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Comparative performance evaluation of two UF pilot plants at the Alto da Boa Vista WTP (São Paulo, Brazil)

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Abstract. Ultrafiltration is an emerging technology for drinking water treatment because it produces better water quality as compared with conventional treatment systems. More recently, the combination of UF technology with other processes in order to improve its performance has been observed. These associations aim to maximize the contaminants removal and reduce membrane fouling. The operational performance of contaminants removal and water production of two UF pilot plants was compared. The first plant (Guarapiranga) was fed with raw water and the second plant (ABV) with pre-treated water by the coagulation, flocculation and sedimentation processes at Alto da Boa Vista WTP (Sao Paulo, Brazil). Both units operated continuously for approximately 2,500 hours, from September/2009 to January/2010. The results showed that the ABV UF pilot plant was able to operate at higher specific fluxes (6.2 $L.d^{-1}.m^{-2}.kPa^{-1}$ @ 25°C) than Guarapiranga (3.1 $L.d^{-1}.m^{-2}.kPa^{-1}$ @ 25°C). However, the number of chemical cleanings conducted in both pilot units during the considered operation period was the same (4 chemical cleanings for each plant), which shows that the pre-treatment reduced the membrane fouling. The water quality at ABV for all the variables analyzed was better, but the feed water quality was also better due to pre-treatment. The rejection values for the different contaminants were higher at Guarapiranga mainly because of a pollution load reduction after pretreatment at ABV. Even with the better performance of the ABV UF pilot plant, it is necessary to take into consideration the complexity of the complete treatment system, and also the costs involved in the construction and operation of a full-scale treatment unit.

Keywords: ultrafiltration; drinking water treatment; pretreatment; performance comparison; pilot plant

1. Introduction

Membrane separation by ultrafiltration (UF) is an emerging technology for drinking water treatment because of the possibility to obtain better water quality in more compact water treatment plants (WTP), easier to automate with less sludge production and cost-effectiveness as compared to the conventional process (coagulation, flocculation, sedimentation and filtration). It is a potential alternative for drinking water treatment of low-quality water bodies, close to high cost land regions (*i.e.*, metropolises) (Mierzwa 2006). The UF process is capable of separating suspended solids, microorganisms and dissolved molecules with high molecular weight (2.000-400.000 $g.mol^{-1}$) considering the membrane molecular weight cutoff (Degrémont 2007). According to Cheryan (1998), drinking water treatment is potentially the major application of the UF process mainly due to the recently more stringent drinking water regulations which make the conventional water treatment process inadequate

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for some cases, especially for low-quality superficial water bodies.

The main advantages of the UF process as compared with conventional clarification are (Anselme and Jacobs 1996):

- No need for chemicals;
- Size exclusion filtration as opposed to media depth filtration;
- Good and constant quality of the treated water in terms of particle and microbial removal, regardless of the raw feedwater quality;
- Process and plant compactness;
- Simple automation.

Among the 8 main water reservoirs of the Sao Paulo Metropolitan Region (SPMR), Guarapiranga is the one most affected by pollution because it is located very close to the urbanized area, and more than 622,000 inhabitants live around it. The Guarapiranga water supply system comprises the Guarapiranga Reservoir and the Alto da Boa Vista WTP that supply almost 20% of the SPMR water demand (14 $m^3.s^{-1}$). The lack of wastewater treatment in some regions of the SPMR contributes to the Guarapiranga Reservoir contamination owing to direct contributions of wastewater and stormwater runoff. Due to the phosphorus content, the eutrophication process has taken place since 1982, impairing the performance of conventional drinking water treatment process at the Alto da Boa Vista WTP (CETESB, 2003 apud Mierzwa, 2006).

More recently, a growing association of UF technology with other treatment processes, such as coagulation, flocculation, sedimentation and adsorption, has been noticed. This approach aims to maximize the contaminants removal and to improve membrane performance, especially viewing fouling minimization. These treatment systems are called integrated systems and are used mainly when it is necessary to achieve better performances for dissolved organic compounds removal (LOZIER, 2005). According to some authors, such as Lyonnaise des Eaux (1995); Kabsch-Korbutowicz (2006); Qin *et al*. (2006); Sharp e Escobar (2006); Chen *et al*. (2007); Liang; Gong e Li (2008); Xiangli *et al*. (2008); Konieczny *et al*. (2009); and Zularisam *et al*. (2009), pretreatment with coagulation, flocculation and sedimentation, coagulation-flocculation or only coagulation for UF systems enhanced membrane flux, contaminants removal and also reduced fouling problems. The work of Konieczny *et al*. (2009) evaluated the use of three different coagulants on the performance of an ultrafiltration membrane system, in which it was demonstrated that aluminum salt coagulant in a dose of 2.9 mg $Al.L^{-1}$ resulted in the highest treatment efficiency for water production, without considering the overall system. A study developed by Zularisam *et al*. (2009), showed that the ultrafiltration performance could be improved for natural water treatment with an aluminum dosage of 3 mg $Al.L^{-1}$, at a pH value close to 5.5, which is below the pH range recommended for this coagulant. Another consideration about this study is that sludge production was not considered in the system performance evaluation. One aspect that should be mentioned about most works related to the evaluation of pretreatment processes for improving membrane system performance is that they are for laboratory scale evaluation and most of them only focus on membrane permeate production. There are few works that evaluate membranes system performance for natural water treatment for on medium or long term runs, in order to verify or confirm lab scale results as well as for a better understanding about the system behavior and performance as a whole.

Considering medium to long term membrane system evaluations, work of Mierzwa *et al*. (2008), and Arnal *et al*. (2010) demonstrated the feasibility of direct drinking water treatment using ultrafiltration. In the study developed by Mierzwa *et al*. (2008) an ultrafiltration pilot plant operated continuously for almost 3,500 hours, with a consistent performance, average permeate flux of 19.7

$L.h^{-1}.m^{-2}$, with a water recovery of 85%. Some issues about the membrane system operational procedure arised, mainly related to pretreatment options, concentrate discharge and chemical cleaning. The work of Arnal *et al*. (2010) also evaluated the performance of an ultrafiltration system for direct drinking water treatment, for approximately 6 months, but with intermittent operation, 2 hours per day, with an average permeate flux of 200 to 250 $L.h^{-1}.m^{-2}$, and a water recovery of 97%. The main issues reported in the work were related to the periodic chemical cleaning procedure. It should have be pointed out that the main difference between the permeate flux of both works is related to the membranes molecular weight cut off used in each unit, 3,500 and 100,000 Daltons, for Mierzwa *et al*. (2008) and Arnal *et al*. (2010), respectively.

Considering what was presented, a comparison of membrane performance with or without coagulation pretreatment is a relevant issue to be addressed on a research project because it could give a better understanding about the main advantages and drawbacks of each approach, considering the long term operation.

Hence, our aim was to evaluate and to compare the medium term operational performance of two UF pilot plants, one of them treating raw water from the Guarapiranga Reservoir, and the other one treating water after coagulation, flocculation and sedimentation processes at the Alto da Boa Vista WTP.

2. Materials and methods

Two UF pilot plants were installed at the Alto da Boa Vista WTP. The first one (called Guarapiranga) was fed with raw water and the other one (called ABV) was fed with water after coagulation, flocculation, and sedimentation processes. The pretreatment process applied for the ABV pilot plant was consisted of chemical addiction (ferric chloride as a coagulant), flocculation, sedimentation, and filtration, while for the Guarapiranga's pilot plant no pretreatment was applied.

For both UF pilot plants, spiral wound membranes from GE Osmonics were used. The UF membrane characteristics are (GE Osmonics 2009):

- Model: PW4040F
- MWCO: 10.000 $g.mol^{-1}$
- Material: Polietersulfone
- Chlorine tolerance: up to 5000 $mg.day^{-1}$
- Maximum operation temperature: 50ºC
- Recommended pH: Operation – 2.5 to 11
Cleaning – 2 to 11.5
- Membrane area per element: 7.9 m^2
- Typical flux: 15 – 40 $L.h^{-1}.m^{-2}$
- Typical TMP: 500 – 930 kPa
- Maximum headloss per element: 69 kPa
- Element weight : 5.4 kg
- Dimensions:
    - Length: 1.00 m
    - Diameter: 0.1 m

Each pilot plant used only one membrane element installed in a pressure vessel. Fig. 1 shows the process flow diagram for both pilot plants.

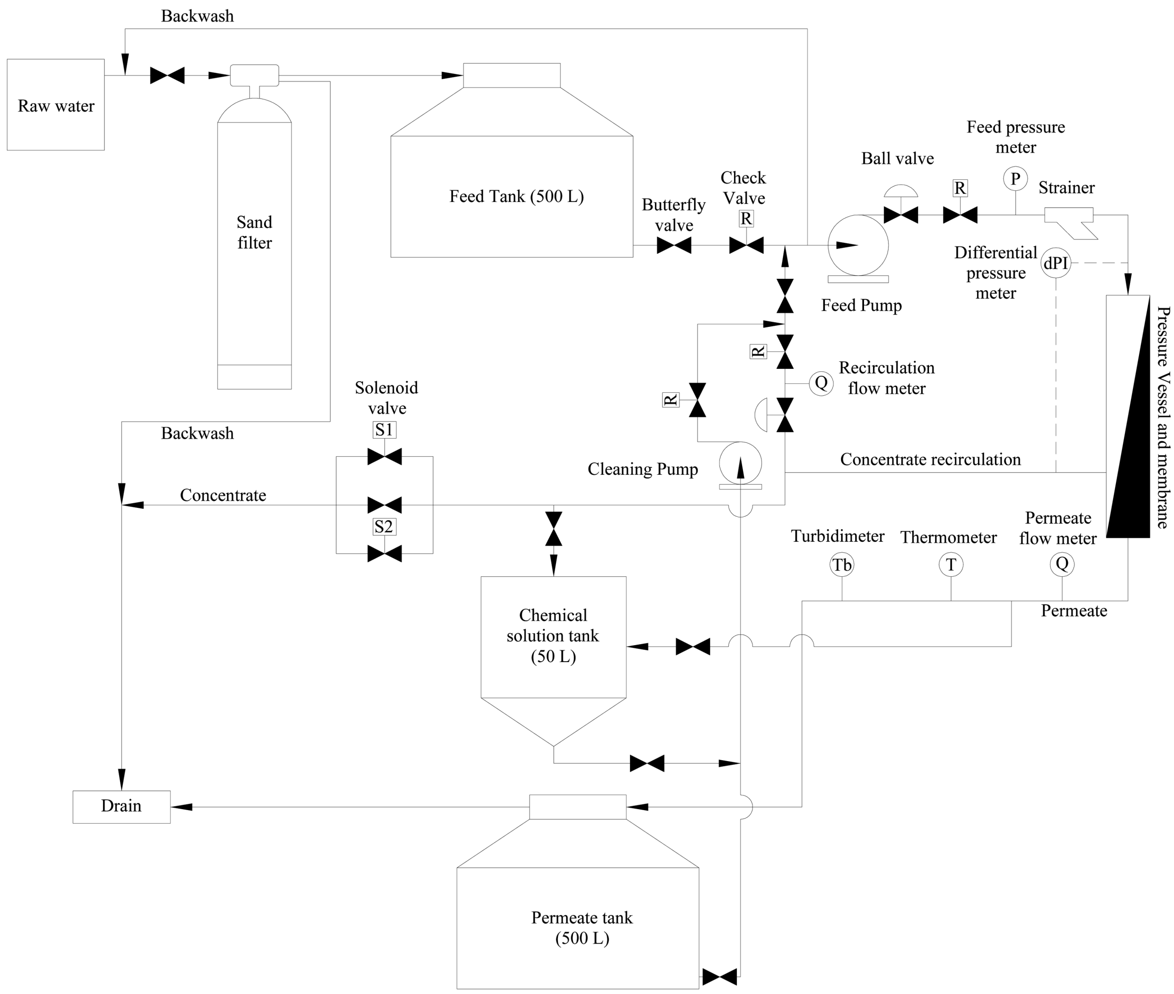

Fig. 1 Flow diagram of UF pilot plant

For assessing the UF systems performance, instruments for measuring feed pressure, membrane head loss, permeate and recirculation flows, and permeate turbidity and temperature were installed in the pilot plants. All the instruments were connected to a data logger for data acquisition and storing every 2 minutes. Once a week, the data stored in the data logger were downloaded to a notebook. The concentrate flow was determined by measuring the concentrate bleed from the system using a scaled bulk.

In the UF pilot plants, the feed water was filtered in a sand filter with 0.073 m^2 of filtration area feeding the feed tank. The maximum flow was 760 $L.h^{-1}$ approximately, which corresponded to a filtration rate of 10.4 $m^3.m^{-2}.h^{-1}$. Backwash was manually performed weekly, using water from the permeate tank through a cleaning pump for 10 minutes (backwash rate of 40 $m^3.m^{-2}.h^{-1}$).

From the feed tank, by pumping, the water went through a strainer and fed pressure vessel with UF membrane. The operation was in the cross-flow feed and bleed operation mode. The pilot plant was adjusted for a flux of 25 $L.h^{-1}.m^{-2}$, approximately, a value recommended by the membrane manufacturer. The feed pressure was controlled by valves installed at the concentrate recirculation line and feed line, using the pressure gauge installed at the feed line. A differential head loss gauge was used to measure membrane head loss. To maintain the water recovery, the concentrate was fully recirculated to membrane feed and just a portion of it was discharged periodically. Concentrate bleeding was conducted by an automatic solenoid valve S1 installed at the concentrate discharge line, and controlled by a timer, which opened the solenoid valve for 10 seconds every 10 minutes. The time was adjusted to maintain a water recovery of 90%, approximately. At the recirculation line, a flow meter was installed. Finally, permeate was discharged to the permeate tank passing through a thermometer, permeate flow meter and turbidimeter.

Every 24 hours, the pilot plants were stopped for 22 minutes, for membrane relaxation and flushing, and after that, the system started to operate for another 24-hour operation cycle. This operational procedure was developed to improve the membrane performance (Mierzwa, 2009).

The membrane chemical cleaning was scheduled to be accomplished once a month, or whenever the membrane head loss reached the limit value. The cleaning procedure was developed as follows:

1. Membrane Rinse: using 100 L of permeate through a cleaning pump;
2. Chemical cleaning solution circulation: NaOH (0.01 M), for a 30-minute period, with permeate and concentrate recirculation to the cleaning solution tank;
3. Membrane soak: 1 hour with cleaning pump off;
4. Membrane Rinse: using 100 L of permeate through cleaning pump;
5. Membrane sanitization: Circulation of peracetic acid (300 $mg.L^{-1}$) for 5 minutes;
6. Membrane Rinse: using 100 L of permeate through cleaning pump;

To evaluate the pilot plants performance in terms of water production, the data logger registered date, hour and the values of feed pressure, differential pressure, recirculation flow, permeate temperature, flow, and turbidity.

The data analysis consisted of flow normalization for a temperature of 25°C and calculation of global water recovery, water recovery by passage, transmembrane pressure, normalized flux, and specific flux.

Samples from feed and permeate were periodically collected for water quality evaluation. TOC, apparent color, turbidity, pH and UV 254 absorbance were analyzed. When applicable, the analyses were performed according to the Standard Methods for the Examination of Water and Wastewater. TOC analyses were performed using a Shimadzu TOC-V CPH analyzer. Measures of UV light absorption were made using a UV/visible spectrophotometer from Shimadzu, model UVmini-1240.

3. Results and discussion

Table 1 presents the data related to the systems operational performance, and Table 2 shows the operations periods of both pilot plants (Guarapiranga and ABV).

The results showed that the ABV pilot plant was capable of operating with significant higher fluxes (mean of 6.2 $L.d^{-1}.m^{-2}.kPa^{-1}$) than Guarapiranga (mean of 3.1 $L.d^{-1}.m^{-2}.kPa^{-1}$). This difference is attributed mainly to the pretreatment effect that enhances feed water quality, diminishing the membrane resistance for water passage and membrane fouling (Fig. 2), which is in accordance with the results presented in reviewed papers. It can be observed in Table 1 that, regardless of the flux difference between the two pilot plants, the number of chemical cleanings conducted during the total operation period was the same; this could mostly be related to the biofouling process than to the NOM fouling. Since the flow reduction due to NOM fouling is faster and results in a sharply

Table 1 Water production results

Period	System water recovery (%)		Normalized flux ($L.h^{-1}.m^{-2}$)		Normalized specific flux ($L.d^{-1}.m^{-2}.kPa$)		Transmembrane pressure (kPa)		Recovery by passage (%)		Permeate turbidity (NTU)	
	Guarap.	ABV	Guarap.	ABV	Guarap.	ABV	Guarap.	ABV	Guarap.	ABV	Guarap.	ABV
1	89,6	89,1	16,9	23,2	4,4	6,8	91,6	82,9	4,6	8,9	0,037	0,032
2	90,3	90,0	18,8	20,4	3,8	4,2	119,1	119,0	5,8	7,9	0,048	0,037
3	88,6	92,5	14,9	20,7	3,3	7,3	107,3	68,0	4,9	9,6	0,055	0,037
4	87,8	90,8	13,4	21,2	3,0	5,8	108,0	88,0	4,6	9,4	0,063	0,052
5	87,6	90,0	12,6	20,4	2,4	6,2	126,4	78,6	5,5	8,9	0,054	0,040
6	85,4	89,5	13,8	18,8	3,9	5,9	85,0	77,0	6,8	8,5	0,054	0,041
7	85,6	90,8	10,9	22,3	2,8	5,4	94,0	98,1	4,8	9,9	0,060	0,044
8	85,6	93,3	10,6	32,0	3,0	7,3	85,2	104,8	4,7	12,9	0,060	0,044
9	85,7	91,6	10,4	36,9	1,9	6,5	133,1	137,2	5,5	15,9	0,059	0,043
10	84,0	90,7	9,8	26,9	2,5	6,1	93,7	106,1	5,2	12,8	0,064	0,050
Mean	**87,0**	**90,8**	**13,2**	**24,3**	**3,1**	**6,2**	**104,3**	**96,0**	**5,2**	**10,5**	**0,055**	**0,042**

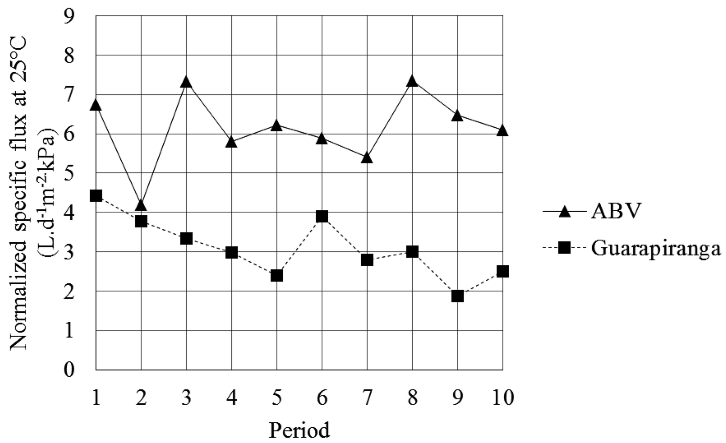

Fig. 2 Normalized specific flux

permeate flow reduction after system start up, reaching a stable value after a certain period of time, minutes to hours, as observed by Lowe and Hossain (2008), additional flux decline is gradual, most probably related to bacteria adhesion and growth. These results clearly show the influence of the coagulation process only in membrane fouling reduction. Thus, the main benefit of using the coagulation process is related to the improvement of membrane permeate flow, which will reduce the necessary membrane area. Flux variation observed in Fig. 2 had been occurred because both systems operated with constant feed pressure, which resulted in the flow decline between chemical cleanings.

Considering water recovery, both systems had the same performance, based on raw water input, because in the clarification process used at ABV there is a water loss resulting from filters backwash and sludge humidity. For both membrane systems water recovery, considering the use of spiral wound

Table 2 Operation periods

Per.	Interval		Time of operation		Observations	
	Guarapiranga	ABV	Guarapiranga (hours:minutes:seconds)	ABV (hours:minutes:seconds)	Guarapiranga	ABV
1	16/09 to 02/10/2009	20/9 to 01/10/2009	380:18:00	269:37:00		Chemical Cleaning 20/SEP/2009.
2	02/10 to 19/10/2009	01/10 to 17/10/2009	410:48:00	374:10:00		
3	19/10 to 29/10/2009	17/10 to 24/10/2009	238:24:00	154:13:00		Chemical Cleaning 17/OCT/2009
4	29/10 to 06/11/2009	24/10 to 03/11/2009	186:24:00	250:12:00	Chemical Cleaning 09/NOV/2009	Stopped operation 03/NOV/2009 due electrical problems.
5	18/11 to 27/11/2009	19/11 to 28/11/2009	214:24:00	214:26:00	Chemical Cleaning 27/11/2009. Restarted operation 01/DEC/2009	Restarted operation 19/NOV/2009 after electrical repairs
6	01/12 to 09/12/2009	01/12 to 07/12/2009	194:24:00	151:22:00		
7	09/12 to 18/12/2009	08/12 to 19/12/2009	213:36:00	275:40:00		
8	18/12 to 23/12/2009	19/12 to 24/12/2009	116:06:00	128:46:00	Stopped operation 23/DEC/2009 due piping brake. Chemical cleaning 28/DEC/2009. Restarted operation 07/JAN/2010.	Chemical cleaning 19/DEC/2009
9	07/01 to 14/01/2010	09/01 to 16/01/2010	200:30:00	167:41:00	Chemical cleaning 14/JAN/2010.	Chemical cleaning 09/JAN/2010.
10	20/01 to 08/02/2010	16/01 to 27/01/2010	452:48:00	268:41:00		
TOTAL			**2607:42:00**	**2254:48:00**	**Chemical cleanings: 4**	**Chemical cleanings: 4**

membranes is very high, but the concentrate problem still remains. One option for improving water recovery for the direct membrane treatment system is to treat the concentrate by coagulation and flocculation process and recycle it to the membrane feed tank. The advantage of this approach, compared with coagulation and flocculation pretreatment of raw water, is the reduced flow and higher contaminant concentration for the coagulation and flocculation process, which could not be applied for the ABV ultrafiltration concentrate, because most of the contaminants will not be affected by this process.

Fig. 3 shows the results obtained after the collected samples were analyzed. There were 8 pair of samples (feed and permeate) analyzed for each UF system along the operation period, showing that both systems produced water with high quality, slightly better for the ABV UF system, due to the

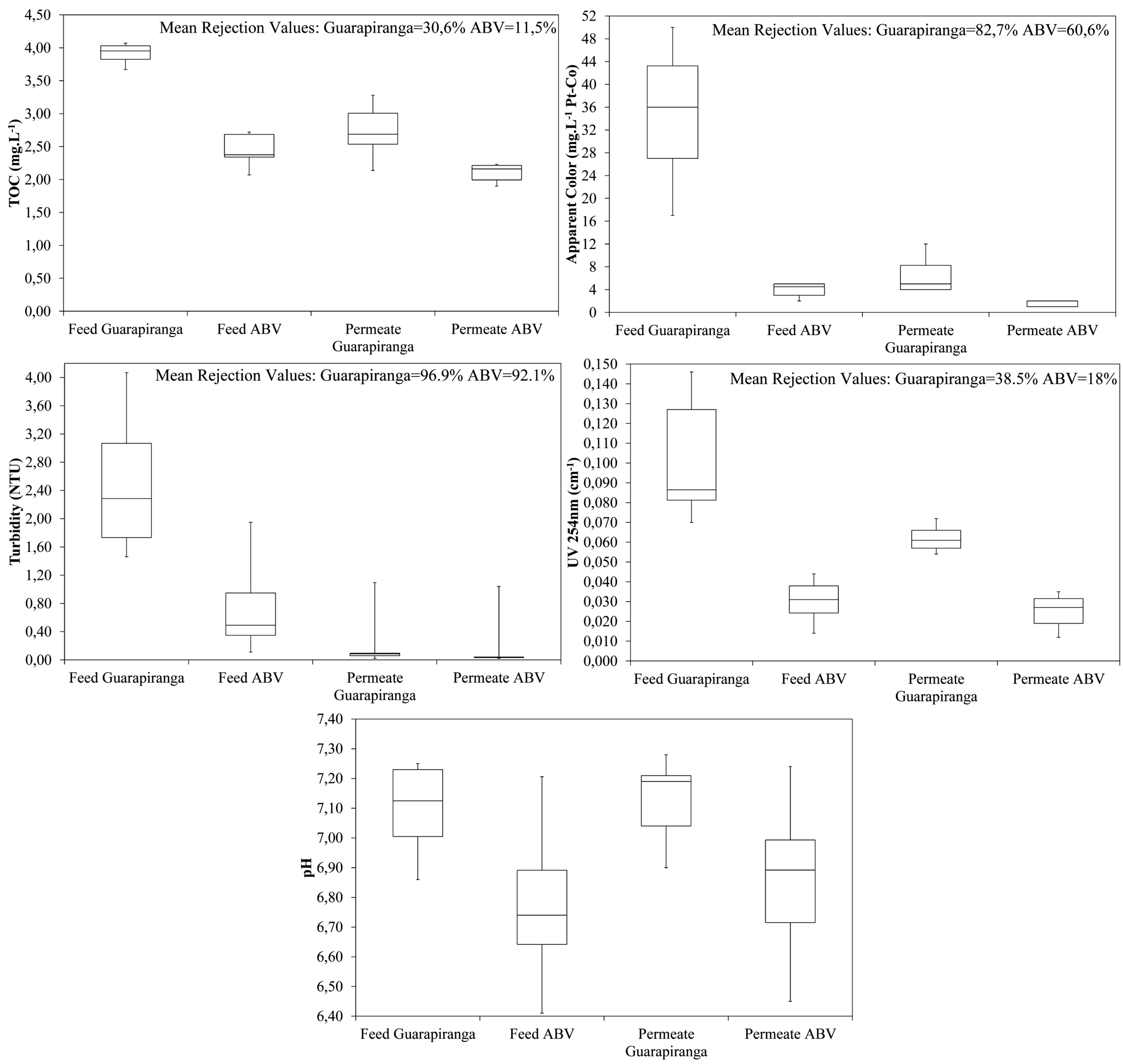

Fig. 3 TOC, apparent color, turbidity, UV absorption and pH results

better feed water quality provided by the pretreatment. However, the rejection values were higher in the Guarapiranga UF system because of the higher contaminant load.

There was an effective rejection for turbidity and the permeate was always less than 0.2 NTU. These results were similar to other studies such as Mierzwa *et al*. (2008), Qin *et al*. (2006), Choi *et al*. (2005) and according to the specialized literature, Cheryan (1998) and Anselme and Jacobs (1996), showing that UF membrane is an effective barrier for suspended solids, but can also remove dissolved organic compounds, specially NOM.

Observing the results for TOC and UV-254 nm obtained by direct membrane treatment (Permeate Guarapiranga) and by the clarification process (Feed ABV), it could be noted that they are in the same range of values, which means these processes have similar performance for TOC removal, but coagulation and flocculation are more efficient for removing compounds that absorb UV light at 254 nm wave length. However, it is important to note that this observation is based on a limited set of analyses, and a more detailed evaluation should be performed to obtain stronger evidences of this behavior.

Comparing the results for TOC and for UV light absorption for both pilot units, feed water supports the conclusion about the influence NOM on membrane fouling, and permeate production, but it is not sufficient to explain why frequencies of chemical cleaning procedures were similar, as could be observed in Table 2. This means that there are other mechanisms related to membrane permeate flux reduction, certainly biofouling.

Regardless of the application of pretreatment for the ABV, it resulted in better water quality and production; the operational cost of coagulation, flocculation and sedimentation may not justify these benefits. The operational cost of pretreatment in this case basically involves: chemical cost, sludge conditioning and disposal costs and land cost. Hence, even knowing that direct UF would need more membrane area to achieve the same water production, the additional pre-treatment cost may not justify the water quality and quantity benefits. Therefore, this evaluation must be performed case-by-case, taking into consideration factors such as water quality restrictions about specific contaminants, pretreatment cost and land availability.

According to these preliminary results, the use of coagulation pretreatment should be evaluated based on a technical and economic analysis, considering the additional membrane area necessary to have the same system productivity for direct treatment, compared to the complexity involved for installing and operating a clarification pretreatment unit, including the procedures for sludge dewatering and final disposal. Coagulation flocculation process could be an option for concentrate treatment improving a membrane treatment system water recovery.

4. Conclusions and recommendations

The results of the study showed that:

- Due to the pretreatment, which reduces membrane resistance for water passage and fouling, the ABV pilot plant was able to operate at higher normalized specific fluxes than Guarapiranga.
- The ABV permeate water quality was slightly better than that of Guarapiranga for all the water quality variables analyzed, but with no significant relevance for drinking water quality standards. However, the feed water quality at ABV was also better because of the pretreatment effects, which resulted in a reduced efficiency for contaminant rejection as compared with the results from the Guarapiranga pilot plant.

- Based on the results obtained in this study, it could be concluded that the coagulation and flocculation process only affects membrane permeability, by reducing NOM fouling effects, but does not result in any operational improvement, as compared to the unit operated without pretreatment, mainly for chemical cleaning frequencies.
- The results showed that the pre-treatment with coagulation, flocculation and sedimentation was able to enhance the UF pilot plant performance in terms of water quality and quantity. However, the associated pretreatment costs may not justify the benefits. This analysis has to be performed on a case-by-case basis, taking into account specific water quality restrictions, pre-treatment costs and land availability for implementing pre-treatment processes.

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