PULP AND PAPER MILL EFFLUENT POST-TREATMENT USING MICROFILTRATION AND ULTRAFILTRATION MEMBRANES

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The aim of this study was to assess the application of microfiltration and ultrafiltration membranes as alternatives for post-treatment of wastewater from a pulp and paper mill. Filtration tests were conducted using laboratory bench equipment. For optimizing the treatment methods, the optimal operating conditions of flow rate, pressure and backwash interval were determined for each membrane, as the first step. The performance of the microfiltration (MF)and ultrafiltration (UF) membranes was evaluated with regard to removal efficiency for true color, chemical oxygen demand (COD), turbidity, ABS254, lignin/tannin, total solids and also in relation to permeate flux. The membranes were then subjected to chemical cleaning using a hypochlorite solution. The results indicated that these membranes improved wastewater quality and the chemical cleaning of the membranes was effective.

Keywords: industrial wastewater treatment, fouling, membrane separation process, wastewater of pulp and paper mill, pollution, membrane cleaning, membrane fouling

INTRODUCTION

Pulp and paper industries (PPIs) are of great importance to the world, particularly to the Brazilian economy. In Brazil, economic statistics reveal that the paper industry is progressively increasing its exports, which contributes significantly to the national gross domestic product (GDP). According to data from the Brazilian Pulp and Paper Association,[1] Brazil stands fourth in pulp production and ninth in paper production in the worldwide rank.

In contrast to their significant contributions to the economy, PPIs also stand out as some of the most polluting industries in the world,[2] because they are a source of various solid, liquid, and gaseous pollutants. In addition, considerable volumes of wastewater are producedas a consequence of high water consumption in pulp and paper production processes. According to Eskelin *et al.*,[3] about 25 m^3 to 225 m^3 of water are consumed per ton of pulp produced; therefore, the potential pollution of water bodies by the release of this wastewater is a major concern.

Wastewater from kraft pulp industries contains high concentrations of organic matter, color, phenolic compounds of high molecular weight, and other toxic substances that can cause significant damage to aquatic environments, such as reduction in phytoplankton, toxic effects on fish, and eutrophication,[4,5] if dumped without proper pretreatment.

Wastewater treatment plants (WTPs) of PPIs usually perform a primary treatment, followed by a secondary treatment, which typically addresses biological pollutants. These treatment systems consist mainly of aerated lagoons or activated sludge processes that enable reduction of organic matter, ranging from 90 to 95% reduction in biochemical oxygen demand (BOD) and 40 to 60% in chemical oxygen demand (COD).[6] However, even with these high removal percentages, residual organic matter in wastewater may be above the acceptable limit.

Currently, conservation and reuse of water resources have emerged as important components of proper environmental management owing to the shortage of water and increasing conflicts over water usage. There is a worldwide tendency towards the development and application of advanced wastewater treatment systems that enable significant improvements in final wastewater quality by applying standards that are becoming increasingly restrictive,[7] or enabling the reuse of treated wastewater in the production process itself, or in other beneficial uses rather than discharging it into water bodies. Furthermore, membrane separation processes (MSP) are potential options for wastewater treatment in pulp and paper mills.[8]

The membrane separation technique involves passing water through a synthetic membrane in order to remove solid particles of small diameter, such as organic and inorganic molecules, bacteria, and viruses, without biological and chemical transformation during the filtration. Microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), and electrodialysis (ED) are the most commonly used separation techniques; the difference between these techniques lies in their capacity, form of separation of the pollutants, and the type and intensity of the driving force used to promote separation.[9]

In the fields of water and wastewater treatment, the use of membranes has intensified, owing to its numerous advantages, such as the possibility of obtaining high-quality wastewater that can be used for different purposes in compact, automated, and modular treatment facilities. Nowadays, the cost of membrane systems is competitive compared to other conventional treatment systems.

However, the economic operation of membrane systems depends on the capacity to which the permeate can be operated at the lowest possible pressure for long periods without reducing efficiency. Thus, compression and reversible or irreversible accumulation of materials on the surface of membranes are relevant factors,[9] since fouling of membranes increases resistance to filtration and leads to an increased demand for energy and higher cleaning frequency and consequently to increased consumption of chemicals and operational costs. The amount of permeate flux during the entire operation period can be affected by other factors, besides the fouling of membranes, such as those related to the feed system, filtration module, porosity of the membrane, and operating conditions (operation pressure and flow rate).[10] Some measures can be taken to reduce fouling of membranes, including optimization of operation conditions, such as permeate flux, feed flow rate near the membrane surface, operating pressure, backwash, and chemical cleaning.

To this end, this research is aimed at the post-treatment of wastewater from a pulp and paper mill in a separation system using microfiltration and ultrafiltration membranes in order to improve the final quality of the permeate through optimization of the operational parameters of the filtration unit.

EXPERIMENTAL

Material and methods

In this study, wastewater from a large pulp and paper mill in Brazil was used for analysis. The treatment plant uses a biological treatment system of activated sludge, and the wastewater sample was collected at the exit of the secondary decanter. The collection and preservation of samples were carried out according to standard NBR9898.[11]

The research involved two steps. In Step I, ideal operating conditions of the MF and UF membranes were determined by investigating the flow rate, operating pressure, and backwash frequency. In Step II, the efficiency of the membranes for wastewater treatment was assessed. For characterizing raw wastewater, as well as MF and UF permeates, physicochemical analyses of turbidity, true color, total solids, chemical oxygen demand (COD), pH, absorbance at 254 nm wavelength (ABS_{254}), and lignin/tannin were performed, in compliance with the Standard Methods for the Examination of Water and Wastewater.[12]

A pilot unit of MF and UF membranes was employed with a diaphragm type pump that operates at pressures up to 4 bar and pumps the wastewater from a polypropylene storage tank with 10 L capacity towards the permeation module. The equipment is based on the principle of tangential filtration, with the filtration occurring from the outside to the inside of the hollow fibers of the membrane (Fig. 1).

The membrane modules were fed through the interior of pressurized castings, collecting the permeate in the hollow fibers at the end of the modules, as opposed to the feed. The MF membrane consisted of polyetherimide with an average pore size of 0.4 µm, and the UF membrane consisted of polyether-sulphone with 50 kDa cut-off; both membranes possessed a filtering area of 0.090 m² and packaging density of 1000 m²/m³. Both membranes were produced by simple extrusion, using the technique of phase inversion by immersion and precipitation.

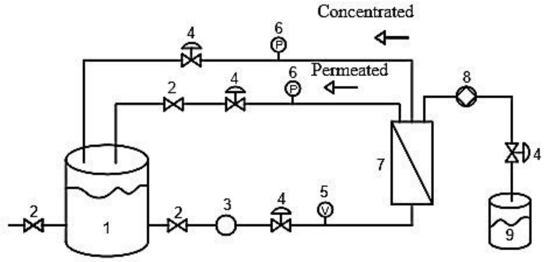


Figure 1: Schematic illustration of the microfiltration/ultrafiltration system

Hydraulic permeability and chemical cleaning of membranes

For determining the hydraulic permeability of the membrane (Lp), filtration tests were performed using distilled water under varying transmembrane pressures (TMP). From the plotted values of permeate flux versus TMP, a straight-line equation was obtained, whose slope represented the hydraulic permeability value of the membrane.

Lp could be calculated to determine whether the membranes required cleaning as well as to evaluate the efficiency of the method. For each filtration test, Lp was investigated and measurements were carried out before the filtration period and after chemical cleaning. After each test, the membranes were subjected to chemical cleaning, keeping the membranes submerged in a solution of sodium hypochlorite at a concentration of 1g/L for a period of 1 h.

Step I – Effect of operating conditions on permeate flux

The effect of operating conditions on permeate flux was assessed by monitoring the flux profile during the operation of the system under different conditions. The Reynolds numbers were 1226, 1653, and 2043, for inflows of 72, 96, and 144 L/min, respectively. At the end of each test, the removal efficiencies for turbidity and COD by the membranes were assessed. These tests were conducted under a pressure of 1 bar.

The operating pressure was optimized by analyzing the critical flow profile. Critical pressure was determined by analyzing increments in pressure and monitoring permeate flux throughout the operation. Based on Amaral *et al.*[13] five operating pressures were adopted for investigating critical pressure: 0.5, 0.75, 1.0, 1.25, and 1.5 bar. Permeate flux was regularly measured with a time interval of 15 min for each pressure test, totaling 75 min of operation.

Backwash tests were performed to verify the permeate flux recovery in contrast to the physical cleaning operation of membranes, with a time interval of 10 min of backwash with pulses of 30 and 60 s under a pressure of 1 bar. Backwash pulses were controlledusing a metering pump.

Step II – Efficiency assessment of MF and UF membranes

After obtaining suitable conditions of flow rate, operating pressure, and backwash, wastewater (referred to as raw wastewater) was passed through the MF and UF membranes, which were subjected to hydraulic permeability tests before the filtering tests and after the chemical cleaning.

In order to assess the effectiveness of the treatments used, the permeate flux and the removal efficiency of several parameters were investigated (COD, turbidity, and true color) in samples of permeate throughout the filtration period, every 20 min for 2 h of operation. pH, lignin/tannin, ABS_{254}, and total solids were analyzed in samples of the permeate, after 2 h of operation.

Statistical analysis of data

To determine ideal operating conditions for the MF and UF membranes (Step I), analyze the effect of flow velocity, and estimate the backwash effect on permeate flux, a nested analysis of variance (ANOVA) was used, with the factors being membrane type (MF and UF) nested in operation time (period). In this step, the influence of the Reynolds number on the quality of the permeate was assessed through COD and turbidity parameters (dependent variables). Thus, we used a completely randomized design (CRD), made up of two dependent variables and the Reynolds number factor (Re_1, Re_2 and Re_3). The effect of the backwash permeate flow was also examined with a nested experimental design analysis of variance (ANOVA) with two factors, of which the main factor was the operation time and the second factor was the membrane type.

To assess and compare the performances of the MF and UF membranes in wastewater treatment, two different statistical methodologies were used. The parameters, permeate flux, COD, true color and turbidity, used for the operation test, were analyzed and compared through a nested design with two factors (membrane type nested inside operation time parameter). The parameters analyzed at the end of the test (lignin/tannin, ABS254nm, pH, and total solids) were compared by applying the Student's *t*-test for independent samples.

In order to evaluate the effectiveness of the chemical cleaning of the membranes, a Student's t-test was applied to independent samples; this being the slope of the line generated by hydraulic permeability before the filtration period and after the chemical cleaning of the membranes was considered.

All data were checked beforehand for normality and homogeneity of variances using the Kolmogorov-Smirnov's and Bartlett's tests, respectively.[14] The difference between the averages was estimated using the post-hoc Tukey test. The significance level for all tests, which were repeated three times, was 5%. Statistical analyses were performed using Statistica software ® (version 6.0).

RESULTS AND DISCUSSION

Step I: Investigation of ideal operating conditions for MF and UF membranes

Effect of flow rate on permeate flux

Figure 2 shows the relationship between permeate flux and operation time for different flow rates. Permeate flux did not remain constant and tended to decrease for both UF and MF with time. This result is expected in these systems because of the accumulation of solids on the membrane surfaces.

In the UF, the increased turbulence in the system didnot affect the permeate flux values significantly because flux values did not differ statistically from other examined flux profiles, despite the Re_3 (Table 1) contributing to greater flux values throughout the filtering time. In the MF membrane, flow hydrodynamics affected the permeate flux values. During 15 min of operation, the Re_3 contributed to flux values significantly more than other Reynolds numbers, because higher flow rates in regions close to the membrane surfaces create shear forces sufficient for removing at least a part of the retained solid material by promoting favorable conditions for cake reduction and, consequently, higher permeate flux values. According to Chang and Fane[15] and Ueda *et al.*,[16] turbulence promotes movement of the hollow fibers in the membranes, which is also favorable for filtration and the minimization of fouling.

For all the studied flow hydrodynamics, the permeate flux values for the MF membrane were significantly higher than those for the UF (Fig. 2), which could be explained by the larger average pore diameter of the MF membranes than those of the UF, enabling higher permeate flux under the given applied pressure.

In order to investigate the final quality of permeate obtained from different values of Reynolds numbers, COD and permeate turbidity were analyzed at the end of the operation. Turbidity values obtained using ANOVA for MF and UF were $F_{2\text{-}8}$(15.75; p= 0.0045) and $F_{2\text{-}8}$(13.75; p= 0.005), respectively; COD values for MF and UF were $F_{2\text{-}8}$(12.5; p = 0.0073) and $F_{2\text{-}8}$ (24.07; p = 0.0014), respectively.

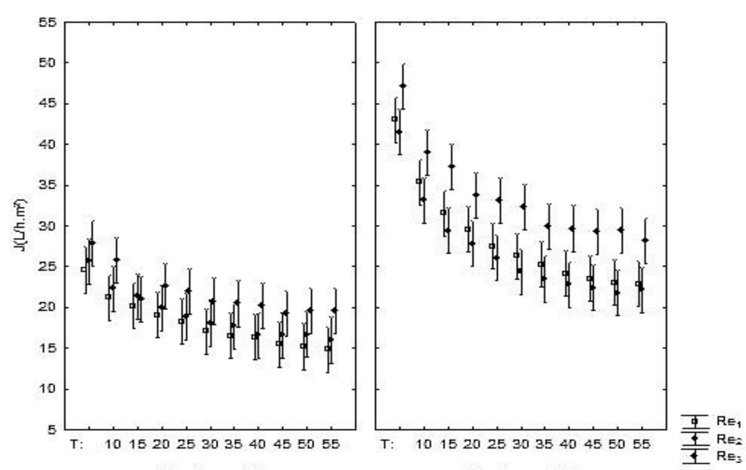
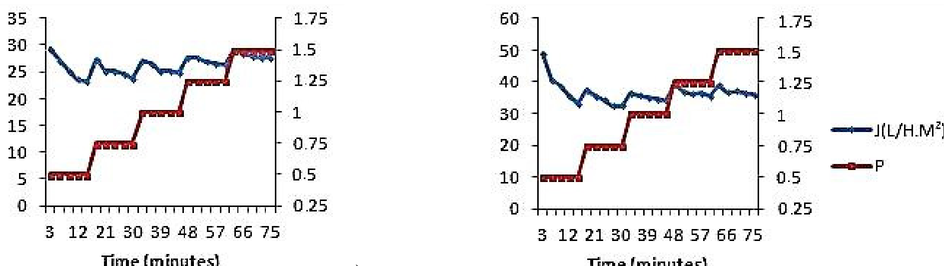


Figure 2: Plots of permeate flux *versus* operation time for different flow rates through the membranes (p = 1 bar)

Table 1
Results of Tukey test for turbidity and COD removal using MF and UF under different flux regimes

Parameter	Reynolds number	Turbidity and COD averages[a], and standard deviations		Raw wastewater
		MF	UF	
Turbidity (NTU)	$Re_1 = 1226$	0.85b ± 0.083	1.07b ± 0.24	221
	$Re_2 = 1653$	0.56a ± 0.13	0.55b ± 0.03	
	$Re_3 = 2043$	0.46a ± 0.02	0.49a ± 0.06	
COD (mg/L)	$Re_1 = 1226$	259.6b ± 10.6	231.6b ± 9.6	948
	$Re_2 = 1653$	255ab ± 18.2	210.3b ± 2.52	
	$Re_3 = 2043$	184.3a ± 24.0	163.3a ± 18.9	

[a] averages followed by the same letter are not different



a) b)

Figure 3: Critical flux for (a) UF and (b) MF membranes

The results of the statistical tests used in this step (CRD) revealed a significant difference between the averages of the parameters observed at different flux regimes. For both MF and UF, the flow hydrodynamics significantly influenced the removal of COD and turbidity from the wastewater (both $p < 0.05$). These results showed that increased turbulence in the system led to improvements in the performance of the membranes. Thereafter, an average test aimed at verifying statistical differences between the averages was conducted. From the results obtained in this step, $Re_3$was selected for application to the remaining tests in this study. These results are presented in Table 1.

Operating pressure

Figure 3 shows the results of the experiment for determiningthe critical flux obtained for the UF and MF membranes.

According to Figure 3, the critical flux was not explicitly reached within the assessed limits, this because it was not possible to identify a sudden decline in the flux within the tested pressure ranges, in other words, the permeate flow drops showed similar profiles during pressure variations. For both the MF and UF, an initial increase (although of little significance) in permeate flux was observed with increased pressure. The flux in the membrane increased and then decreased rapidly with increases in pressure; the permeate flux continuously decreased within each analyzed pressure. Benhabiles *et al.*[17] reported that any increase in operating pressure results in a temporary increase of permeate flux. According to Hong *et al.*[18] and Benhabiles *et al*.[17] the accumulation of solid materials on the membrane surface increases proportionately as pressure increases, since more sedimentary particles settle on the membrane.

A pressure of 0.75 bar was selected to continue the experiments of MF and UF, because larger values of applied pressure incur high system operation costs, especially in full-scale units, while showing no significant increase in permeate production.

Effect of backwash frequency on permeate flux

To determine backwash frequency, tests were performed every 10 min with washing processes lasting 30 and 60 s, which were sufficient for re-establishing the permeate flux for UF during the entire period of operation. Figure 4 shows the results of the backwash tests.

The backwash dragged solid particles along the membrane surface, and consequently, reduced fouling. Amaral *et al.*,[13] Chang *et al.*,[19] and Côté *et al.*[20] showed that for permeate flux recovery it is necessary to minimize fouling. In this manner, the backwash was implemented to enable cake removal, and improve the condition of the permeate flux.

Although the technique used in this study enabled flux recovery, when comparing the results for different times of backwash pulses (Fig. 4), increasing the backwash time from 30 s to 60 s did not result in any significant difference in permeate flux. The average permeate flux for the MF operation for 30 s was 96.26 $L.m^{-2}.h^{-1}$, while the average flux of operation for 60s was 94.60 $L.m^{-2}.h^{-1}$; for the UF, these values were 54.3 and 44.16 $L.m^{-2}.h^{-1}$ for 30 s and 60 s, respectively. These results suggest that the use of backwash for 30 s every 10 min was more effective because it incurred less loss of permeate production, while achieving the same flux recovery.

Step II – Efficiency of MF and UF in wastewater treatment

Wastewater characterization

The results of physicochemical characterization of Kraft raw wastewater subjected to treatment by the MF and UF membranes are shown in Table 2.

Permeate flux analysis for color, COD and turbidity using MF and UF for kraft wastewater

Figure 5 shows the flux profiles of the permeate and the results of residual color, COD and turbidity after filtering.

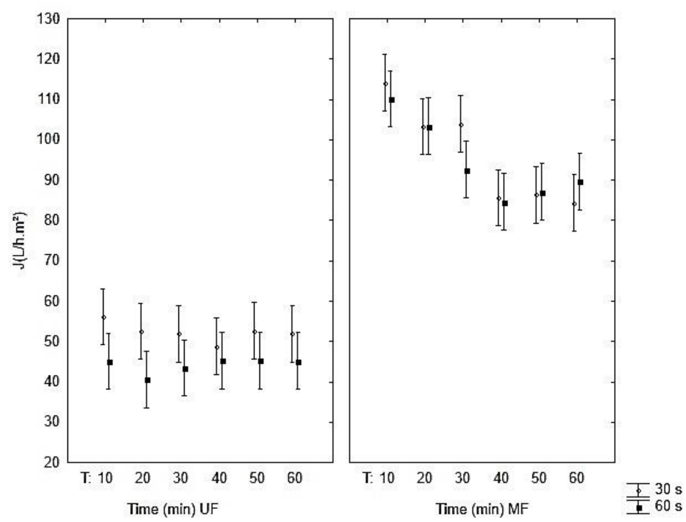


Figure 4: Permeate flux profiles for different modes of backwash operation

Table 2
Characterization of raw wastewater samples subjected to MSP

Parameter	Concentration
Turbidity	221 NTU
COD	948 mg/L
Total solids	1918 mg/L
Total suspended solids	171 mg/L
ABS_{254nm}	7.049
True color	2963 uC
Apparent color	4049 uC
Lignin/tannin	95 mg phenol/L
pH	7.88

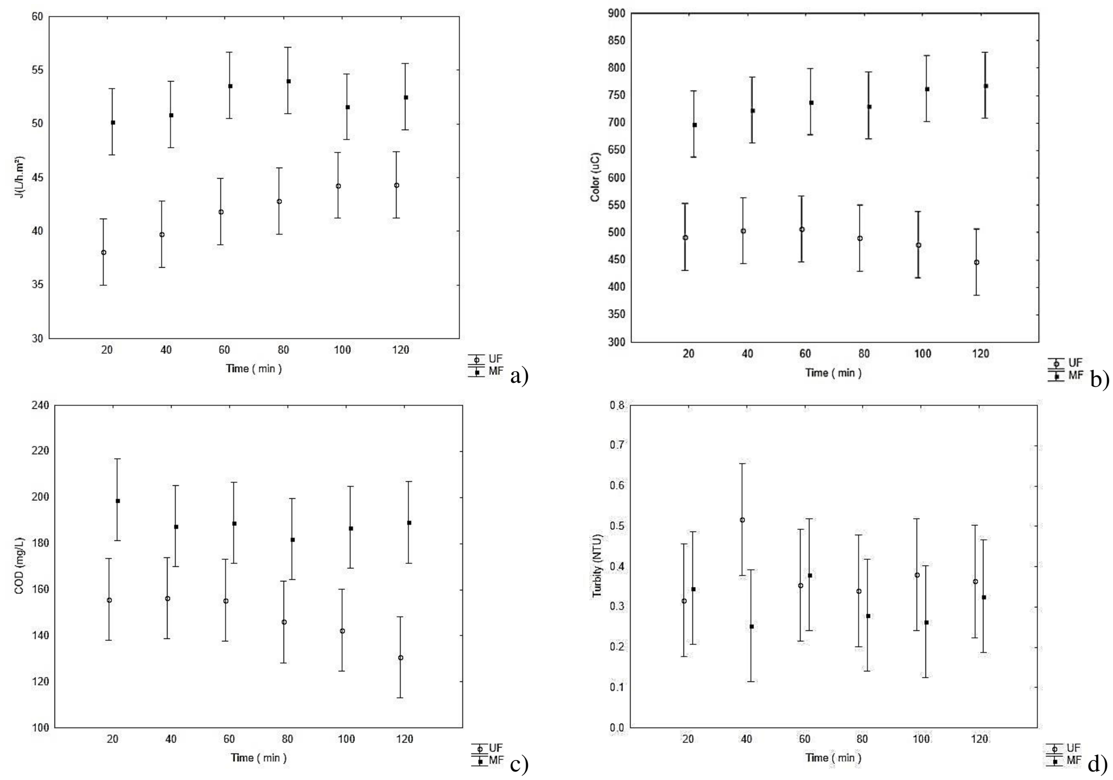


Figure 5: Parameters analyzed after the operation of MF and UF systems: (a) permeate flux ($L.m^{-2}. h^{-1}$),(b) true color (uC), (c) COD (mg/L), and (d) turbidity (NTU). The points refer to the average values of three replicates and the bars represent average significant difference

According to Figure 5 (a), the flux behavior and significant differences over the operation of the MF and UF systems can be observed. The average rates of flux for the MF and UF were 52.2 $L.m^{-2}. h^{-1}$ and 41.2 $L.m^{-2}.h^{-1}$, respectively. The permeate flux remained almost constant in the two membranes until the end of the experiment, indicating that there was no significant fouling or formation of cake. Therefore, it can be inferred that the backwash and the tangential flux enabled the maintenance of the flux rate of the permeate throughout the period of operation, suggesting that the fouling in both MF and UF was mainly due to clogged pores and formation of cake.

The results of this experiment showed that it is possible to operate the MF and UF membranes at a stable flux without increasing the TMP. Under these circumstances, the fouling tendency was small, and the optimization of factors such as hydrodynamics, pressure, and backwash all contributed to this result.

As shown in Figure 5 (b), 84% of true color was removed on average with UF and 75% with the MF. Moreover, the MF and UF membranes differed statistically with regard to color removal at all operation times, UF exhibiting higher performance.

Bertazolli and Pelegrini[21] reported the importance of removing effluent color, as this can affect the photosynthetic activities in rivers and lakes, causing changes in aquatic biota, especially in the vicinity of the discharge. Khosravi *et al.*[22] evaluated the use of nanofiltration in the treatment of pulp and paper effluent. The operating conditions were as follows: tangential velocity of 1 to 1.3 m/s, corresponding to a Reynolds number within a range of 750-1200 at 17 and 40 °C, wherein five different membranes (each with an area of 0.036 m²) were tested simultaneously. All membranes achieved more than 99% color removal at both temperatures, and the value of color in the collected permeate was generally less than 10uC.

The average COD removal by the UF and MF was 84.3% and 80%, respectively (Fig. 5(c)). Sun *et al.*[23] reported that membrane separation processes contribute more significantly to COD removal compared to gravitational sedimentation. Therefore, membranes act as barriers to the passage of particles and macromolecular components of wastewater, ensuring low concentration of organic matter in the permeate.

The most commonly used treatment method in the pulp and paper industries is still the biological system. According to Bryant *et al.*[6] pulp treatment systems (activated sludge or aerated lagoons) achieve average reductions of 90 to 95% for BOD, but only of 40 to 60% for COD, showing the need for additional post-treatment, besides the biological treatment process, to meet the emission standards of most countries.

According to the results shown in Figure 5 (d), 99% of turbidity was removed in the two treatment methods used. The results also showed that the values of turbidity in the permeate collected did not vary significantly between the MF and the UF, indicating that the MF was sufficient for efficient particle removal from the wastewater.

Analysis of removal of lignin/tannin, ABS_{254nm} and total solids using MF and UF membranes

A composite samplewas characterized for the removal of lignin/tannin, pH, and total solids after treatment for 120 min using the MF and UF systems (Table 3).

The UF membrane allowed lignin removal of 82.5% from the wastewater, while the MF membrane allowed 76.5%. These values of removal are statistically different ($p<0.05$); that is, the UF membrane was significantly more effective than the MF in lignin removal.

Bhattacharjee and Bhattacharya[24] studied ultrafiltration of black liquor, which is known for containing high concentrations of lignosulfonate organic compounds, in a pulp and paper mill. The y achieved 75% lignin removal at a TMP of 8 $kg.cm^{-2}$.

Using the wastewater from the secondary clarifier of a WTP of a pulp and paper mill, Quartaroli[25] achieved 60% of lignin removal through microfiltration with a final concentration of lignin at 23.5 mg phenol/L. The operating conditions for the microfiltration unit were as follows: pressure on the membrane of 0.25 MPa, backwash pressure of 0.3 MPa, backwash interval of 10 min, and tangential inflow rate of 3.9 m/s.

Because organic matter possesses the ability to absorb ultraviolet radiation, the absorbance of a sample at a wavelength of 254 nm becomes a potential parameter for indirect determination of organic carbon present in the effluent.[26]At a wavelength of 254 nm (Table 3), 73.6% of absorbance was reduced by UF and 56.4% by MF. This reduction may be due to the removal of compounds with double and triple bonds (aromatics), indicating elimination of complex organic compounds. The UF membrane removed approximately 13% more aromatics than the MF membrane, and according to the t-test, the absorbances of the permeates from the MF and UF were different from each other. These results may indicate the application of advanced oxidative processes during the post-treatment of wastewater for further reduction of aromatic compounds. Some studies have already tested this configuration.[27-28]

As shown in Table 3, the membranes behaved in a similar manner in the removal of total solids, with no significant differences between the MF and UF membranes. Similar results were found by Kuritza,[29] who achieved a reduction of 40% of total solids using tangential microfiltration in the wastewater treatment of a pulp and paper mill. The operation conditions were as follows: applied pressure on the membrane of 0.25 MPa, backwash pressure of 0.3 MPa, backwash interval of 10 min, tangential inflow rate of 3.9 m/s, flow rate of feed pump of 6.6 L/min, and average operating temperature of 30°C.

Table 3
Student's *t*-test results for efficiency of lignin/tannin removal, pH value and total solids after MF and UF filtration

Analyzed parameter	Concentration of raw wastewater	Concentration in UF sample	Removal (%)	Concentration in MF sample	Removal (%)	*T*	Value of P[a]
Lignin/tannin	95	16.63 ± 0.85	82.5	22.33 ± 1.44	76.5	5.88	0.0[a]
pH	7.88	8.64 ±0.03	-	8.62 ± 0.005	-	0.10	0.9
TS	1918	1016 ± 65.12	47	1021 ± 33.07	46.7	0.97	0.3
ABS_{254nm}	7.49	1.86 ± 0.02	73.6	3.07 ± 0.56	56.44	4.42	0.0[a]

[a]significant to 5% of error probability through the *t*-test

Table 4
Values of hydraulic permeability coefficients of UF and MF membranes ($L.m^{-2}.h^{-1}.bar^{-1}$) before the filtration period and after chemical cleaning

Treatment	Average and standard deviation of Lp before the filtration period	Average and standard deviation of Lp after chemical cleaning	T	P[a]
MF	14.72a[b] ± 1.63	14.01a[b] ± 0.89	0.66	0.544
UF	6.95a[b] ± 0.48	6.73a[b] ± 0.31	0.65	0.55

[a] significant to 5% of error probability, by *t*-test;[b]Averages followed by the same letter are not different

Efficiency analysis of chemical cleaning of membranes

Chemical cleaning was performed to assess the recovery of the membrane filtration capacity. According to Mota,[30] the optimization of the physical cleaning procedures and application of other techniques to minimize the formation of the cake layer are essential to ensure the success of the MSP.The hydraulic permeability of the membranes (Lp) was determined before experiments and after every cleaning procedure. Table 4 shows the results of average values of hydraulic permeability of the membranes.

As shown in Table 4, chemical cleaning of membranes resulted in the recovery of the hydraulic permeability, because there were no statistical differences in the hydraulic permeability of the membranes before the experiment and after chemical cleaning ($p > 0.05$), showing that fouling did not occur, but cakes were formed.[31]

According to Mota,[30] chemical cleaning can be classified into maintenance and recovery cleaning. Maintenance cleaning is performed frequently using solutions, usually of sodium hypochlorite, in low concentrations, while recovery cleaning is performed when the fouling is severe and permeability cannot be recovered by maintenance cleaning. Highly concentrated chemical solutions are used in this case.

In this research, recovery cleaning was not required because maintenance cleaning was sufficient for the removal of clogs and the recovery of the hydraulic permeability of the membranes.

CONCLUSION

Considering the respective average removal of 84% and 75% of true color and 84.3% and 80% of COD from the wastewater by using the UF and MF membranes, it can be concluded that the MF and UF membranes are very efficient alternatives for advanced treatment of wastewater generated in pulp and paper mills. In addition, 82.5% and 76.5% of lignin was removed from the wastewater using the UF and MF membranes, respectively. The reduction in turbidity was 99% for both membranes.

Analyzing the results obtained in this study, the UF membrane showed higher performance in the removal of COD, true color, lignin/tannin, and ABS_{254}.The optimization of operation parameters for the system was extremely important for increasing the success rate of the treatment. The best performance of filtering operations was obtained by applying Re_3 (2043), under a critical pressure of 0.75 bar and backwash for every 10 min with a pulse of 30 s. The method of chemical cleaning of the membranes with sodium hypochlorite was shown to be effective.

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REFERENCES

[1] BRACELPA – Brazilian Association of Pulp and Paper, Annual Report 2013/2014, available at: <http://www.bracelpa.org.br/shared/iba_2014_pt.pdf>, accessed: March 20, 2014.
[2] M. Ali and T. R. Sreekrishnan, *Adv. Environ.Res.*, **5**, 175 (2001).
[3] K. Eskelinen, H. Särkkä, T. A. Kurniawan and A. Sillanpää, *Desalination*, **255**, 179 (2010).
[4] CETESB – Environmental Sanitation Technology Company, Environmental Technical Guide for the Pulp and Paper Industry, P + L series,vol. 1, 2008.
[5] P. A. Soloman, A. C. Basha, M. Velan, N. Balasubramanian and P. Marimuthu, *Sep. Purif. Technol.*, **69**, 109 (2009).
[6] C. W. Bryant, J. J. Avenell, W. A. Barkley and R. N. Thut, *Water Sci. Technol.*,**26**, 417 (1992).
[7] L. Serrano, A. Ferrer, J. Labidi and A. Rodríguez, *Cellulose Chem. Technol.*, **48**, 557 (2014).
[8] T. F. L. Asano, H. Burton, R. Leverenz and G. T. Tsuchihashi, "Water Reuse: Issues, Technologies and Applications", McGraw-Hill, New York, 2007.
[9] M. A. P. Reali, L. P. Sabogal and L. A. Daniel, in "Environmental Engineering: Concepts, Technology

and Management", edited by M. do Carmo Calijuri and D. Gasparini Fernandes Cunha, Elsevier, Rio de Janeiro, 2013.

[10] N. Ghaffour, M. W. Naceur, N. Drouiche and H. Mahmoudi, *Desal. Water Treat.*, **5**, 159 (2009).

[11] ABNT – Brazilian Association of Technical Standards, NBR 9898: Preservation and Sampling Techniques of Liquid Effluents and Receiving Waters, vol. 1, 1997.

[12] APHA – American Public Health Association, Standard Methods for the Examination of Water and Wastewater, 21st ed., APHA, AWWA, WEF, Washington, DC, 2005.

[13] M. C. S. Amaral, H. L. Andrade and C. L. Lange, *J. Sanit. Environ. Eng.*, **18**, 65 (2013).

[14] J. H. Zar, "Biostatistical Analysis", Prentice Hall, New Jersey, 1999.

[15] S. Chang and A. Fane, *Filtr. Separat.*, **39**, 26 (2002).

[16] T. Ueda, K. Hata, Y. Kikuoka and O. Seino, *Water Res.*, **3**, 489 (1997).

[17] M. S. Benhabiles, N. Abdi, N. Drouiche, H. Lounici, A. Pauss *et al.*, *Mat. Sci. Eng. C*, **32**, 922 (2012).

[18] S. P. Hong, T. H. Bae, T. M. Tak, S. Hong and A. Randall, *Desalination*, **143**, 219 (2002).

[19] I. S. Chang, P. Le-Clech, B. Jefferson and S. Judd, *J. Environ. Eng.*, **128**, 1018 (2002).

[20] P. Côté, H. Buisson, C. Pound and G. Arakaki, *Desalination*, **113**, 189 (1997).

[21] R. Bertazzoli and R. T. Pelegrini, *Quím. Nova*, **25**, 477 (2002).

[22] M. Khosravi, G. B. Gholikandi, S. A. Bali, R. Riahi and R. H. Tashaouei, *Water Res. Manag.*, **25**, 2989 (2011).

[23] D. D. Sun, C. T. Hay and S. L. Khor, *Desalination*, **195**, 209 (2006).

[24] C. Bhattacharjee and P. K. Bhattacharya, *Sep. Purif. Technol.*, **49**, 281 (2006).

[25] L. Quartaroli, Master's Thesis in Forest Sciences, Universida de Estadualdo Centro Oeste, Irati, 2012.

[26] S. Fogelman, M. Blumenstein and H. Zhao, *Neural Comp. Appl.*, **5**, 203 (2006).

a. A. Matilainen and M. Sillanpää, *Chemosphere*, **80**, 351 (2010).

[27] E. C. Werta, F. L. Rosario-Ortiza, D. D. Druryb and S. A. Snyder,*Water Res.*, **41**, 1481 (2007).

[28] Y. Zhao, J. M. Boyd, M. Woodbeck, R. C. Andrews, F. Qin *et al.*, *Environ. Sci. Technol.*, **42**, 4857 (2008).

[29] J. Kuritiza, Master's Thesis in Forest Sciences, Universidade Estadualdo Centro Oeste, 2012.

[30] V. F. T. B. Mota, Master's Thesis in Sanitation, Environment and Water Resources, Universidade Federal de Minas Gerais, 2012.

[31] F. Meng, S. R. Chae, A. Drews, M. Kraume, H.-S.Shin *et al.*, *Water Res.*, **43**, 489 (2009).