Effect of biomass features on oxygen transfer in Conventional Activated Sludge and Membrane BioReactor systems

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Abstract

The aim of the present study was to compare the oxygen transfer efficiency in a conventional activated sludge and a membrane bioreactor system. The oxygen transfer was evaluated by means of the oxygen transfer coefficient $(k_La)_{20}$ and α-factor calculation, under different total suspended solids concentration, extracellular polymeric substances, sludge viscosity and size of the flocs. The $(k_La)_{20}$ and α-factor showed an exponential decreasing trend with total suspended solid, with a stronger $(k_La)_{20}$ dependence in the conventional activated sludge than the membrane bioreactor. It was noted that the $(k_La)_{20}$ in the conventional activated sludge become comparable to that in membrane bioreactor when the TSS concentration in the conventional activated sludge was higher than 5 gTSS L^{-1}. Operating under high carbon to nitrogen ratio, the $(k_La)_{20}$ increased in both conventional activated sludge and membrane bioreactor because of the sludge deflocculation and a weaker dependence of $(k_La)_{20}$ with total suspended solid was noted.

The results indicated that the most important parameters on the oxygen transfer efficiency were in order: the total suspended solid concentration, flocs size, sludge viscosity, the protein to polysaccharides ratio and extracellular polymeric substances content.

Based on the influence of the main biomass features affecting the $(k_La)_{20}$ and considering the typical operating conditions in both systems, those of membrane bioreactor appeared to be more favorable to oxygen transfer efficiency compared to conventional activated sludge process.

Keywords: Aeration efficiency, activated sludge properties, EPS, Membrane Bioreactor, Oxygen transfer; Energy consumption

1. Introduction

Energy saving has become one of the most debated topic in the field of any industrial activity, including also wastewater treatment plants (WWTP) (Henriques and Catarino, 2017; Torregrossa et al., 2018). Aeration is the most energy-intensive operation in wastewater treatment, amounting to 45-75% of plant energy costs (Rosso et al., 2008; Li et al., 2017; Wu et al., 2019); this operation is crucial in WWTPs, since dissolved oxygen (DO) represents an essential factor in biological processes for the treatment of both municipal and industrial wastewater (Tang et al., 2015).

Over recent years, several aeration machineries manufactories have developed innovative devices with the aim to increase the aeration efficiency in terms of mass of oxygen transferred per unit energy required (Zheng et al., 2018). In parallel, the plant facilities were upgraded by equipping those machineries that are more efficient in order to maximize the amount of oxygen that transfers from air to water (Hewawasam et al., 2017). Nevertheless, oxygen transfer process does not depend entirely on diffusers or aerators design, but also on the biomass characteristics (Germain and Stephenson, 2005). Indeed, several investigations have linked the limitation to the oxygen transfer to solids concentrations and viscosity of mixed liquor, as well as the content of soluble microbial products (SMP) and extracellular polymeric substances (EPS) (Germain et al., 2007). Therefore, a better understanding of the energy saving strategies requires deeper investigations on the oxygen transfer phenomena in relation with biomass characteristics.

Whilst on the one hand the energy-saving necessity led operators and manufactories to implement strategies and devices with low environmental impact, on the other, the more stringent environmental laws has driven researchers toward advanced technologies that are more energy-consuming (Krzeminski et al., 2012). Among these, the membrane bioreactors (MBRs) technology is largely considered the first alternative to the conventional activated sludge (CAS) process because of the higher effluent quality, compatible with the water reuse requirements, and the lower footprint (Hoinkis et al., 2012). Nonetheless, in MBR the main power requirement comes from aeration, which is used for oxygen supply and membrane scouring to prevent fouling formation (Germain et al., 2007). Therefore, the improvement of aeration design with a reduction of the energy consumption is of great importance to push the widespread application of MBRs (Xu et al., 2017).

In MBR systems, the biomass features may differ significantly from that of CAS plants, including the higher viscosity and EPS content, the smaller particle size, etc. (Di Bella et al., 2010). Similarly, some operating parameters, like the hydraulic retention time (HRT), the solid retention time (SRT), the food to microorganisms ratio (F/M), might be significantly different to that of CAS (Bertanza et al., 2017). All these factors highly affect the oxygen transfer efficiency, which is usually expressed in terms of global oxygen transfer coefficient (k_La); moreover, the alpha-factor (α-factor), defined as the ratio of k_La under process and clean water conditions, accounts for the effects of activated sludge features (Verrecht, 2010). Some of the above parameters are known to be associated with lower oxygen transfer efficiency, as TSS concentration, viscosity and EPS content, whereas others, like particle size, HRT and F/M, are favorable to oxygen transfer (Germain et al., 2007). The main differences between CAS and MBR in terms of biomass features and operating conditions, as well as the different contribution to oxygen transfer efficiency, make difficult the possibility to assess a comprehensive analysis on aeration efficiency by default. In several studies, it was speculated that the main factor affecting the difference between oxygen transfer in CAS and MBR systems is the flocs size (Fan et al., 2017). For this reason, because the mass transfer is linked to the contact area between gas and liquid phase, the MBR should be favored because of the smaller particles size (Germain et al., 2007). Nevertheless, a comparison between the impact of the particles size on the oxygen transfer efficiency in CAS and MBR was not investigated so far and, in general, very limited data of k_La and α-factor for MBRs have been reported (Xu et al., 2017).

In this light, the aim of this study was to analyze the oxygen transfer in CAS and MBR systems. In detail, the study was aimed at assessing:

1) the comparison between the k_La in CAS and the MBR at different TSS concentration;

2) the impact of the activated sludge flocs size on the oxygen transfer efficiency in CAS and MBR;
3) the influence of the main biomass features on the k_La.

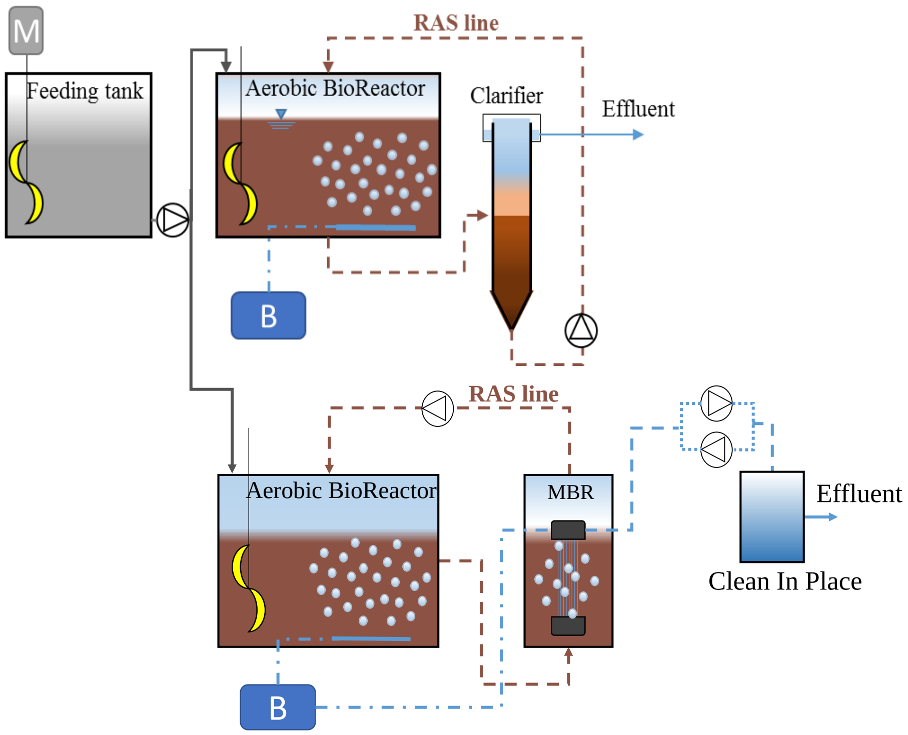
2. Material and methods

2.1 CAS and MBR plant configuration

As aforementioned, in the present study two bench scale plants, one CAS and one MBR, were started-up to study the oxygen transfer efficiency. The CAS plant consisted in one aerobic reactor (25 L of volume) and a clarifier (3 L of volume, $7.84 \cdot 10^{-3}$ m^2 of surface). The MBR was realized according to the submerged side-stream configuration, consisting in one aerobic reactor (24.5 L of volume) and another one (2.5 L of volume) where an ultra-filtration (UF) hollow fibers (HF) membrane module (Zee-Weed®, specific area = 0.1 m^2 and nominal porosity = 0.04 μm, courtesy of GE,) was placed. The aerobic reactors of both the CAS and MBR were geometrically identical (L x l x h = 0.35 m x 0.35 m x 0.20 m) and were equipped with two equal fine bubble air diffusers each, for dissolved oxygen supply. The airflow rate was maintained constant at 6 L min^{-1}. Fibers scouring was achieved by supplying air to the membrane, in order to mitigate the fouling formation.

Both the systems were fed with a synthetic medium with a flow rate of 1 L h^{-1}, resulting in a HRT of approximately 25 h. The synthetic wastewater was stored into a continuously mixed tank from which it was fed through two peristaltic pumps to the aerobic reactors of the CAS and MBR systems. In the CAS, the activated sludge from the bottom of the clarifier was recycled to the aerobic reactor with a flow rate of 2 L h^{-1}, whereas in the MBR the retentate from the membrane compartment was recycled to the aerobic reactor with a flow rate of 6 L h^{-1}. The permeate flux was kept almost to 18 L m^{-2} h^{-1}, while the net effluent flow rate was equal to 1 L h^{-1}. The membrane filtration cycle was divided into 5 min of filtration and 1 min of backwashing, by pumping back a small volume of permeate through the membrane.

A schematic layout of the CAS and MBR systems is depicted in Figure 1.



2.2 Experimental campaign

The experimental campaign had a duration of 70 days and it was divided into two different periods, named Period 1 and Period 2. During Period 1 (50 days), the CAS and MBR were fed with a synthetic wastewater having a C/N/P ratio of approximately 100:10:2. During Period 2 (20 days), the amount of nitrogen and phosphorous in the synthetic medium was decreased, resulting in a C/N/P ratio of 100:2.5:0.5, in order to favour the activated sludge deflocculation in the CAS because of unbalanced nutrients condition. The main features of the synthetic wastewater are reported in Table 1.

Parameter	Unit	Period 1	Period 2
COD (*as sodium acetate*)	mg L^{-1}	382.8±20.1	392.4±26.3
NH_4-N (*as ammonium chloride*)	mg L^{-1}	37.8±3.9	18.9±3.2
PO_4-P (*as hydrogen potassium phosphate*)	mg L^{-1}	7.9±1.2	3.8±0.7
C:N:P	-	100:10:2	100:2.5:0.5

Both plants were seeded with conventional activated sludge collected from the aeration tank of the "*Acqua dei Corsari*" wastewater treatment plant located in Palermo (Italy), with initial concentrations of 3 gTSS L^{-1} and 6 gTSS L^{-1} for CAS and MBR, respectively.

2.3 Determination of the oxygen transfer coefficient

The oxygen transfer coefficient (k_La) was evaluated within the same aerobic reactors, first with tap water (before the inoculum) in order to calculate the (k_La) referred to clean water conditions, then with the biomass at different TSS concentrations. All the tests were performed in batch conditions and at room temperature according to the non-steady-state batch test (Stenstrom et al., 2006). Before starting the oxygen transfer measurement, the dissolved oxygen in water was removed. More precisely, in the test with tap water a chemical oxygen demand (sodium sulphite and cobalt chloride as catalyst) was added to the water, whereas in the test with biomass deoxygenation was achieved because of the oxygen consumption by bacteria. The air blower was then switched on and, after a while, the dissolved oxygen concentration reached the saturation value due to the aeration (reoxygenation phase) at an airflow rate of 6 L min^{-1}. The dissolved oxygen concentration was measured through an oxygen probe (WTW CellOX-325) coupled to an oximeter (WTW MULTI340i).

The standard model for evaluating oxygen transfer is given by Equation 1.

$$\frac{dC}{dt} = k_L a \cdot (C_S - C_0) \qquad (eq. 1)$$

where:

- C = dissolved oxygen concentration (mg/L);
- t = time (min);
- k_La = volumetric mass transfer coefficient (min^{-1});
- C_S = dissolved oxygen saturation concentration at steady state (mg L^{-1});
- C_0 = dissolved oxygen concentration at time zero (mg L^{-1}).

The equation used for data analysis with nonlinear regression is given in Equation 2 and is a derivation from Equation 1:

$$C = C_S - (C_S - C_0) \cdot e^{(-k_L a \cdot t)} \qquad (eq. 2)$$

By plotting the C values achieved during the reoxygenation phase in a graph $ln(C_S\text{-}C)/(C_S\text{-}C_0)$ *vs t*, the volumetric mass transfer coefficient was obtained as the slope of the regression line.

The k_La was then referred at the temperature of 20 °C by using the equation 3:

$$(k_L a)_{20} = (k_L a)_T \cdot 1.024^{T-20} \qquad (eq. 3)$$

The α-factor was obtained as the ratio of process to clean water conditions, as follows (eq. 4):

$$\alpha = \frac{(k_L a)_{process,water}}{(k_L a)_{clean,water}} \qquad (eq. 4)$$

The oxygen transfer coefficient was periodically measured within the aerobic reactors of both CAS and MBR plants at different TSS concentrations, by concentrating or diluting the biomass samples.

2.4 Analytical methods

Extracellular polymeric substances extraction was carried out in accordance with the Heating Method (Le-Clech et al., 2006). Therefore, for both the extracted SMP and EPS fractions, the carbohydrate and protein concentrations were determined according to the phenol–sulphuric acid method with glucose as the standard (DuBois et al., 1956) and by the Folin method with bovine serum albumin as the standard (Lowry et al., 1951), respectively.

The particle size distribution of both the activated sludge from CAS and MBR was measured by means of a high-speed image analyses sensor (Sympatec Qicpic) that provided the particle size distribution and the granulometric curve. The average size of the activated sludge flocs was calculated as the diameter of the particles corresponding to the 50% of the granulometric distribution. The morphology of the activated sludge flocs was evaluated with microscopic image observations performed by a phase contrast microscope (BX-53-Olympus).

Microscopic observations were performed under phase contrast at 100× and 1000× magnifications. The filamentous microorganisms were morphologically identified using the Eikelboom classification system. Filamentous microorganism abundance and dominance were estimated according to the literature (Jenkins et al., 2004).

The activated sludge viscosity was evaluated by means of a rotational rheometer (Brookfield digital viscometer, model DV-E) equipped with concentric cylinders and an adapter for low viscosity at constant temperature (20°C).

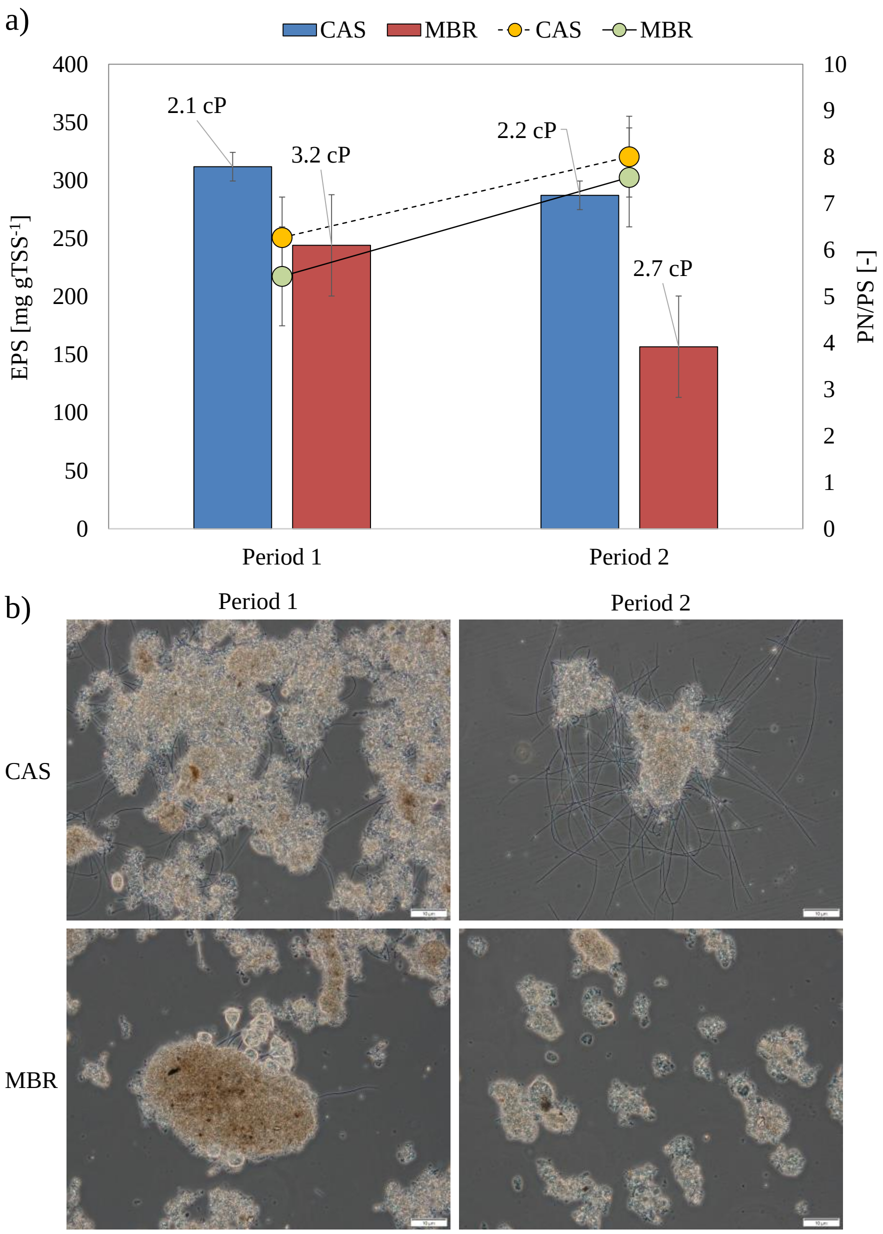
2.5 Statistical analysis

In order to evaluate the influence of the main biomass features (TSS concentration, EPS content and composition, sludge viscosity and size of the flocs) on the oxygen transfer coefficient, the multiple regression analysis was performed. More precisely, the dependent variable was the oxygen transfer coefficient, whereas the independent variables were the biomass features. The regression coefficients (*Beta coefficient*s) was used to evaluate the degree of influence of each biomass feature on the $(k_La)_{20}$, according to the literature (Germain et al., 2007).

3. Results and discussion

3.1 Features of the activated sludge in the CAS and MBR

The main features of the activated sludge in the CAS and MBR in Period 1 and Period 2, in terms of EPS content and composition, flocs size and morphology, are shown in Figure 2.



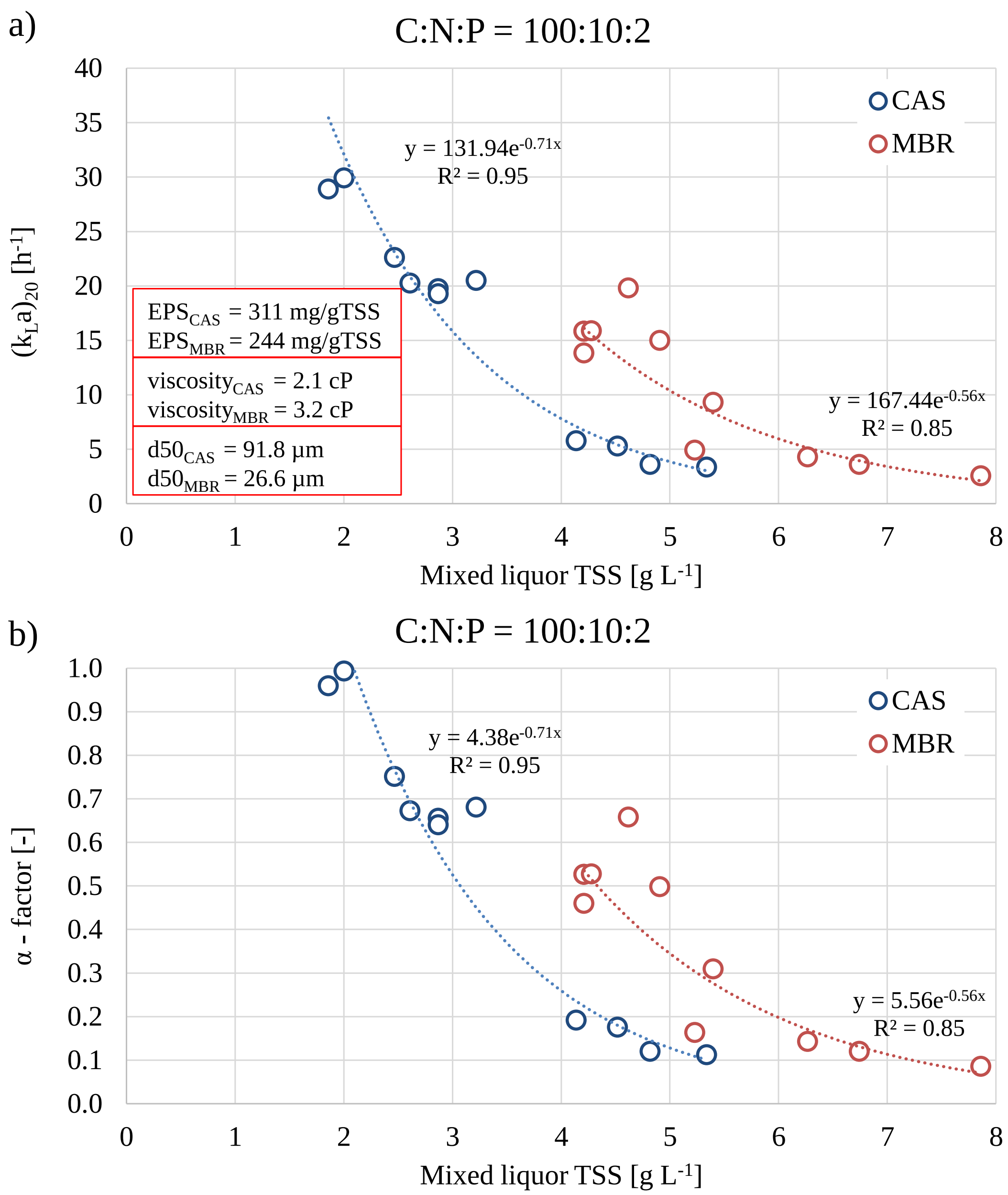
The average EPS content of CAS was of approximately 311 mg g^{-1}TSS in Period 1, whereas it slightly decreased to 287 mg g^{-1}TSS in Period 2. Similarly, the EPS content of MBR decreased from 244 mg g^{-1}TSS to 156 mg g^{-1}TSS from Period 1 to Period 2, indicating that the nutrient unbalance determined a decrease in the EPS secretion by bacteria in both systems. The EPS composition changed as well from Period 1 to Period 2. More precisely, the protein (PN) to carbohydrate (PS) ratio (PN/PS) increased from 6.2 to 8 and from 5.4 to 7.5 in the CAS and MBR, respectively. Therefore, the nutrient unbalance caused a simultaneous decrease in the amount of the total EPS and the enrichment in the proteinaceous fraction of the extracellular polymeric matrix.

The activated sludge viscosity did not change significantly from Period 1 to Period 2 in the CAS (2.1 cP *vs* 2.2 cP), whereas it slightly decreased in the MBR (3.2 cP *vs* 2.7 cP).

The morphology of the activated sludge flocs significantly changed from Period 1 to Period 2. Indeed, in Period 1 the flocs were slightly irregular but compact in the CAS (average size of 91.8 μm), with a common presence of filamentous bacteria (*Nocardia* sp, *Microthrix Parvicella* and *Type 0675*). In Period 2, the activated sludge morphology changed to open-flocs structure (average size of 25.1 μm) with a predominance of filamentous bacteria like *Type 021N*, *Type 0965* and *Thiotrix sp*. In the MBR, the activated sludge flocs were very small but with a regular and compact shape. The size of the flocs was close to 27 μm on average in Period 1 because of the deflocculation effect exerted by the membrane. In Period 2, average size of the activated sludge flocs further decreased to approximately 12 μm, whereas no significant changes in the morphology was observed. Filamentous bacteria like *Type 021N*, *Type 0965* and *Thiotrix sp,* were found dominant even in the MBR, although their effect on the flocs morphology was marginal compared to that in the CAS.

3.2 Oxygen transfer coefficient in the CAS and MBR: Period 1

Biomass with TSS concentrations ranging from 1.5 gTSS L^{-1} and 5.3 gTSS L^{-1} and from 4.2 gTSS L^{-1} and 7.8 gTSS L^{-1} were examined in the CAS and MBR, respectively, during Period 1. The oxygen transfer coefficient and the α-factor obtained in the CAS and MBR at different TSS concentration in Period 1 are depicted in Figure 3.



The $(k_La)_{20}$ coefficient showed and exponential decrease with the increase in TSS in both the CAS and MBR (Fig. 3a), in good agreement with previous findings (Wu et al., 2019). In general, the $(k_La)_{20}$ values obtained by Wu and co-workers were slight lower compared to what achieved in the present study for a similar TSS concentration range. These variations could be likely due to different testing conditions (e.g. aeration intensity, diffuser typology, reactor geometrical features, mixed intensity, etc.). The $(k_La)_{20}$ decreased sharply from 30 h^{-1} to less than 5 h^{-1} when the TSS concentration increased from 2 gTSS L^{-1} to 4 gTSS L^{-1} in the CAS, whereas further increases in TSS did not produced significant decrease in $(k_La)_{20}$. Similarly, the $(k_La)_{20}$ coefficient in the MBR decreased from approximately 16 h^{-1} to 4 h^{-1} when the TSS concentration increased from 4 gTSS L^{-1} to 8 gTSS L^{-1}. The α-factor (Fig. 3b) was of approximately 0.96 in the CAS at 2 gTSS L^{-1}, whereas it significantly decreased in the range between 3 gTSS L^{-1} and 4 gTSS L^{-1} standing at a steady value of approximately 0.15. In the MBR the maximum values of the α-factor were observed at 4 gTSS L^{-1} (α=0.5), whereas it decreased to less than 0.1 at TSS concentrations higher than 7 gTSS L^{-1}.

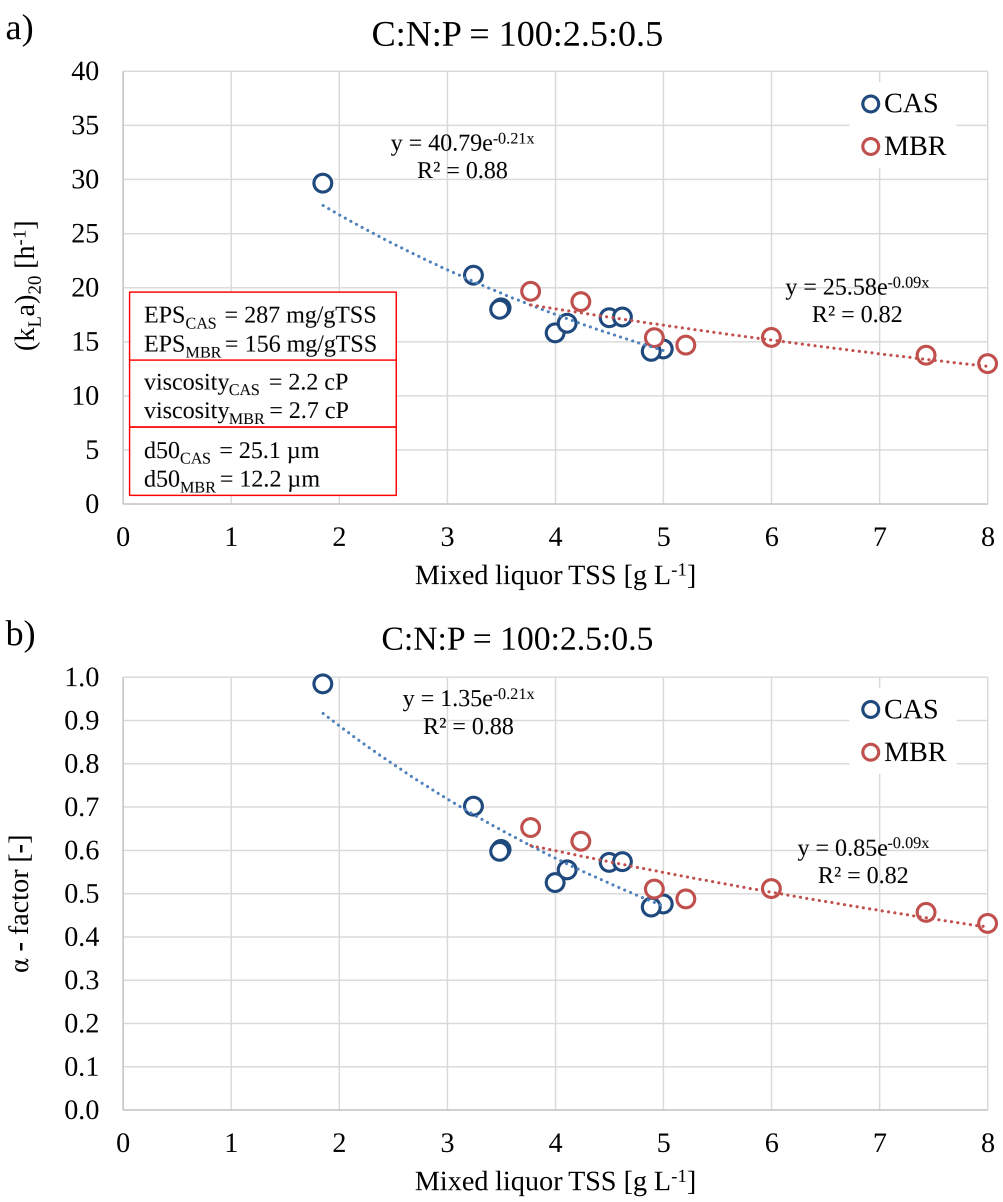
By comparing the exponential decreasing trends observed in the CAS and MBR, it was noted that the dependence of $(k_La)_{20}$ on TSS was stronger in the CAS than the MBR. Under the typical operating TSS concentration in CAS (3 gTSS L^{-1}) and MBR (8 gTSS L^{-1}), the obtained results confirmed that oxygen transfer coefficient was lower in the MBR (3.6 h^{-1} *vs* 20 h^{-1}). Nevertheless, it is worth noting that the $(k_La)_{20}$ values in the CAS become comparable with that in MBR when the TSS concentration in the CAS was higher than 5 gTSS L^{-1}, which is typical of plants operating under extended aeration. Within a range of TSS between 4 gTSS L^{-1} and 6 gTSS L^{-1} the $(k_La)_{20}$ value resulted significantly higher in the MBR, thereby suggesting that under similar operating conditions the features of the activated sludge features in the MBR were more favorable to oxygen transfer.

Differences between the activated sludge features in the CAS and MBR were observed in terms of EPS content and average size of the flocs. Indeed, although the mixed liquor viscosity was higher in the MBR on average, the specific EPS content was higher in the CAS (311 mg g^{-1}TSS *vs* 244 mg g^{-1}TSS), as well as the average size of the activated sludge flocs, which resulted approximately equal to 92 µm and 27 µm in the CAS and MBR, respectively. The above results suggested that the oxygen transfer coefficient and the α-factor, in addition to TSS concentration, strictly depend on the EPS content and size of the activated sludge flocs. These results are in good agreement with the literature, in which the negative effect of the EPS on $(k_La)_{20}$ was previously observed by several researchers (Mueller et al., 2002; Germain et al., 2007).

It is reasonable to speculate that the decrease of $(k_La)_{20}$ in the MBR, due to the increase of TSS concentration, was compensated by the lower EPS content and the smaller size of the activated sludge flocs. Therefore, the latter might be the reason of the weaker relationship of the $(k_La)_{20}$ with TSS in the MBR compared to the CAS system (Freitas and Teixeira, 2001).

3.3 Effect of activated sludge deflocculation on oxygen transfer: Period 2

In Period 2 the amount of nitrogen and phosphorous in the synthetic influent wastewater was decreased in order to simulate the effects of a nutrients unbalanced wastewater on the oxygen transfer efficiency. Figure 4 depicts the relationship between the $(k_La)_{20}$ (Fig. 4a) and the α-factor (Fig. 4b) with the TSS concentration in the CAS and MBR in Period 2.

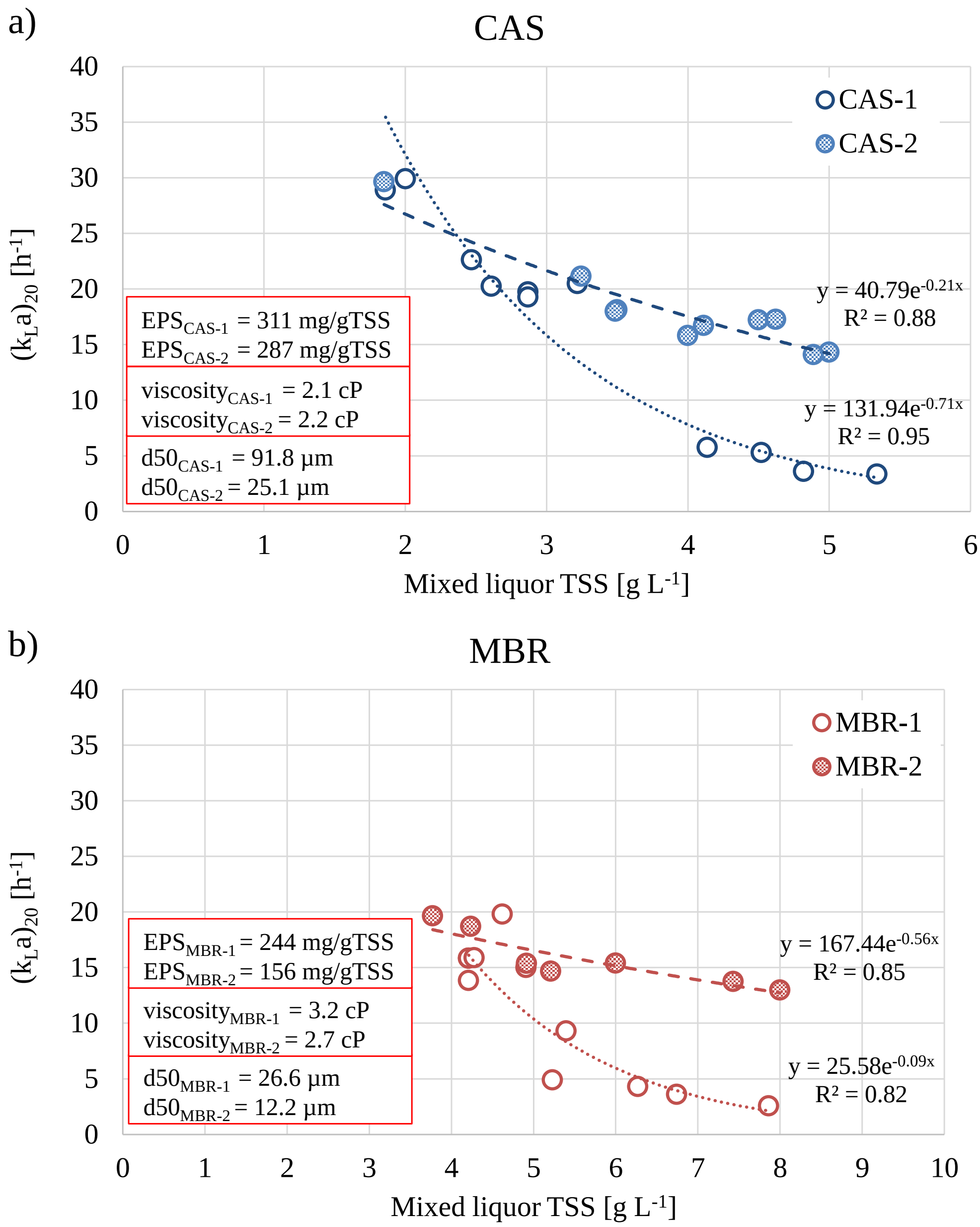


The results shown in Figure 4 indicated that $(k_La)_{20}$ increased in both CAS and MBR plants because of the nutrients unbalance. Overall, a weaker dependence of $(k_La)_{20}$ with TSS was observed compared to Period 1. Indeed, although the $(k_La)_{20}$ showed the same exponential decreasing trend observed in Period 1, the $(k_La)_{20}$ values obtained in Period 2, at equal TSS concentration, significantly increased. The $(k_La)_{20}$ in the CAS decreased from 30 h^{-1} to less than 15 h^{-1} when the TSS concentration increased from 2 gTSS L^{-1} to 4 gTSS L^{-1}, whereas in Period 1 it decreased to less than 5 h^{-1} within the same range of TSS. At higher TSS the $(k_La)_{20}$ did not decreased further, standing at a constant value of approximately 15 h^{-1}. Similarly, the $(k_La)_{20}$ decreased from 20 h^{-1} to approximately 13 h^{-1} in the MBR when the TSS concentration increased from 4 g TSS L^{-1} to 8 g TSS L^{-1}, showing a weaker dependence with TSS compared to CAS system. The α-factor decreased from 0.97 to 0.48 when the TSS concentration increased from 2 g TSS L^{-1} to 5 g TSS L^{-1}, whereas in the MBR it decreased from 0.65 to 0.42 within a range of TSS between 3.6 g TSS L^{-1} and 8 g TSS L^{-1}.

Overall, the differences between the oxygen transfer in the CAS and MBR significantly reduced in Period 2. Because of the nutrients unbalance, the physical properties of the activated sludge significantly changed in both the systems. The average EPS content decreased from 311 mg g^{-1}TSS to 287 mg g^{-1}TSS and from 244 mg g^{-1}TSS to 156 mg g^{-1}TSS in the CAS and the MBR, respectively. Similarly, the size of the activated sludge flocs significantly decreased in the CAS from 91.8 µm to 25.1 µm, indicating the occurrence of a massive deflocculation, whereas in the MBR the size of the flocs decreased to a lesser extent from 26.6 µm to 12.2 µm. The achieved result indicated that the decrease in the EPS content and the size of activated sludge flocs significantly improved the oxygen transfer in both the systems. Moreover, both the $(k_La)_{20}$ and the α-factor resulted very similar in both systems. Previous studies highlighted significantly poorer oxygen transfer efficiency in presence of filamentous organisms, concerning in particular to the *Thiothrix eikelboomi*, due to the enhancement of sludge viscosity and particular cell surface (Liu et al., 2018; Wu et al., 2019). In the present study, despite in Period 2 it was observed a significant growth of filamentous organisms (including the

Thiothrix eikelboomi), their negative effect on oxygen transfer could be masked by the beneficial variation of other parameters, such as EPS, open floc structure and average floc size.

A comparison of the oxygen transfer, in terms of $(k_La)_{20}$, with the TSS in Period 1 and Period 2 in the CAS and MBR is depicted in Figure 5.



In the CAS, at TSS lower than 2.5 g TSS L^{-1} the $(k_La)_{20}$ was slightly higher in Period 1, whereas at higher TSS concentration the $(k_La)_{20}$ was higher in Period 2. As aforementioned, the dependence of the $(k_La)_{20}$ with TSS significantly reduced in Period 2 and their relationship became almost linear.

The above observations were replicable for the MBR, although the increase in the $(k_La)_{20}$ was lower compared to the CAS.

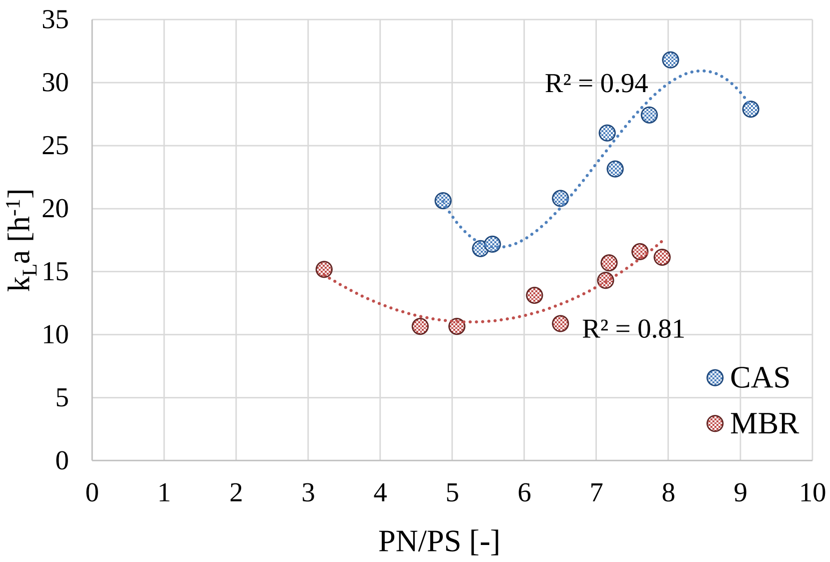
The higher increasing trend of $(k_La)_{20}$ observed in the CAS system was likely due to the greater deflocculation effect observed in this system. In view of a slight decrease in the specific EPS content (<10%), the only characteristic of the activated sludge flocs that significantly changed in the CAS from Period 1 to Period 2 was the average size of the bioaggragates and the higher abundance of filamentous bacteria. Therefore, it can be stated that the increase in the $(k_La)_{20}$ in the CAS was mainly driven by the activated sludge deflocculation. In previous literature, it was observed a negative impact of the filamentous overgrowth on the oxygen transfer (Liu et al., 2018). The authors noted a significant worsening in the oxygen transfer efficiency due to the filamentous microorganisms that caused the increase of the EPS content in the activated sludge and its viscosity. Nevertheless, the authors only speculated that the filamentous overgrowth caused an increase in the activated sludge viscosity, thus decreasing the oxygen transfer efficiency. In the present study, the filamentous overgrowth observed mainly in the CAS during Period 2, did not cause a significant increase in the activated sludge viscosity. In contrast, it modified the sludge morphology creating open-flocs structure having much greater specific surface area and greater exposure to the bulk solution.

The effect of the decrease in the floc size was lower in the MBR, because it was smaller since the beginning. Nevertheless, it was compensated by the decrease of the EPS content, close to 36%. This result was in good agreement with previous literature, which reported the negative impact of the bio-surfactants like EPS in the oxygen transfer efficiency (Capodici et al., 2014).

Based on the above results, it can be concluded that the nutrient unbalance improved the oxygen transfer in both the CAS and MBR, although the mechanisms involved in the increase in the $(k_La)_{20}$ were different.

3.4 Impact of EPS composition on oxygen transfer

The above results indicated that the decrease of the EPS content improved the oxygen transfer. In light of this, with the aim to better clarify the role of the EPS compounds on the oxygen transfer behavior, the $(k_La)_{20}$ was correlated with the protein (PN) to carbohydrates (PS) ratio (PN/PS) (Fig. 6).



The $(k_La)_{20}$ and the PN/PS showed a good correlation in both the CAS and MBR plants. More precisely, the $(k_La)_{20}$ significantly increased when the PN/PS was higher than 5, showing an exponential trend in both systems. The $(k_La)_{20}$ almost doubled in the CAS when the PN/PS increased from 5 to 8, whereas in increased for approximately 50% in the MBR. Therefore, the increase of protein in the EPS matrix was found to be favorable to oxygen transfer. This result was in contrast with previous literature (Germain et al., 2007), where the EPS component that influenced positively the oxygen transfer was found to be the carbohydrate. Germain and co-workers observed that the carbohydrates of the EPS increased flocs porosity and therefore the oxygen diffusivity. In the present study, the highest PN/PS was observed in Period 2 in both systems, when, because of the filamentous overgrowth and the deflocculation, the floc porosity likely increased independently of EPS composition. As previously discussed, the abundance of filamentous bacteria in Period 2 caused the change in the activated sludge morphology to open-flocs structure that was likely favorable to oxygen transfer. Besides, it is worth mentioning that the prevalence of the proteins over the carbohydrates in the EPS matrix increased the sludge hydrophobicity, because of the hydrophobic nature of the proteinaceous molecules (Ras et al., 2013). Given the hydrophobic nature of the air bubbles (Shi et al., 2014), it is possible to speculate that the increase in the proteinaceous fraction of the EPS matrix, improved the oxygen transfer because of the establishment of hydrophobic interaction between the activated sludge flocs enriched in proteins and the air bubbles (Ferreira et al., 2010; Mena et al., 2011). Therefore, the in $(k_La)_{20}$ in addition to TSS, EPS content and floc size, was found to be dependent of the protein content of the extracellular polymeric matrix.

3.5 Relative influence of the biomass features on $(k_La)_{20}$

Based on the above considerations, the main features of activated sludge that affected the $(k_La)_{20}$ were the TSS, the total EPS content, the PN/PS, the sludge viscosity and the average size of the flocs. In order to evaluate their degree of influence on the oxygen transfer coefficient, a multiple regression analysis was carried out considering the values of $(k_La)_{20}$ obtained during the entire experiment. The beta coefficients and the statistical significance parameters obtained by the regression analysis are reported in Table 2.

Parameter	**CAS**	**MBR**
TSS	-4.48	-3.01
EPS	-0.86	-0.50
PN/PS	0.68	0.98
Viscosity	-1.03	-1.75
Flocs size	-1.62	-2.37
F	31.6	14.5
p-level	<0.05	<0.05

The obtained results indicated that the degree of influence of the investigated parameters for both the systems were in order: the TSS concentration, flocs size, viscosity, PN/PS and EPS content. More precisely, the TSS, the EPS, the viscosity and the flocs size had a negative influence, meaning that an increase in these parameter led to a decrease of the $(k_La)_{20}$, whereas the only parameter having a positive influence was the PN/PS. As afore discussed, the TSS concentration had a higher influence on $(k_La)_{20}$ in the CAS than the MBR, as well as the EPS. In contrast, the activated sludge viscosity, the flocs size and the PN/PS had a greater influence in the MBR.

Based on the typical operating conditions of CAS and MBR systems, the activated sludge viscosity is generally higher in the MBR, because of the higher TSS concentration they operate (Germain et al., 2007), as well as the average size of the flocs is significantly lower in the MBR (Campo et al., 2017). Moreover, because of the higher sludge retention time and the lower F/M, the amount of EPS is lower, whereas that of proteins in relation to carbohydrates in the EPS matrix is higher in the MBR. Indeed, endogenous metabolic condition imposed by the low F/M, are reported to produce a selective enrichment of proteins in the EPS, due to the biodegradation of the carbohydrates that from a molecular point of view are structurally more simple than proteins (Duan et al., 2014). In contrast, in CAS systems, although the TSS concentration is lower, the amount of EPS is higher than MBR because of the higher F/M.

Based on the afore discussed degrees of influence of the main biomass features affecting the $(k_La)_{20}$, the operating conditions in MBR systems and its activated sludge features, appeared to be more favorable to oxygen transfer efficiency compared to CAS systems. Nevertheless, an excessive deviation of the above reported parameters from the ranges investigated in the present study could led to different results because of the increase of the degree of influence of such parameter on the oxygen transfer efficiency.

Conclusions

A comparison between the oxygen transfer efficiency in CAS and MBR was performed in the present study. The $(k_La)_{20}$ and α-factor showed exponential decreasing trends with TSS in the CAS and MBR, even if it was noted that the dependence of both parameters on TSS was stronger in the CAS than the MBR. Although under the typical operating conditions in terms of TSS concentration in the CAS and MBR the oxygen transfer coefficient was lower in the MBR (3.6 h^{-1} vs 20 h^{-1}), it was noted that the $(k_La)_{20}$ values were higher in the MBR within a range of TSS between 4 gTSS L^{-1} and 6 gTSS L^{-1}.

The achieved results indicated that under similar operating conditions the features of the activated sludge flocs in the MBR were more favorable to oxygen diffusion process because of the smaller particle size.

Moreover, the results indicated that the TSS, the EPS, the viscosity and the flocs size had a negative influence on the $(k_La)_{20}$, whereas the only parameter having a positive influence was the PN/PS. The TSS concentration had a greater influence on $(k_La)_{20}$ in the CAS than the MBR, as well as the EPS. In contrast, the activated sludge viscosity, the flocs size and the PN/PS had a greater influence in the MBR.

Based on the degrees of influence of the main biomass features affecting the $(k_La)_{20}$ and considering the typical operating conditions in both systems, those of the MBR appeared to be more favorable to oxygen transfer efficiency compared to CAS.

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FIGURE CAPTIONS

Figure 1: Layout of the CAS and MBR

Figure 2: Average EPS content, composition, and activated sludge viscosity (a), microscopic observation of the sludge in the CAS and MBR during Period 1 and Period 2.

Figure 3: Oxygen transfer coefficient (a) and α-factor *vs* TSS in CAS and MBR in Period 1

Figure 4: Oxygen transfer coefficient (a) and α-factor *vs* TSS in CAS and MBR in Period 2

Figure 5: Comparison between the $(k_La)_{20}$ in Period 1 and Period 2 in the CAS (a) and MBR (b).

Figure 6: Relationship between the $(k_La)_{20}$ and the PN/PS ratio of the EPS in the CAS and MBR

TABLE LEGENDS

Table 1: Features of the synthetic wastewater

Table 2: Beta coefficients and statistical significance parameters obtained by regression analysis for $(k_La)_{20}$