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Biomass effects on oxygen transfer in membrane bioreactors

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ABSTRACT

Ten biomass samples from both municipal and industrial pilot and full scale submerged membrane bioreactors (MBRs) with mixed liquor suspended solids concentrations (MLSS) ranging from 7.2 to 30.2 $g\,L^{-1}$ were studied at six air-flow rates (0.7, 1.3, 2.3, 3, 4.4 and 6 $m^3\,m^{-3}\,h^{-1}$). Statistical analyses were applied to identify the relative impacts of the various bulk biomass characteristics on oxygen transfer. Of the biomass characteristics studied, only solids concentration (correlated with viscosity), the carbohydrate fraction of the EPS (EPS_c) and the chemical oxygen demand (COD) concentration of the SMP (SMP_{COD}) were found to affect the oxygen transfer parameters k_La_{20} (the oxygen transfer coefficient) and α-factor. The relative influence on k_La_{20} was MLSS > aeration > EPS_c > SMP_{COD} and on α-factor was MLSS > SMP_{COD} > EPS_c > aeration. Both k_La_{20} and α-factor increased with increasing aeration and EPS_c and decreased with increasing MLSS and SMP_{COD}. MLSS was found to be the main parameter controlling the oxygen transfer.

1. Introduction

Combining membrane technology with biological treatment, the membrane bioreactor (MBR) is an alternative to the conventional-activated sludge (CAS) process (Stephenson et al., 2000). The sedimentation tanks of the CAS are replaced by membrane filtration, reducing the footprint significantly and improving effluent quality by removal of suspended and colloidal material (van der Roest et al., 2001). However, high running costs, arising partly from operating membranes at high solids concentrations, restrict the use of MBRs (Hong et al., 2002). The MBR main power requirement comes from aeration, which is used for supply of dissolved oxygen (DO) and to maintain solids in suspension. Biological aeration requirements are higher than in CAS because of the lower oxygen transfer rate due to highly concentrated biomass (Cornel et al., 2003; Rosenberger, 2003). Additionally, membrane cleaning in submerged MBRs is provided by air scouring and agitation of fibres—the latter in the case of hollow fibre membranes (Germain et al., 2005).

In MBRs, as in all aerobic wastewater processes, both the biomass characteristics and the design of the aeration system affect the oxygen transfer (Mueller et al., 2002). Biomass is a heterogeneous mixture of particles, microorganisms, colloids, organic polymers and cations, of widely varying shapes, sizes and densities. All these parameters impact on oxygen transfer (Germain and Stephenson, 2005). Mass transfer is also linked with contact area size between gas and liquid phases, i.e. bubble shape and solids concentration

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(Garcia-Ochoa et al., 2000). Bubble characteristics differ depending on the kind of aerator used and the bubble coalescence effect created by the biomass characteristics (Germain and Stephenson, 2005). The aeration in MBRs is generally provided by fine bubble aerators, used to keep the tank well mixed and provide oxygen to the biomass. In addition, in submerged MBRs, coarse bubble aerators situated under the membrane modules are used to scour and/or gently agitate the membranes in order to control membrane fouling (Stephenson et al., 2000).

For a better understanding of the phenomena occurring in aerated MBR biomass, closer investigations of each of its characteristics are needed to improve the aeration efficiency and so reduce operating costs. Such investigations have been generally limited to impacts of solids concentration and viscosity. Other characteristics worth considering include soluble microbial products (SMP) and extracellular polymer substances (EPS); both mainly of microbial origin (Wingender et al., 1999). The SMP is ostensibly soluble and part of the liquid phase, whereas EPS is bound to the cells and thus part of the solid phase. In the current study, the effects of MBR sludge characteristics on oxygen transfer in a bubble column has been investigated using sludges from full and pilot scale municipal and industrial MBRs. The same experimental set-up was used to perform experiments to allow direct comparison of the effect of biomass characteristics and airflow on oxygen transfer without the added effects of the different plant designs. Diffuser optimisation will not be considered in the present study as it has been extensively investigated (Metcalf and Eddy, 2003).

2. Material and methods

2.1. Oxygen transfer coefficient, k_La, and α-factor determinations

The non steady-state batch test under endogenous respiration conditions and with no recycle flow described by WEF and ASCE (2001) was used to determine the k_La of the biomass samples. Oxygen transfer tests were performed in a 0.02 m^3 working volume bubble column of 2.5 m in height and 10 cm in diameter. The fine bubble diffuser was a single 6 cm diameter *Sanitaire* ceramic disc. The column was filled with biomass and the airflow was turned off until the DO concentration reached 0.8 mg L^{-1} or below and then adjusted to a specific airflow rate. The airflow rate was corrected for the impact of the liquid head pressure and normalised at atmospheric pressure. The DO concentration was monitored using a DO probe (*OxyGuard*) connected to a combined meter and data logger (*OxyLog*). The DO probe was located 1 m above the diffuser at a 45° angle in order to obtain a steady current on the probe membrane. The DO concentration and temperature were recorded until the DO reached its saturation value. Software (*OxyLog*) was used to download the data on a computer (*Partech Instruments*, St Austell, UK).

Ten biomass samples of 25 L were collected from seven different submerged MBRs (Table 1). The two pilot-scale and five full-scale plants all treated municipal wastewater except for Plant B, which treated both municipal and dairy wastewater. The plants were operated with either Zenon hollow fibres or Kubota flat sheet membranes. The samples were taken to Cranfield University Sewage Treatment Works Pilot Hall, transport times being <24 h. A homogeneous biomass sample of approximately 300 mL was taken from each container before the oxygen transfer experiments. The biomass characteristics of the sample were determined in the laboratory.

The non-linear regression method was used to determine k_La and the steady state dissolved oxygen saturation concentration, $C^*_{\infty f}$. (SPSS 11.0, SPSS UK Ltd, UK). The oxygen transfer coefficient values, k_La_f, were standardised at a temperature of 20 °C and are referred as k_La_{20} in this paper. The α-factor was calculated as the ratio of k_La_{20} in the biomass to k_La_{20} in clean water.

2.2. Analytical methods

Particle size distributions were determined by laser diffraction using a *Malvern* Mastersizer 2000 (Malvern Instruments

Table 1 – Biomass and plant characteristics of the submerged MBR sludges studied

Plant	A	A	B	C	D	E	F	D	G	G
MLSS (g L^{-1})	7.2	9.3	12.0	13.7	13.9	16.8	17.3	17.9	28.9	30.2
MLVSS (g L^{-1})	5.3	6.9	8.7	10.8	10.4	13.4	13.9	13.2	19.5	19.3
EPS_c (mg L^{-1})	111.4	265.5	167.0	184.1	175.3	226.2	201.8	130.1	252.2	154.1
EPS_p (mg L^{-1})	711.0	919.7	873.0	874.0	734.5	924.5	1216.0	1222.0	865.0	828.0
EPS_{COD} (mg L^{-1})	1442	1873	1802	1788	1570	1736	1846	1814	1536	1798
SMP_c (mg L^{-1})	4.63	7.00	3.44	15.25	9.94	7.75	9.38	9.75	20.75	8.56
SMP_p (mg L^{-1})	4.50	10.00	27.50	25.50	9.50	41.50	61.00	63.00	57.00	22.0
SMP_{COD} (mg L^{-1})	72	54	72	180	108	198	180	136	106	90
Viscosity at 12.24 s^{-1} (mPa s)	13.3	39.8	10.8	75.8	44.6	55.9	99.3	87.6	122.3	213.0
MMD (μm)	88.9	68.0	85.4	62.1	60.9	42.5	80.4	70.2	38.5	43.1
Plant scale	PP	PP	FS	PP	FS	FS	FS	FS	FS	FS
Type of membrane	Zenon	Zenon	Kubota	Kubota	Kubota	Kubota	Kubota	Kubota	Kubota	Kubota
Membrane area (m^2)	122	122	7680	5.6	1600	2880	320	1600	60	60

PP: pilot plant scale; FS: full scale; c: carbohydrate; p: protein.

Ltd., Malvern, UK) and reported as the mass median diameter (MMD) (Houghton et al., 2002). Viscosity was analysed at shear rates from 0.4 to 22 s^{-1} in a DV-E Brookfield digital viscometer using an Ultra Low (UL) Adapter, which consists of a cylindrical spindle rotating inside a tube (Brookfield Viscometers Ltd, Harlow, UK). Viscosity in this paper is quoted at a shear rate of 12.24 s^{-1}. The SMP were extracted by centrifuging the biomass for 5 min at 5000 rpm (Rotanta 96R, Hettich-Zentrifugen, Tuttlingen, Germany) and the supernatant filtered through 0.2 μm glass fibre filters (GF 52, Schleicher and Schuell, London, UK). The EPS were extracted following the heating procedure of Zhang et al. (1999). Protein and carbohydrate concentrations were determined by UV absorbance on a UV/visible spectrophotometer (Model 6505 S, Jenway, Dunmow, UK) with reference to bovine serum albumin (Sigma, Poole, UK) and glucose standards (Sigma, Poole, UK), respectively. The carbohydrate concentration was determined following the method of Dubois et al. (1956). Chemical oxygen demand (COD) was measured using a photometric method (Merck, VWR International Ltd., Poole, UK). Suspended solids were measured according to standard methods (APHA, 1998).

2.3. *Statistical analysis*

Statistical analysis was performed to determine the influence of biomass characteristics and airflow rates on oxygen transfer. The multiple regression analysis was chosen to analyse the relationship between the independent variables (biomass characteristics and aeration) and the dependent variable (oxygen transfer coefficient). Modified or standardised regression coefficients, called *Beta coefficients*, were used to interpret the regression model. They have a common unit of measurement and so allow direct comparison of the impact of each independent variable (Hair et al., 1998). Prior to the multiple regression analysis, the relationships between the biomass characteristics were examined by computing a Pearson product-moment correlation matrix. In case of multicollinearity, the process of determining the contribution of each independent variable would be made more difficult because the effects of the independent variables would be mixed or confounded. If variables are highly correlated to each other, only one of them should be kept to represent this group of variables in the multiple regression analysis. Correlation coefficients, r, equal to +1 or −1 represent a perfect positive or negative correlation respectively. A correlation coefficient value of 0 represents a lack of correlation. The data was analysed using Statistica (StatSoft Inc., 2000).

3. Results

Biomass with MLSS concentrations ranging from 7.2 to 30.2 $g\,L^{-1}$ were examined (Table 1). The oxygen transfer characteristics (k_La_{20} and α-factor) were compared with the volumetric airflow rates and MLSS concentrations. An increase in volumetric airflow led to an increase in k_La_{20} (Fig. 1), whereas an increase in MLSS resulted in an exponential decrease in $k_La_{20,}$ as shown in Fig. 2 for the mean values (individual graphs for each airflow rate studied showed the same exponential trend). The k_La_{20} decreased sharply for biomass conditions at MLSS concentrations ranging between 7.2 and 17.9 $g\,L^{-1}$. At MLSS concentrations $\geq$17.9 $g\,L^{-1}$, k_La_{20} values were very low; further increases in MLSS did not lead to a significant decrease in k_La_{20}. At very high MLSS concentrations (>17.9 $g\,L^{-1}$) the impact of volumetric airflow rate became insignificant. Biomass with the lowest MLSS

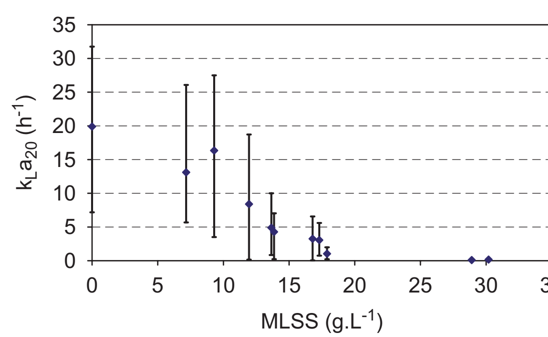

Fig. 2 – k_La_{20} averaged for all volumetric airflow rates vs. MLSS concentration (mean values and ranges).

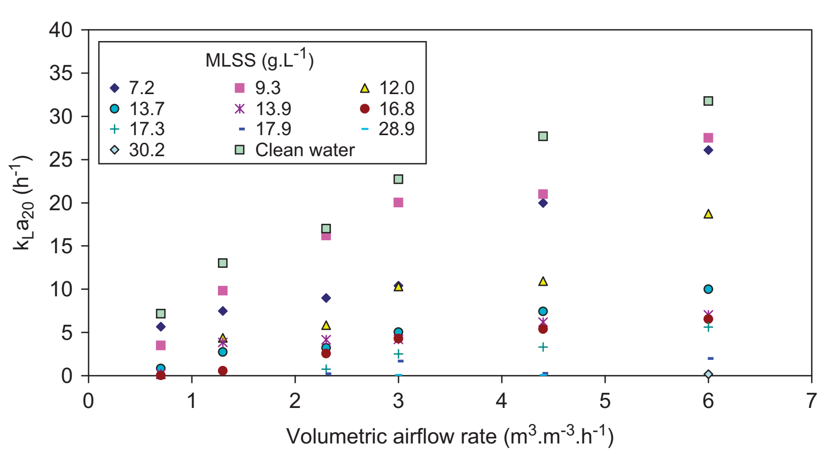

Fig. 1 – k_La_{20} vs. volumetric airflow rate for the 10 MLSS concentrations studied.

Table 2 – Pearson-r correlation matrix of the characteristics of the biomass studied for their impact on oxygen transfer

	MLVSS	SMP_{COD}	EPS_{COD}	SMP_p	EPS_p	SMP_c	EPS_c	MMD	Viscosity
MLSS	0.98	0.36	−0.11	0.78	0.31	0.80	0.41	−0.70	0.86
MLVSS		0.51	−0.02	0.83	0.40	0.78	0.41	−0.70	0.89
SMP_{COD}			0.28	0.55	0.46	0.32	0.06	−0.38	0.53
EPS_{COD}				0.31	0.69	−0.19	0.28	0.13	0.11
SMP_p					0.80	0.44	0.14	−0.30	0.80
EPS_p						0.05	0.03	0.09	0.55
SMP_c							0.41	−0.70	0.84
EPS_c								−0.63	0.37
MMD									−0.55

concentrations and the highest volumetric airflow rates led to the highest k_La_{20} values, whereas biomass with the highest MLSS and the lowest volumetric airflow led to the lowest k_La_{20} values, which were sometimes below the limit of detection (Fig. 1). Both the biomass characteristics and the volumetric airflow rate were found to have an impact on k_La_{20}.

Prior to the multiple regression analysis, the biomass characteristics (Table 1) were assessed for linear multicollinearity. The three variables found to be consistently highly correlated to each other (p-level>0.01 and $r\geqslant 0.86$) were MLSS and MLVSS concentrations and viscosity (Table 2). Due to high correlations between these three variables, their separate effect on the oxygen transfer could not be determined. The MLSS was therefore chosen to represent this group of variables in the multiple regression analysis.

The independent variables included in the regression model were MLSS, EPS_c, EPS_p, EPS_{COD}, SMP_c, SMP_p, SMP_{COD}, MMD and volumetric airflow rate (aeration); units of biomass variables were the same as Table 1 and the aeration variable was in $m^3\,m^{-3}\,h^{-1}$. The dependent variable was k_La_{20} in h^{-1}. The variables found to have an impact on k_La_{20} were MLSS, EPS_c, SMP_{COD} and aeration (Table 3). According to the Beta coefficients, their degrees of influence were, from the greatest to the lowest: MLSS$>$aeration$>EPS_c>SMP_{COD}$. The MLSS and the SMP_{COD} had a statistically negative influence on k_La_{20}, i.e. an increase in these variables led to a decrease in k_La_{20}, whereas the aeration and the EPS_c had a statistically positive influence on k_La_{20}: an increase in these variables led to an increase in k_La_{20}. However, EPS_p, EPS_{COD}, SMP_c, SMP_p, and MMD were found to have no impact on k_La_{20} within the range of parameters studied.

No particular relationship was observed between aeration and α-factor (Fig. 3), whereas an increase in MLSS led to an exponential decrease in α-factor as shown in Fig. 4 for the mean values (individual graphs for each airflow rate studied showed the same exponential trend). The α-factor decreased sharply for biomass conditions with MLSS up to $17.9\,g\,L^{-1}$. No significant decrease in α-factor was observed for further increases in MLSS concentration.

The same independent variables as for the k_La_{20} study were entered in the regression models, with α-factor as the dependent variable. The variables found to have an influence on α-factor were, from the greatest to the lowest effect and according to the Beta coefficients: MLSS$>SMP_{COD}>$EPS-

Table 3 – *Beta coefficients* and statistical significance parameters obtained by regression analysis for k_La_{20}

MLSS	−0.66
Aeration	0.56
EPS_c	0.33
COD_{SMP}	−0.31
R^2	80%
F	$F_{(4,39)}=38.9$
p-level	<0.001

c$>$aeration (Table 4). MLSS and SMPCOD had a statistically negative influence on α-factor, i.e. an increase in these variables led to a decrease in α-factor. In contrast, EPS_c and aeration had a statistically positive influence on α-factor: an increase in these variables led to an increase in α-factor. According to the β coefficients (Table 4). MLSS had the greatest effect on α-factor. SMP_{COD} and EPS_c exerted almost the same degree of influence. The EPS_p, EPS_{COD}, SMP_c, SMP_p, and MMD were not detected as variables having a significant influence on α-factor within the range of parameters studied.

Therefore the same parameters were found to affect k_La_{20} and α-factor: volumetric airflow rate, MLSS concentration (therefore also: MLVSS and viscosity), SMP_{COD} and EPS_c. However EPS_p, EPS_{COD}, SMP_c, SMP_p and MMD did not have an impact on oxygen transfer. In summary, both k_La_{20} and α-factor, respectively increased with increasing aeration and EPS_c and decreased with increasing in MLSS and SMP_{COD}. The order of their degrees of influence for k_La_{20} were: MLSS$>$aeration$>EPS_c>SMP_{COD}$ and for α-factor: MLSS$>SMP_{COD}>EPS_c>$aeration.

4. Discussion

Several studies have also reported an exponential correlation between α-factor and MLSS concentration: (Muller et al., 1995; Rosenberger, 2003; Krampe and Krauth, 2003). These studies were undertaken in tanks of different geometries using dissimilar aeration devices leading to different energy dissipation rates and shear stresses. For the present study, high variations were observed around the means (Fig. 5) and these related to changes in volumetric airflow rate.

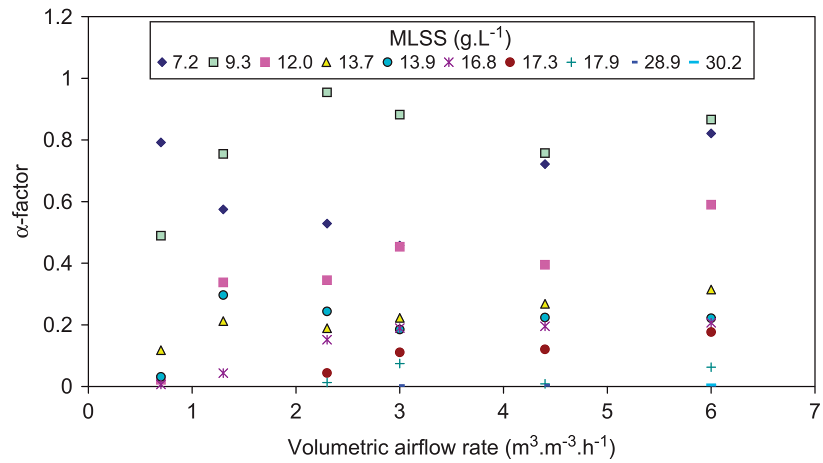

Fig. 3 – α-factor vs. volumetric airflow rate for the 10 MLSS concentrations studied.

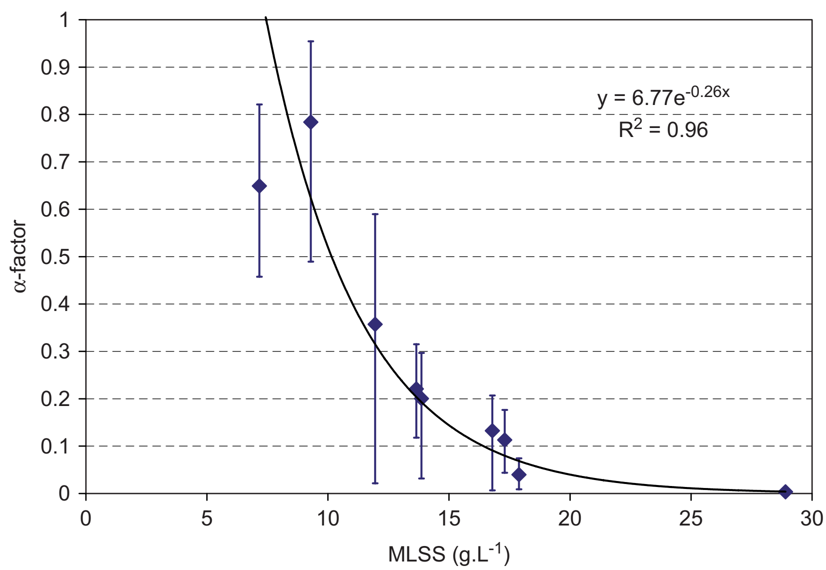

Fig. 4 – α-factor averaged for all volumetric airflow rates vs. MLSS concentration (mean values and ranges).

Table 4 – *Beta coefficients* and statistical significance parameters obtained by regression analysis for α-factor

MLSS	−0.75
COD_{SMP}	−0.40
EPS_c	0.38
aeration	0.21
R^2	89%
F	$F_{(4,39)} = 91.2$
p-level	<0.001

MLSS was found to be the main parameter controlling both k_La_{20} and α-factor, corroborating several studies which have established the negative effects of solids concentration on oxygen transfer (Ju and Sundararajan, 1994; Muller et al., 1995; Freitas and Teixeira, 2001; Krampe and Krauth, 2003; Rosenberger, 2003). Moreover, the MLSS concentration also accounted for the effects of the viscosity, which has been shown to have a noticeable effect on oxygen transfer (Garcia-Ochoa et al., 2000; Badino et al., 2001; Jin et al., 2001; Rosenberger, 2003). The MLSS concentration can be controlled by adjusting sludge wastage (Stephenson et al., 2000). Therefore oxygen transfer can be improved by keeping the MLSS low i.e., $<$10–15 g L^{-1}.

In order to be able to reach the active sites of the bacterial cell membrane, the oxygen contained in the air bubbles needs to penetrate the liquid film surrounding the flocs (SMP) and then diffuse through the floc matrix (EPS) (Mueller et al., 2002). The COD fraction of the SMP was found to have an influence on oxygen transfer but not the carbohydrate and protein fractions. The COD mainly pertains to organic material in wastewater, which includes proteins and

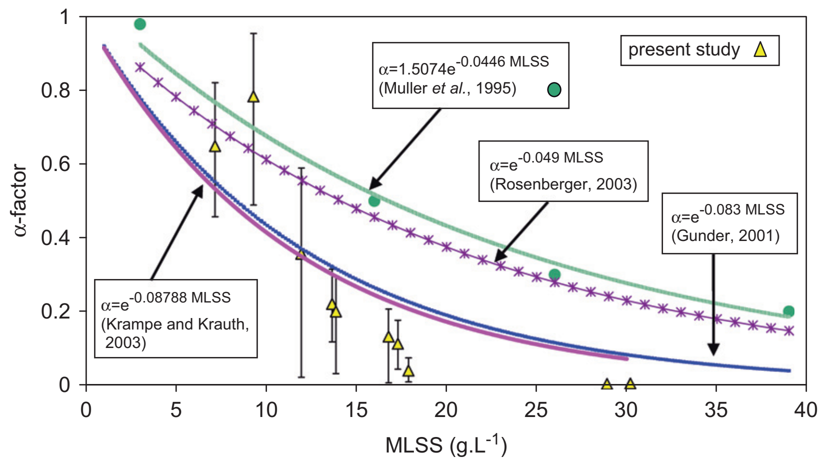

Fig. 5 – Comparison of the correlations obtained between α-factor and MLSS concentration for several studies (means and ranges showed for the present).

carbohydrates. Some compounds in the wastewater liquid phase that have a major impact on the oxygen transfer are surfactants (WEF and ASCE, 2001; Mueller et al., 2002). As surfactants are organic molecules, the COD measurement can be expected to partly account for the surfactants present in the biomass. Surfactants affect the two terms making up k_La, by reducing the liquid film mass transfer coefficient, k_L, and by increasing the surface area, a (Mueller et al., 2002). In the present study, an increase in SMP_{COD} led to a decrease in both k_La_{20} and α-factor, suggesting that the liquid film coefficient was more affected by the SMP_{COD} than the surface area. The impact of the SMP_{COD} on the oxygen transfer parameters could be explained by the presence of surfactants in the biomass.

Only the carbohydrate fraction of the EPS_e was found to have an impact on oxygen transfer. This substance contributes to the fundamental structure of the EPS matrix, facilitating the aggregation of cells and the formation of large flocs (Wingender et al., 1999). Large flocs possess higher porosities than small ones, corresponding to higher diffusivities (Mueller et al., 2002). The EPS_c was the main EPS fraction influencing oxygen transfer, suggesting that, in the present study, the carbohydrate of the EPS increased floc porosity and therefore diffusivity.

Among the three biomass parameters found to affect the oxygen transfer parameters, the MLSS concentration was the easiest to control. Therefore, by operating MBRs at MLSS concentrations below 10–15 $g L^{-1}$, their oxygen transfer efficiency could be improved and their aeration costs kept reasonable.

5. Conclusions

- An increase in solids concentration led to an exponential decrease in both k_La_{20} and α-factor.
- The k_La_{20} and α-factor were affected by the same parameters: the volumetric airflow rate, the MLSS concentration (and its correlated parameters; MLVSS and viscosity), the SMP_{COD} and the EPS_c.
- The MLSS was the main parameter controlling k_La_{20} and α-factor and should be $<$10–15 $g L^{-1}$ to improve the oxygen transfer efficiency.
- The presence of SMP_{COD} had a negative effect on oxygen transfer, probably due to the presence of surfactants.
- EPS_c, by facilitating the formation of large flocs, increased the porosity of the flocs and therefore their diffusivity, which was beneficial to oxygen transfer.

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