of this new FCF system in treating this effluent are the following:

- The elimination of stirred tanks at the flocculation stage and the substitution by an in-line flocculator leading to less energy consumption and maintenance.
- The use of the multiphase pump makes the microbubble generation unit safe and easy to operate when compared to broadly used saturator vessels. Yet, there is a decrease in the microbubble generation unit control needs and the microbubbles generated are slightly bigger, allowing for flotation kinetics enhancement, while flocs breakage and/or collision difficulty are not observed.

4. Conclusions

An FCF system was tested and evaluated treating bus washrack wastewater and showed a capacity for high hydraulic-load (>15 m h^{-1}) as well as water turbidity and color reduction. With regard to water reuse, FCF treated water seems to suit the bus wash purpose. The aerated flocs formed in the presence of the Tanin base flocculant and microbubbles (Sauter mean diameter of 75 μm) within the in-line rapid flocculator (retention time equal to 10 s) presented rise rates greater than 45 m h^{-1} allowing prompt solid/liquid separation.

Symbols

A(r) – Expanded area of the floc image
r – Radius of the circumference used to expand the image
D_2 – Two dimensional fractal dimension
ε – Flux dissipated energy
υ – Fluid viscosity
ρ – Fluid specific weight
d – Flocs average diameter
σ– Floc strength
D_{32} – Microbubbles Sauter mean diameter

Table 7
FCF validation. Conditions: [Tanfloc SL] = 500 mg L^{-1}; pH = 7 ± 0.1

Water	TS (mg L^{-1})	TSS (mg L^{-1})	TDS (mg L^{-1})	TC (mg L^{-1})	TOC (mg L^{-1})	COD (mg L^{-1})	Turbidity (NTU)	Color (Hz)
Bus wash wastewater	643 ± 70	160 ± 30	456 ± 23	45 ± 3	20 ± 5	259 ± 40	198 ± 25	308 ± 51
ETAR treated water[a]	450 ± 37	11 ± 3	433 ± 40	62 ± 3	33 ± 3	241 ± 23	13 ± 2	65 ± 16
FCF treated water[b]	526 ± 60	12 ± 2	514 ± 54	65 ± 3	35 ± 5	231 ± 35	10 ± 4	62 ± 9

[a] Hydraulic load, 9 m h^{-1};
[b] Hydraulic load, 25 m h^{-1}.

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