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Internal versus external submerged membrane bioreactor configurations for dairy wastewater treatment

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ABSTRACT

Two submerged membrane bioreactor (SMBR) configurations, one with the membrane module internal (SMBRi) and the other one external (SMBRe) to the biological tank, were used for the treatment of dairy industry effluent and evaluated in terms of pollutant removal capacity and fouling, focusing on the production of soluble microbial products (SMP) and extracellular polymeric substances (EPS). Both the MBRs presented excellent chemical oxygen demand (COD) removal efficiency (98% average), color (98%), and nutrients (86% for total nitrogen and 86–89% for total phosphorus); however, it was shown that shearing caused by the sludge recirculation pumps in the SMBRe reduced biomass growth considerably. The SMBRe presented better performance in terms of fouling than the SMBRi, which was associated with the higher concentration of suspended solids and SMP and EPS in the SMBRi. The SMP concentrations (mgSMP/gMLVSS) were superior in the SMBRe, showing that the friction from recirculation pumps leads to the breakdown of flocs and/or cells and to the release of polymeric material into the mixed liquor. Since this effect was more intense for SMP quantified in terms of extracellular transparent polymers, the conclusion was that apparently these substances participate in cellular metabolism in a different way than the carbohydrates and proteins, and that these can be more associated with released substances due to shear stress.

Keywords: Submerged membrane bioreactor (SMBR) configuration; Fouling; Soluble microbial products (SMP); Extracellular polymeric substances (EPS); Dairy wastewater

1. Introduction

The liquid effluents generated in dairy production processes have elevated levels of organic matter, fat, suspended solids, and nutrients, and are considered these industries' main source of pollution [1]. However, several problems during the conventional treatment of these effluents, which normally includes primary treatment for suspended solids and fat removal and secondary biological treatment, have been reported. These problems are related to the elevated production of scum, low sludge settleability, difficulties in removal of nutrients (nitrogen and phosphorus), and problems in the degradation of fat, oils, and other specific types of pollutants [2,3]. Taking

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these difficulties into consideration, membrane bioreactors (MBRs) are considered as a promising process for dairy wastewater treatment.

The MBRs consist of systems for effluent treatment that associate biological reactors with membrane separation processes, usually micro- or ultrafiltration. The application of MBRs for wastewater treatment and reuse has rapidly grown in the last decades due to their advantages in comparison to conventional systems. These advantages include the fact that they are rather compact systems with the capability to generate treated effluents of high quality and free from suspended solids that are independent of sludge settleability characteristics. Furthermore, MBRs can operate with high solid retention times, reducing sludge treatment and disposal costs [4].

Despite the high potential of the application of MBRs for the treatment of effluent from dairy industries, there are only few articles published in scientific journals dealing with this application. The papers that have been published usually refer to the treatment of small flows of wastewater generated intermittently in milk production farms [5,6], cheese whey [7], synthetic effluent [8], domestic sewage combined with effluent from small dairy farms [9], or more recently to the combination of coagulation and MBR for dairy wastewater treatment [10]. We found no paper references to the treatment of real effluents from large dairy industries making use of submerged aerobic MBR.

The MBRs can operate with sidestream or submerged membrane modules. In the first case, sludge is pumped into the membrane module, located externally to the biological reactor. The recirculation pump, besides pressurizing the feed and providing the driving force for permeation, also generates a crossflow velocity responsible for the reduction of the solid particles deposition onto the membrane surface [11].

In the second case, the membrane module is positioned inside a tank, which can be a biological tank or an external one, and permeate is removed by suction. In this case, aerators are usually positioned at the base of the membrane module so as to induce turbulence near the membrane, reducing cake formation. The submerged configuration presents the advantage of operation with lower fluxes, guaranteeing higher permeability and lower fouling, and is preferable for large-scale applications [12]. Moreover, the energy expenditure of a submerged MBR is significantly lower than a sidestream configuration, given the great amount of energy required by the recirculation pumps. While a sidestream MBR demands up to 6 KWh/m^3 of treated effluent, the demand of the submerged MBR is usually lower than 1 KWh/m^3 [13].

The advantages of positioning the membrane module in an external tank in relation to the biological tank (termed membrane tank) in a submerged MBR have recently been raised. This alteration can result in a more stable operation and in a better fouling control [14]. Since the membrane is not directly inserted into the biological tank, the external submerged MBR may present lower fouling resulting from abrupt alterations in flow or toxicity shocks and better effluent quality as short-circuiting is avoided [15]. Furthermore, chemical cleaning and module maintenance are facilitated, since the membrane can be isolated without the need to be removed from inside the tank. On the other hand, the extra pump for circulation may modify the sludge characteristics and will increase energy consumption [15].

It is possible to find studies that compare the performance of submerged and sidestream MBRs [11,14,16,17]. For example, Le-Clech et al. [11] compared the fouling potential of a sidestream MBR and an MBR with submerged module inside the biological tank. Clouzot et al. [14] evaluated the rheological properties and the activity of the biomass from a sidestream and a submerged MBR external to the biological tank.

Nonetheless, pertaining literature still lacks studies which compare the performance of internal and external submerged MBRs. Brannock et al. [15] developed a computational fluid dynamics (CFD) model which accounts for membrane module positioning in submerged MBR. The authors observed that the internal configuration showed higher amount of "short circuiting" and "dead zones". However, there is still no study presenting conclusive experimental data on the advantages and disadvantages of the two configurations, especially in relation to fouling and production of soluble microbial products (SMP) and extracellular polymeric substances (EPS).

The SMP are defined as compounds produced by micro-organisms that are found dispersed in the mixed liquor after having been released during metabolism or cellular lysis. The EPS are complex mixtures of organic aggregates that form a hydrated gel matrix responsible for the aggregation of micro-organisms into biofilms and flocs [18]. These classes of organic substances have been considered as one of the most relevant factors for fouling [19–21].

In this way, the objective of this work was to compare the performance of two MBR configurations: one with the membrane submerged in the biological tank and the other with the membrane submerged in a membrane tank external to the biological tank. The MBRs were applied to the treatment of dairy industry effluent and the removal efficiencies of organic material and nutrients of both systems were evaluated. Moreover, focus was given on membrane fouling and on the EPS and SMP production.

2. Materials and methods

2.1. Dairy industry effluent

The effluent fed into the two evaluated MBRs originated from a large dairy industry located in the state of Minas Gerais, Brazil, which produces UHT milk, yoghurt, cheese, cream cheese, and *fromage frais*. The milk processing capacity of the industry is $800\,m^3$/day.

The effluent was collected at the effluent treatment station of the industry after screening and flotation with compressed air. Seven samples were collected throughout the reactors operation. Approximately 150 l of the industrial effluent was collected each time and placed in 50-liter containers, which were stored in a cold chamber at 3˚C until the effluent was fed into the reactor.

2.2. Experimental apparatus

Two submerged membrane bioreactors (SMBRs) with different configurations were evaluated. In the first MBR, the membrane was inserted into the biological tank. In the second MBR, the membrane was accommodated external to the biological tank in a membrane tank positioned in series to the first one. The bench-scale bioreactors were built by the company *PAM Membranas Seletivas Ltda.* (Rio de Janeiro, Brazil). Each MBR was equipped with one hollow-fiber microfiltration membrane module (polyetherimide, average pore size of 0.4 µm, membrane area of $0.044\,m^2$, and packing density of $500\,m^2/m^3$), also provided by the same company. In the modules, permeate was collected at the upper end and at the opposite end, there were small holes for air introduction and promotion of aeration between the fibers.

The bioreactor with the membrane submerged inside the biological tank (henceforth referred to as submerged membrane bioreactor—internal to the biological tank, SMBRi) consisted of three acrylic tanks (a 40-liter feed storage tank, a 20-liter total volume biological tank, in which the membrane was inserted, and a five-liter tank for storing the permeate), a pump to promote both microfiltration and backwash, three-way solenoid valves, level sensors, needle valves for flow adjustment, rotometers to indicate permeate, backwash and air flows, a pressure indicator, and a skid with an electric panel for the automatic control of permeation and backwash operations.

In the second bioreactor, the membrane was inserted into a membrane tank (5.5 l) positioned in series to the biological tank. This MBR will be referred to as submerged membrane bioreactor—external to the biological tank (SMBRe) throughout this work. The sludge was recirculated between the biological tank and the membrane tank by two peristaltic pumps. It is important to note that the membrane tank only served as an external filtration reservoir and that there was no sludge settling in it due to small hydraulic residence time.

A schematic of the two evaluated MBRs can be found in Fig. 1.

2.3. Operational conditions

The two MBR configurations were operated at the same time and raw effluent from the same 50-liter container was provided to each feed tank from the two MBRs. The reactors were initially inoculated with sludge from the activated sludge reactor from the industry supplying the effluent and underwent an acclimatization period before the start of the tests. The hydraulic retention time (HRT) was fixed at 6 h and the solids retention time (SRT) at 60 days (the defined values were based on existing literature and previous tests as explained elsewhere [22]). The mixed liquor volume in the MBRs was maintained at 3.9 L; so, only a small part of the total biological tank was actually used. The operational flow was 0.70 L/h and the permeate flux was $16\,L/h.m^2$. For the two reactors, the air flow to the biological tank was $0.5\,Nm^3/h$ and to the membranes modules was also $0.5\,Nm^3/h$, resulting in a specific air demand of $11.4\,Nm^3{}_{ar}/h\,m^2{}_{membrane}$. The SMBRe operated with a sludge recirculation flow of 4.0 L/h.

The membrane module used in the SMBRe presented mean water permeability for the clean membrane of $153\,L/h\,m^2$ bar. The SMBRi module, despite having been provided by the same supplier, presented a higher water average permeability of $235\,L/h\,m^2$.bar.

Backwash flow was adjusted to 2.0 L/h and it was triggered automatically for 45 s every 15 min of permeation. This frequency is similar to the one used by other authors [23,24]. The membrane chemical cleaning was performed when the operating pressure reached the maximum value provided by the pump (0.50–0.60 bar) or when necessary for the performance of other tests like resistance in series or critical flux (results not presented in this work). The chemical cleanings were performed using a 200 ppm solution of sodium hypochlorite for 20 min in an ultrasound bath. This procedure was similar to the one optimized by Amaral [25].

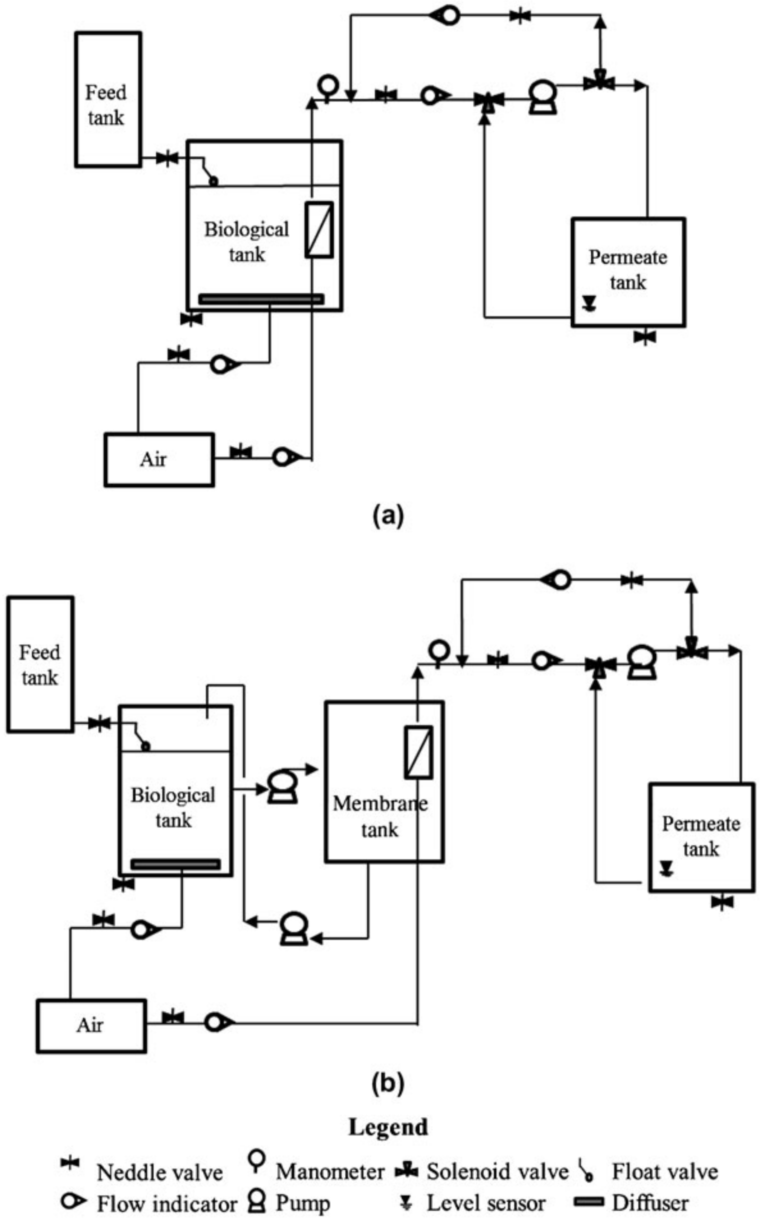

Fig. 1. Schematic of bioreactors with submerged membrane (a) internal (SMBRi) and (b) external (SMBRe) to the biological tank.

2.4. Process monitoring

During the MBR operation, the pressure was recorded daily. Also, the feed and permeate chemical oxygen demand (COD) concentration [26], apparent color (Spectrophotometer Hach DR2800), and turbidity (Turbidimeter Hach 2100AN) were determined on a daily basis. The results for permeate COD concentration and color and the removal efficiencies for the two MBRs were compared via the Mann-Whitney test for nonparametric samples carried out with the assistance of the *Statistica 7.0* software [27] at a 0.05 level of significance.

Sludge aliquots were also collected for analysis of mixed liquor volatile suspended solids (MLVSS) three times a week. A greater volume of feed and permeate was collected weekly for analysis of total nitrogen (Shimadzu TNM-1), ammonia, total phosphorus, BOD, and total solids. All the analyses were performed in accordance with the recommendations of the Standard Methods for the Examination of Water and Wastewater [26].

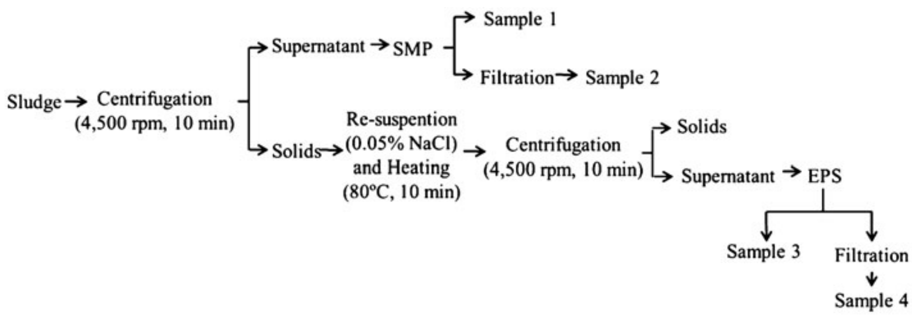

Fig. 2. Scheme of SMP and EPS extraction.

2.5. SMP and EPS concentration

Although, theoretically, SMP refers only to soluble substances, in this study organic matter found both in soluble and colloidal form in mixed liquor was called SMP (or, as named elsewhere, free EPS). Moreover, substances aggregated to sludge suspended solids which could be removed by heating have been considered to be EPS (or bound EPS).

The extraction of SMP and EPS is shown in Fig. 2. First, the sludge was centrifuged at 4,500 rpm for 10 min and the supernatant liquid, mainly consisting of SMP, was collected. The solids resulting from the centrifugation were resuspended with 0.05% sodium chloride solution and heated at 80˚C for 10 min for EPS release [28]. This new suspension was centrifuged again and the supernatant liquid, constituting mainly of EPS, was collected.

A fraction of the supernatant SMP and EPS extractions was reserved (samples 1 and 3, respectively) and another fraction was filtered through standard AP40 filter (samples 2 and 4), so that the soluble and colloidal constituents could be characterized separately. The four samples were characterized in relation to carbohydrates [29], proteins [30], and transparent extracellular polymers (TEP) [31]. Soluble SMP concentrations corresponded to the those obtained from sample 2; colloidal SMP to concentrations obtained from sample 1 minus sample 2; soluble EPS, sample 4; and colloidal EPS, sample 3 minus sample 4.

The TEP are a class of organic substance present in fresh and salt waters that are predominantly made up of large polysaccharide molecules [32]. Although the SMP and EPS are traditionally quantified only in terms of carbohydrates and proteins, in this study, TEP was also monitored because, according to De La Torre et al. [31], they are an important component of the SMP and EPS, not quantified by the traditional polysaccharide Dubois method, which presents good correlation with the fouling rate and can be the key to understanding this mechanism.

3. Results and discussion

3.1. Systems efficiency

Table 1 presents the average and standard deviation for MLVSS concentration, relationship between feed and micro-organism (F/M), and organic load for the SMBRe and SMBRi.

As observed, the suspended solids concentration in the SMBRi was much higher than that in SMBRe. At the start of the operation, both the reactors were inoculated with the same sludge and, therefore, presented similar MLVSS concentrations, close to 3,000 mg/L. Through acclimatization, it was possible to notice that the biomass concentration in the SMBRi grew with a greater velocity than in the SMBRe (data not shown). At the end of the acclimatization, the solids concentration in the SMBRi had stabilized with values close to 20,000 mg/L, while in the SMBRe it was approximately 6,000 mg/L. As both MBRs operated under the same conditions and received the same effluent as feed, this great difference in the biomass growth could only be justified by the friction caused by the sludge recirculation pumps in the SMBRe. Apparently, this friction caused stress to the biomass

Table 1
MLVSS, organic load and F/M for SMBRe and SMBRi

Parameter	SMBRe		SMBRi	
	Average	Standard deviation	Average	Standard deviation
MLVSS (mg/L)	5,973	793	20,269	1,127
Organic load (kgCOD/ m^3.d)	12.3	3.6	13.4	2.4
F/M (kgCOD/ kgMLVSS.d)	2.4	0.7	0.7	0.1

and strongly interfered in its growth. Le-Clech et al. [11] showed that the MLVSS concentration in a sidestream MBR was 1–20% lower than the one in a submerged MBR operating under the same conditions, which was justified by the recirculation pumps in the sidestream MBR. However, in the system studied here, this difference was much greater.

The F/M ratio in the SMBRe could be considered high, since the majority of MBRs in real scale treating industrial effluents operate with F/M less than 0.25 kgCOD/kgMLVSS.d [12]. This high value can be explained by high organic load and low concentration of MLVSS. However, it did not undermine the efficiency of the MBR in any way, as will be shown later. For the SMBRi, the F/M relationship presented rather lower values, as well as the standard deviation since high sludge concentrations dampen down the variations in organic load.

Fig. 3 presents feed and permeate COD concentrations for both MBRs evaluated and the respective removal efficiencies.

Both MBRs, as observed, presented elevated organic matter removal efficiencies, which can be justified by the high biodegradability of the effluent [33]. The COD concentrations of the SMBRi permeate oscillated between 89 and 30 mg/L (average and standard deviation = 58 ± 20 mg/L) and of the SMBRe permeate, between 108 and 39 mg/L (average and standard deviation = 65 ± 19 mg/L). The stability provided by MBRs could also be noted because, despite the great oscillations in the feed's COD concentration, no accentuated alteration in the permeate quality occurred at any time.

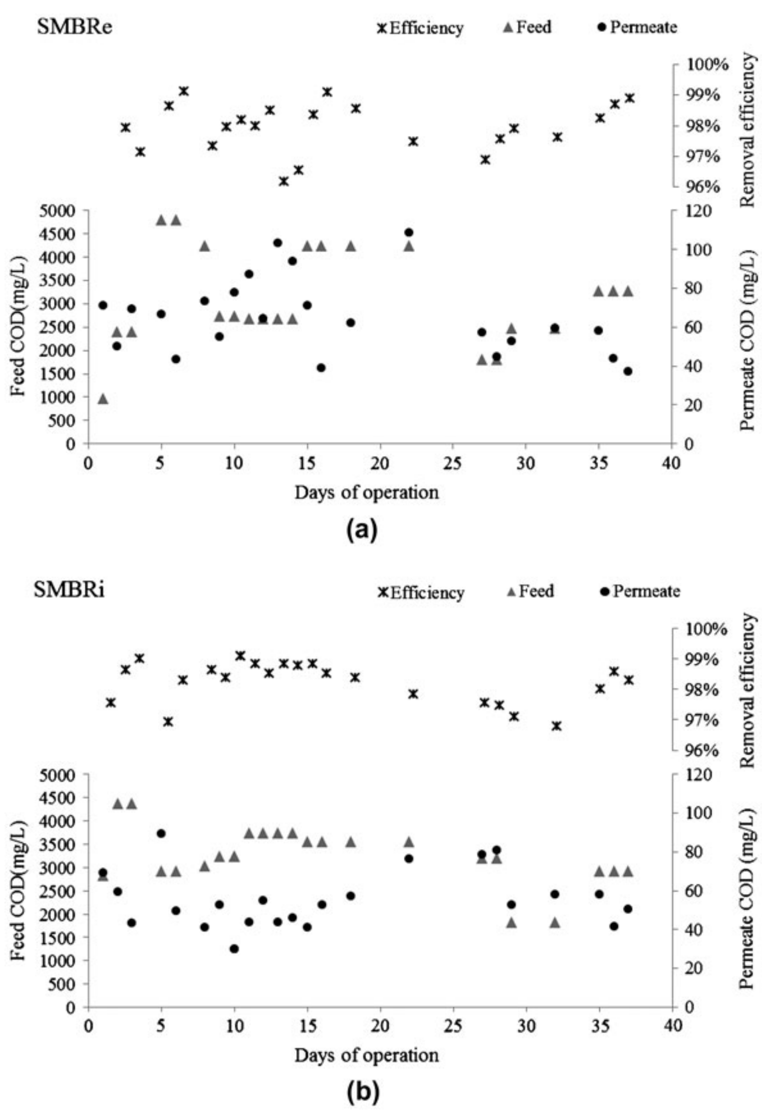

Fig. 3. Removal efficiencies and concentrations of COD for the (a) SMBRe and (b) SMBRi.

Farizoglu et al. [7] evaluated the use of an aerobic jet loop reactor coupled to membranes for the treatment of whey produced during cheese-making. The authors obtained COD removal efficiencies between 94 and 99%; however, the HRT and SRT applied, equal to 0.82–2.8 days and 1.1–2.8 days, respectively, were quite different from those used in this work. Another paper by Castillo and collaborators [5] presents the results of tests using a MBR for the treatment of synthetic wastewater simulating the white waters produced while washing the equipments used in cheese manufacturing. The concentration of COD in the effluent varied between 800 and 1,200 mg/L and in the permeate, it was about 75 mg/L, corresponding to removal efficiencies of 90–94%. Hirooka et al. [6] worked with a similar effluent and obtained 88–99% of COD removal. It appears that the efficiencies obtained in this work are similar to those presented in other related studies, or even higher. This comparison should be drawn carefully, however, because even though all effluents in question came from milk processing, they do not necessarily have the same characteristics.

As for COD, apparent color from feed and permeate was monitored daily and high removal efficiencies could also be observed. The SMBRe and SMBRi permeate color varied between 11 and 30 Pt-Co units (average and standard deviation = 20 ± 4) and between 18 and 42 Pt-Co units (average and standard deviation = 30 ± 7), respectively. It should be noted that the turbidity of permeates was very low, always below 2 NTU.

The normality of the permeate COD, COD removal efficiency, permeate apparent color, and apparent color removal efficiency data were tested through the Shapiro-Wilk test performed through the *Statistica 7.0* software [27], which showed that none of the samples followed the normal distribution. In this way, the data obtained for both MBRs were compared through the nonparametric Mann–Whitney test, the results of which can be seen in Table 2. Since a 5% significance level was established, the results indicated that there is a significant difference between the sample groups when the p_{calc} value is less than 0.05.

The results of the test show that the performance of the SMBRi and of the SMBRe in terms of COD cannot be considered different to a 5% significance level. On one hand, as the biomass concentration was higher and the F/M was lower in the SMBRi, it could be expected that it presented higher COD removal efficiencies. Nevertheless, on the other hand, this condition brought about the production and release of a greater quantity of SMP in the environment, as will be shown in the next section. Thus, the organic matter of the feed was probably more efficiently degraded in the SMBRi, but the higher SMP generation made the permeate COD concentrations similar on both MBRs.

Table 2
Mann–Whitney statistical test results

Variable	COD	COD removal efficiency	Color	Color removal efficiency
n (SMBRe)	24	24	24	24
n (SMBRi)	24	24	21	21
p_{calc}	0.1432	0.1939	0.000015	0.0149

n—number of samples.

In contrast, the Mann-Whitney test applied to the apparent color results indicated that the two MBRs could be considered as significantly different. In this case, the SMBRe presented better performance. As apparent color is deeply dependent in the presence of suspended or colloidal particles, this result is probably due to the fact that, as will be shown in detail later, the concentration of colloidal substances in mixed liquor of SMBRi was approximately two times greater than the one in SMBRe. Thereby, once microfiltration membranes do not efficiently retain colloidal material, it is expected that most of these compounds have passed to the permeate, which probably conferred SMBRi higher apparent color.

Table 3 presents the mean values of the main physical/chemical parameters pertaining to four samples collected from feed and permeate of the two evaluated MBRs and the respective removal efficiencies.

Besides the high removal efficiencies of organic matter and color discussed previously, good removal of nutrients can also be noted. The elevated solids retention times usually applied in MBRs contribute to the nitrification in these systems because the nitrification bacteria, responsible for the conversion of ammonia into nitrate, are notoriously slow-growth microorganisms [12]. Moreover, the tropical climate and the high temperatures of the country also contribute to the systematic occurrence of nitrification in the biological systems implemented in Brazil [34]. Hence, the high ammonia removal efficiencies were predictable. However, given that the reactor is totally aerated and does not have anoxic zones, the significant TN removals, which indicated denitrification, were not expected initially. Nonetheless, this phenomenon might have occurred due to the reduction in the oxygen transfer efficiency stemming from the sludge's high viscosity. In this way, internal regions of the biological flocs possibly did not receive oxygen and

Table 3
Mean values of the main physical/chemical parameters from feed permeate, and the removal efficiencies of the SMBRe and of the SMBRi

Parameter	SMBRe			SMBRi		
	Feed	Perm.	Removal (%)	Feed	Perm.	Removal (%)
Apparent color (Pt-Co units)	2603.3	20.3	99.0	2326.9	30.0	98.6
COD (mg/L)	2,835	66	97.9	2,953	54	98.2
BOD (mg/L)	1,365	3	99.8	1,120	6	99.5
TN (mg/L)	43	5	86.3	50	7	86.1
NH_3–N (mg/L)	35	1	97.9	43	1	96.0
TP(mg/L)	29	2	86.2	36	1	89.0
TS (mg/L)	2,830	1,613	40.5	3,366	1,647	45.7
TFS (mg/L)	1,538	1,487	5.3	1,527	1,473	5.0
TVS (mg/L)	1,292	127	87.0	1,838	174	84.3

TN—Total Nitrogen; NH_3–N—Ammonia nitrogen; TP—Total phosphorous; TS—Total solids; TFS—Total fixed solids; TVS—Total volatile solids.

transformed themselves into anoxic zones, thus providing favorable denitrification conditions [35]. Moreover, since sludge growth was high, part of the total nitrogen removal may result from a higher nutrient uptake.

The total nitrogen removal was similar in both MBRs. If, on the one hand, the SMBRi had higher sludge concentration, which could cause the reduction of the oxygen transfer rates and more formations of anoxic zones internal to the biological flocs, then on the other hand, the lower F/M relationship of this reactor might have caused a reduction of denitrification due to a greater competition between the denitrifying and the heterotrophic aerobes micro-organisms [34].

Average total phosphorus removals of 86 and 89% can also be noted for the SMBRe and SMBRi, respectively. Traditionally, systems projected to remove phosphorus should contain aerobic and anaerobic reactors in series for selection and growth of phosphate-accumulating micro-organisms. In the case of the conventional biological treatment systems, the partial removal of phosphorus takes place through its assimilation by the biomass for cellular synthesis. In this case, the discarding of excess sludge can result in phosphorus removal that varies between 10 and 30%, depending on the organic load of the effluent and on the operation conditions [36].

Farizoglu et al. [37] evaluated the removal of nutrients in a membrane jet loop reactor treating whey and obtained total phosphorus removal efficiencies between 65 and 85%, similar to those in the present study and greater than those expected for the systems that do not have specific configurations for advanced phosphorus removal. For the authors, these elevated values result from a considerable phosphorus assimilation for cellular synthesis as the biomass concentration in the reactor was high (between 6,000 and 14,500 mg/L), which was also true for both MBRs in this study. Moreover, the authors assumed that part of phosphorous removal was related to precipitation of phosphates with Ca^{2+} and Na^{+} ions, present in great quantities in the effluent in question. The effluent used as feed in this work presented Ca^{2+} concentration relatively high (near to 85 mg/L [22]). Given the low K_{ps} value for calcium phosphate (1.3×10^{-32} [38]), the hypothesis of phosphorus precipitation is quite plausible. So, both justifications presented by Farizoglu et al. [37] are also applicable to the present work.

The SMBRi phosphorus removal was slightly superior to that of the SMBRe for all the samples. This might have been caused by the lower biomass growth rate, and lower nutrients uptake, in the SMBRe owing to the shearing of the recirculation pumps.

3.2. Fouling

The SMBRe operated with an average and standard deviation operational permeability (permeate flux divided by instant operational pressure) of 53 ± 18 L/h m^2 bar and the SMBRil, 70 ± 44 L/h m^2 bar. Nevertheless, as the initial water permeabilities of the clean membranes used in each MBR were somewhat different, as explained in Materials and Methods section, a better comparison of the performance of the systems is made when the results are assessed in

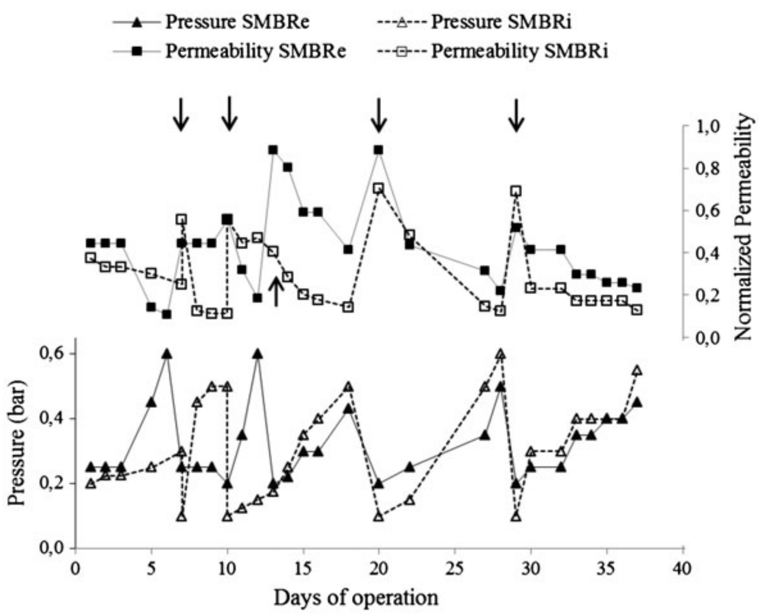

Fig. 4. Operating pressure and normalized permeability of the SMBRe and SMBRi.

terms of normalized permeability (operational permeability in MBR divided by water permeability of the clean membrane). Fig. 4 presents the operating pressure and normalized permeability for the two MBRs. The arrows mark the days when chemical cleaning of the membranes was performed. The chemical cleanings were applied for the membranes of both MBRs, except for day 13 when it was carried out only for SMBRe.

It is possible to verify that the two MBRs operated with relative stability. Generally, the pressure increase happened gradually for both systems, indicating the occurrence of fouling, though not too intense. More accentuated pressure increases were observed for the SMBRe only on days five and 12 and for the SMBRi, only on day eight. The low fouling observed probably results from applying aeration between the membrane fibers through small holes distributed homogenously throughout the module base. Contrary to the usually applied aeration through the positioning of aerators under the membrane module, the aeration method adopted here allows for an improved distribution of the air flow and for better contact between the bubbles and the entire extension of the fibers.

The SMBRe presented better performance in terms of fouling when compared to SMBRi, since its normalized permeability was higher most of the time. This may be related to the higher sludge concentration in the SMBRi, which could have caused more fouling by cake formation. Another reason might be the fact that, as has been discussed earlier, the concentration of colloidal SMP was greater in SMBRi, which could have caused fouling by pore blockage and/or adsorption [19].

3.3. SMP and EPS

The fouling in the two systems was investigated in relation to SMP and EPS concentrations, which was quantified in terms of carbohydrates, proteins, and TEPs. The average total SMP and EPS concentrations (soluble fraction + colloidal fraction) for the two reactors can be seen in Table 4.

The SMP concentrations were higher than the EPS for both reactors, which is in accordance with the literature [12]. As can be observed, the SMP and EPS concentrations in SMBRi were rather high. The results for this MBR are much greater than those obtained for the SMBRe, except for TEP SMP which was quite similar

Table 4
Average total SMP and EPS concentrations in terms of carbohydrates, proteins, and TEP for the SMBRe and SMBRi

Concentration (mg/L)		SMBRe	SMBRi
SMP	Carbohydrates	30.8	73.2
	Proteins	55.0	107.2
	TEP	185.4	191.6
EPS	Carbohydrates	14.5	40.7
	Proteins	51.2	88.2
	TEP	14.5	101.3

in both reactors. This is related to the higher biomass concentration in the SMBRi, and consequently greater production and liberation of metabolic substances. Since, according to the literature, SMP and EPS are strongly related to membrane fouling in MBR, because of adsorption effects, pore blockage, and/or biofilm or cake formation [19,20,39], this difference between SMP and EPS concentrations in each MBR contributed to the greater fouling in SMBRi than in SMBRe.

As MLVSS concentrations were rather different in the two MBRs, Fig. 5 shows the soluble and colloidal SMP and EPS concentration in terms of carbohydrates divided by the biomass concentration for the SMBRe and SMBRi.

As can be observed, temporal variations in the soluble and colloidal SMP and EPS in the two MBRs have approximately the same profile. This might be an indication that the majority of the observed oscillations are related to the changes in feed characteristics and not to other specific operational problems that could happen to each individual MBR, such as deregulation in the level of the biological tank or decrease in permeate flow due to the increase in resistance.

At first, the EPS concentrations in the two MBRs were high. After 5–10 days, these concentrations gradually reduced and, despite the peak observed on day 13 for the SMBRi, the values tended to be low and similar in both reactors at the end of the operation. This might indicate biomass acclimatization to these substances and the development of the capacity to degrade them.

The carbohydrate colloidal SMP for the SMBRe was higher than the one for the SMBRi. This was caused by the shearing that the sludge recirculation peristaltic pumps provided, which could lead to the breakage of flocs and/or cells and to the liberation of polymeric material [40–42]. Kim et al. [42] evaluated the characteristics of the sludge from a sidestream MBR operating with centrifugal and rotatory recirculation pumps. Initially, only 4% of the flocs had a size below 10 μm, but after 24 h of operation this percentage was increased to 23–61%. The authors also concluded that when the pump shear was imposed, EPS were released from the cells to the mixed liquor, since cells are usually encased in EPS matrix, and fine colloidal particles increased.

For the soluble SMP, the concentrations in SMBRe also became higher than in SMBRi after a certain time of operation, which might indicate that a continuous friction has an effect that is increasingly significant in the rupture of flocs and cells, as also was explained by Wang et al. [21]. On the other hand, the pump friction did not cause an expressive effect in the EPS production quantified as carbohydrate.

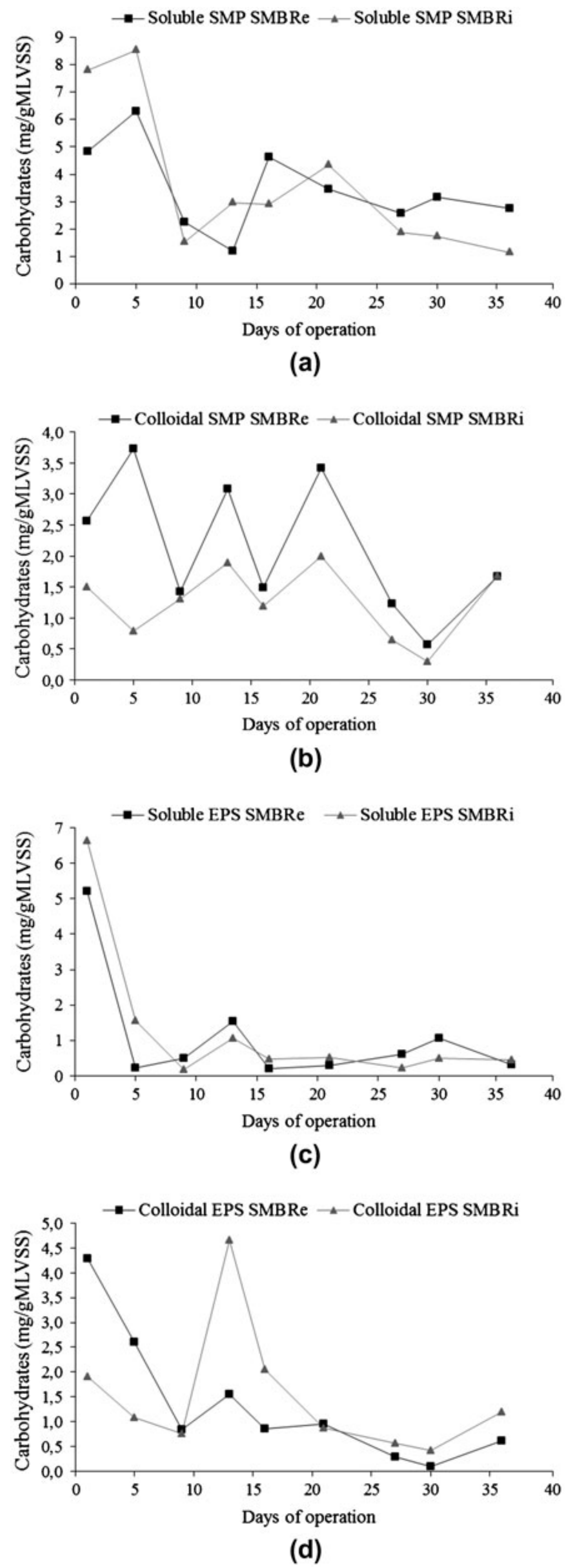

Fig. 5. Concentrations of (a) soluble SMP, (b) colloidal SMP, (c) soluble EPS, and (d) colloidal EPS in terms of carbohydrates in relation to the MLVSS concentrations for SMBRe and SMBRi.

Fig. 6 shows the soluble and colloidal EPS and SMP concentrations in terms of proteins for the two MBRs.

As for carbohydrates, a reduction in the EPS in both SMBRe and SMBRi throughout the operation could be noticed. Similar EPS concentrations were observed for the two MBRs.

Once again, the shear stress provoked by the recirculation pumps had an important effect on colloidal SMP production, since its concentration in SMBRe remained almost always higher than in SMBRi. Similarly to what was observed for carbohydrates, from a certain moment onward, the soluble SMP concentration in SMBRe also acquires constantly higher values than in SMBRi, showing that long-term friction effects can be more expressive.

Fig. 7 shows the soluble and colloidal SMP and EPS concentrations in terms of TEP for the two MBRs.

The variation profile of TEP SMP and EPS is distinct from the profile observed for carbohydrates and proteins, which might mean that this class of substance does not participate in the microbial metabolism in the same way as the others. The soluble TEP SMP of SMBRe seems to increase over time, which means that these compounds were accumulating in the MBR.

The difference between SMP and EPS concentrations in the two MBRs is even clearer when analyzed in terms of TEP. In this case, the concentrations of colloidal SMP, colloidal EPS, and mainly soluble SMP for SMBRe were higher than for SMBRi. The difference between the colloidal EPS had not been evidenced when evaluated in terms of carbohydrates and proteins and, for the soluble SMP, it was only pronounced after some time of operation. However, in terms of TEP, the discrepancy between the concentrations of soluble SMP of the two MBRs was very large (on average, 2.5 times greater in the SMBRe than in the SMBRi).

This shows that the TEP are important constituents of the SMP and that they are not detected by the conventional quantification methods (carbohydrates and proteins). In the same way, the carbohydrates SMP are more related to the extracellular enzyme liberation for specific functions and the proteins SMP are connected to cellular lysis [43], apparently the SMP in terms of TEP can be associated with the substances produced due to the biomass stress provoked by shearing.

In this study, no similarity between the TEP concentration profiles and fouling was observed and the conclusions by De La Torre et al. [31] regarding the influence of this class of substances in fouling could not be proven.

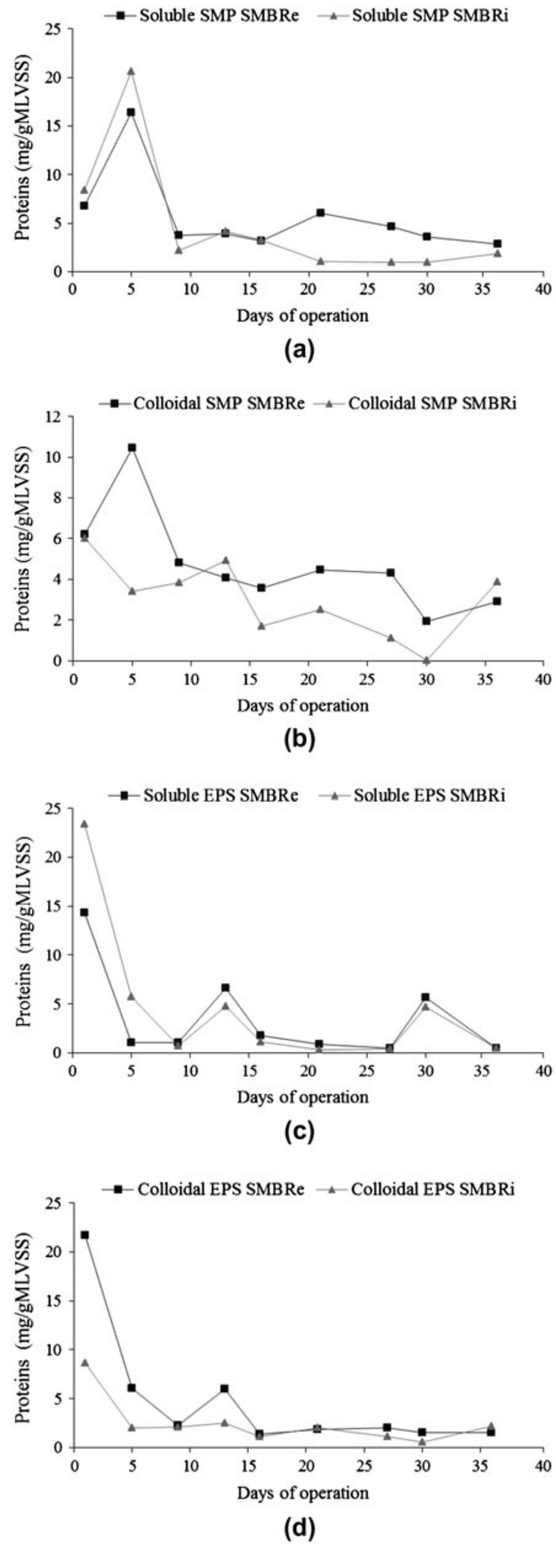

Fig. 6. Concentrations of (a) soluble SMP, (b) colloidal SMP, (c) soluble EPS, and (d) colloidal EPS in terms of proteins in relation to the biomass concentrations for SMBRe and SMBRi.

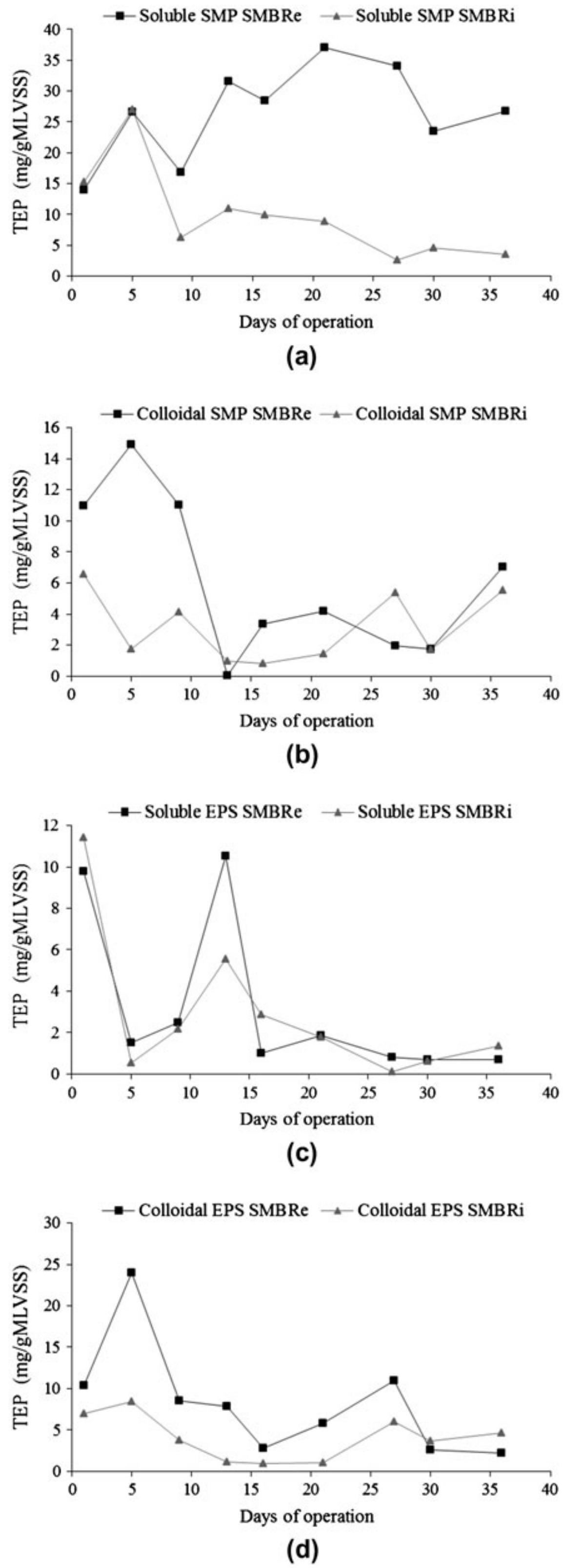

Fig. 7. Concentrations of (a) soluble SMP, (b) colloidal SMP, (c) soluble EPS, and (d) colloidal EPS in terms of TEP in relation to the biomass concentrations for SMBRe and SMBRi.

4. Conclusions

The shearing caused by the sludge recirculation pumps in the SMBRe has great influence on the biomass growth rate. The MLVSS mean concentration in the SMBRe was of 5,800 mg/L, whereas in the SMBRi it was of 19,400 mg/L despite both MBRs being inoculated with the same sludge, operating under the same conditions, and receiving the same effluent as feed.

Both the MBRs presented excellent removal capacity for organic matter, color, and nutrients. In spite of dissimilar sludge concentrations, the COD removal efficiencies of the two MBRs could not be considered as significantly different. On the other hand, SMBRe showed higher color removal efficiency, which was attributed to the greater colloidal substances concentration in SMBRi.

The SMBRe presented better performance in terms of fouling than the SMBRi. This fact is related to higher suspended solids concentration in the SMBRi, which leads to fouling by cake formation. This larger biomass concentration also provoked elevated SMP and EPS production, which also contributed towards the increased fouling in the SMBRi.

When the SMP and EPS concentrations were divided by the MLVSS concentration, it was observed that, although the EPS was similar in the two MBRs, the SMP concentrations, especially in the colloidal form, were higher in the SMBRe. This shows that shear stress provoked by the recirculation pumps leads to breakdown of flocs and/or cells and to the polymeric material liberation into the mixed liquor. This effect was even more pronounced when the SMP were quantified in terms of TEP, which might thus indicate that this class of organic compounds is associated to liberated substances due to biomass stress.

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