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APPROPRIATE TECHNOLOGIES TO COMBAT WATER POLLUTION

Limitations imposed by conventional fine bubble diffusers on the design of a high-loaded membrane bioreactor (HL-MBR)

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Abstract

The operation of membrane bioreactors (MBRs) at higher than usual mixed liquor suspended solids (MLSS) concentrations may enhance the loading rate treatment capacity while minimizing even further the system's footprint. This requires operating the MBR at the highest possible MLSS concentration and biomass activity (e.g., at high loading rates and low solid retention times (SRTs)). Both a negative effect of the MLSS concentrations and a positive effect of the SRT on the oxygen transfer have been reported when using conventional fine bubble diffusers. However, most of the evaluations have been carried out either at extremely high SRTs or at low MLSS concentrations eventually underestimating the effects of the MLSS concentration on the oxygen transfer. This research evaluated the current limitations imposed by fine bubble diffusers in the context of the high-loaded MBR (HL-MBR) (i.e., high MLSS and short SRT—the latter emulated by concentrating municipal sludge from a wastewater treatment plant (WWTP) operated at a short SRT of approximately 5 days). The high MLSS concentrations and the short SRT of the original municipal sludge induced a large fraction of mixed liquor volatile suspended solids (MLVSS) in the sludge, promoting a large amount of sludge flocs that eventually accumulated on the surface of the bubbles and reduced the free water content of the suspension. Moreover, the short SRTs at which the original municipal sludge was obtained eventually appear to have promoted the accumulation of surfactants in the sludge mixture. This combination exhibited a detrimental effect on the oxygen transfer. Fine bubble diffusers limit the maximum MLSS concentration for a HL-MBR at 30 g L^{-1}; beyond that point is either not technically or not economically feasible to operate; an optimum MLSS concentration of 20 g L^{-1} is suggested to maximize the treatment capacity while minimizing the system's footprint.

Keywords Bubble diffusers · High-loaded membrane bioreactor · High mixed liquor suspended solids · Sludge retention time · Sludge stabilization · Alpha factor

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Introduction

The MBR has become a popular wastewater treatment technology. Alternatively to the gravity settlers installed in CAS systems for solid-liquid separation purposes, MBRs are provided with low-pressure filtration membranes achieving higher solid-liquid separation efficiencies. As such, specific advantages of MBRs include the following: (i) a consistent and reliable high-quality effluent that can comply with the most strengthened discharge standards; (ii) low footprint; (iii) low production of highly digested sludge; (iv) stable control conditions for effective nutrient removal; and (v) robustness to handle shock loads; among others (Henze et al. 2008; Judd and Judd 2011; Mannina and Cosenza 2013; Mohammed et al. 2008; Mutamim et al. 2013; Pollice et al. 2008).

Moreover, to operate at MLSS concentrations even beyond the typical MBR MLSS range (e.g., > 15 g L^{-1}) can lead to a HL-MBR which has additional advantages that include the following: (i) increased capacity to treat higher organic loading rates, (ii) increased oxygen uptake rates (OURs) linked to higher chemical oxygen demand (COD) conversion rates, (iii) minimized footprint, reduced volume, and therefore lower construction costs, and (iv) reduced waste solids generation and handling costs (Barreto et al. 2017; Livingstone 2010). Furthermore, these advantages may encourage the design of compact and containerized movable/portable MBRs for the treatment of municipal and industrial wastewaters in remote areas without access to sewer systems offering additional opportunities for water reuse (Hai and Yamamoto 2011; Hai et al. 2014); moreover, on-site/decentralized alternatives can be designed for sanitation provision under emergency situations originated by either natural or man-made disasters (Barreto et al. 2017). A HL-MBR operated at MLSS concentrations of up to 40–50 g L^{-1} can be accomplished by operating the MBR system at a high influent loading rate and at a relatively low or typical SRT (of approximately 5 to 20 days), resulting in a high MLSS concentration composed of primarily active biomass. By following this operation strategy, the treatment capacity of an MBR system can be enhanced by reducing even further the footprint at a given loading rate or, alternatively, for a given footprint increasing the loading rate treatment capacity.

Several authors have evaluated the effects of the MLSS concentration on the oxygen transfer (alpha factor) being the alpha factor the oxygen mass transfer ratio of process water to clean water. Most of the studies were conducted at standard (CAS relevant) MLSS concentrations ranging from approximately 3 to 5 g L^{-1}. Only a few studies were indeed conducted at a high range of MLSS concentrations, up to approximately 39 g L^{-1} (Muller et al. 1995). Overall, those studies indicate that the main limitation to operate an MBR at such high range of MLSS concentrations seems to be the rather poor to negligible oxygen transfer efficiencies observed when using conventional diffused aeration systems (such as fine and coarse bubble diffusers) (Cornel et al. 2003; Durán et al. 2016; Germain et al. 2007; Henkel et al. 2011; Krampe and Krauth 2003; Muller et al. 1995). However, those few evaluations conducted at such high range of MLSS concentrations were carried out at extremely high (even infinite) SRTs; that is, an opposite condition to that required to achieve a HL-MBR. In accordance with Rosso et al. (2008), the oxygen transfer efficiency is proportional to the SRT: the longer the SRT, the higher the oxygen transfer efficiency and the alpha factor. However, the beneficial effect of the SRT on the alpha factor was determined and reported mostly at low MLSS (CAS relevant) concentrations from approximately 3 to 6 g L^{-1}, and there is no information reported on the effects of the SRT on the alpha factors at high (HL-MBR relevant) MLSS concentrations. This suggests that the previously reported alpha factors may not be realistic and directly applicable when designing a HL-MBR with a short (or typical) SRT, an increased loading rate, and a minimized system footprint.

In addition, another discrepancy on the assessment of the alpha factor at different MLSS concentrations lies on the wide range of volumetric air flowrates (VAFRs) applied in previous studies that range from 3.3 up to even 60 $m^3\ m^{-3}\ h^{-1}$ (Cornel et al. 2003; Günder 2000; Krampe and Krauth 2003; Muller et al. 1995), resulting in different alpha factor values reported at similar MLSS concentrations. However, Germain et al. (2007) evaluated the effects of the VAFRs from 0.7 to 6 $m^3\ m^{-3}\ h^{-1}$ on the alpha factors at an MLSS range from approximately 7 to 30 g L^{-1} and could not find any particular relationship between the VAFR and the alpha factor. Last but not the least, all the previous work was carried out using air as the main oxygen source. To our knowledge, only Rodríguez et al. (2011) assessed the alpha factors in the context of MBRs operated with pure oxygen rather than air. When pure oxygen was supplied, they observed no major differences on the alpha factors compared to the studies performed with air.

Designing a HL-MBR for maximizing the treatment capacity while minimizing the system's footprint requires the operation of the biological system at the highest possible biomass activity; which corresponds to the highest biologically active MLVSS concentration obtained by operating the system at high loading rates and relatively low SRTs. This implies that the limitations imposed by conventional bubble diffusers (measured in terms of the alpha factor) at that particular set of operational conditions (high MLSS and low SRT) need to be better understood. The few studies conducted at high MLSS concentrations, which were also conducted at high SRTs, could have underestimated the effect of the MLSS concentration on the alpha factor. Moreover, the beneficial effect of the SRT on the alpha factor was determined and reported mostly at low MLSS (CAS relevant) concentrations from approximately 3 to 6 g L^{-1}, and consequently, there is no information reported on the effects of the SRT on the alpha factors at high (HL-MBR relevant) MLSS concentrations. Therefore, there is a gap in the literature to better understand the effects of the high MLSS concentration on the alpha factor on a mixed liquor produced at relatively standard (low) SRT conditions when using conventional diffusers (within the context of the operational design conditions of the HL-MBR).

This research aimed at evaluating the current limitations imposed by conventional bubble diffusers in the context of the HL-MBR. Particularly, this research investigated the effect of high MLSS concentration on the alpha factor on municipal sludge obtained from a WWTP operated at a short SRT of approximately 5 days (that is, on a mixed liquor composition similar to the mixed liquor expected on a HL-MBR system); the impact of the different MLSS concentrations on the alpha factor at different VAFRs, oxygen sources, and at different sludge stabilization levels were evaluated. In addition, this research provides insight and guidelines on the design and operation of HL-MBR systems considering the limitations imposed by conventional diffusers.

Materials and methods

Design of experiments

To evaluate the performance of conventional bubble diffusers in the context of the HL-MBR operated at high MLSS (high active biomass) concentrations, the oxygen transfer performance of a fine bubble diffuser (SANITAIRE® Silver Series 2, Xylem, USA) was assessed in mixed liquor at MLSS concentrations of approximately 4, 10, 20, 30, and 40 g L^{-1}. Fresh mixed liquor was taken from the municipal WWTP of the city of Zagreb (Zagreb, Croatia) and concentrated up to the desired MLSS concentration value. The evaluation was carried out supplying either air or pure oxygen at different flow rates. Moreover, the aeration performance at each of the assessed MLSS concentrations was evaluated at different degrees of sludge stabilization by repeating the oxygen transfer evaluations after aerating the mixed liquor (sludge) for 24, 48, and 72 h. At each of the evaluated experimental conditions, the overall oxygen mass transfer rate coefficient (K_La) was determined and reported at standard conditions. The K_La was also evaluated in clean water and reported at standard conditions. The K_La values were adjusted considering the oxygen intrusion from the atmosphere. The ratio of the K_La in mixed liquor and in clean water was calculated and reported as the alpha factor.

Analytical methods

MLSS and MLVSS were analyzed according to the standard methods for the examination of water and wastewater as described in APHA (1998). The temperature and DO both in clean water and mixed liquor were determined with a DO probe (WTW Oxi 3310, Germany). The pH was determined with a pH probe (SI Analytics GmbH, Germany). Both the DO and pH determinations were adjusted by the temperature.

Oxygen uptake rate

The OUR determinations were carried out with a biological oxygen meter (BOM) based on the batch respirometric method (Kappeler and Gujer (1992)). The BOM consisted of a glass container equipped with a DO probe (WTW Oxi 3310, Germany) and a stirring plate (IKA® RH B2, Germany). A Master flex peristaltic pump (Cole-Parmer, USA) recirculated the sludge from an aerobic reactor under evaluation through the BOM. When the BOM was filled with the sludge, the pump stopped and the decrease in DO as a function of time was monitored and recorded by the DO probe. After determining the OUR, the sludge was returned back to the reactor. A DO range from 6.5 to 2.5 mg L^{-1} was used to calculate the OURs. OURs were determined in triplicate before and after conducting each specific experiment. Since each experiment was also carried out in triplicate, a total of 12 OUR determinations were carried out for every single experimental condition. The average value of the calculated OUR from each experiment was used for the determination of the reported K_La.

Particle-size distribution and viscosity

The particle-size distribution (PSD) was determined using a Malvern Mastersizer 2000 laser diffraction particle counter (Malvern Instruments Ltd., Malvern, UK). The apparent viscosity at a shear rate of 780 s^{-1} was measured at constant temperature (20 °C) using a viscometer Rheometric RM-180 (proRheo GmbH, Germany).

Experimental procedures

Collection and preparation of the sludge

Fresh activated sludge was collected from the WWTP of the city of Zagreb located in Zagreb, Croatia. The WWTP was designed only for carbon removal. The plant was operated as a CAS process at an SRT of approximately 5 days and at an average MLSS concentration of approximately 4 g L^{-1}. The sludge was collected from one of the aerobic basins at the WWTP for the K_La determinations. The sludge was concentrated either by gravity settling or membrane filtration to reach the desired MLSS concentrations. For reaching the lower range of MLSS concentrations (for instance, 4 and 10 g L^{-1}), the sludge was concentrated mostly by gravity settling at the WWTP facility. The 4 g L^{-1} MLSS concentration was directly prepared by sampling sludge from the aerobic basin without any further concentration step. To prepare the 10 g L^{-1} MLSS concentration, approximately 100 L of sludge was sampled and introduced into 20-L containers. The mixture was settled for approximately 30 min until reaching the desired MLSS concentration by periodically removing the supernatant.

To reach the higher range of evaluated MLSS concentrations (that is, 20, 30, and 40 g L^{-1}), the sludge was concentrated by membrane filtration. A rectangular-based (24 × 24 × 93 cm) 40-L bench-scale MBR provided with hollow fiber membranes (Zenon ZeeWee™-10, 0.4-µm pore size, 0.92-m^2 surface area) vertically submerged was used to concentrate the sludge. Sludge with a starting MLSS concentration of approximately 10 g L^{-1} (from the previously described gravity concentration step) was introduced into the MBR to achieve the desired sludge concentration. The sludge transport time from the WWTP to the laboratory, where the membrane concentration step was conducted, was less than an hour. The concentrated sludge was then aerated in the laboratory for approximately 24 h before initiating the oxygen transfer evaluations.

Experimental set up

The oxygen transfer performance experiments were conducted in a cylindrical plastic reactor with a total working volume of approximately 20 L. The reactor was equipped with a fine bubble diffuser (SANITAIRE® Silver Series 2, Xylem, USA) situated on the bottom of the reactor and a mixer with a propeller length of approximately 0.25 m (Heidolph Instruments GmbH, RZR 2102 control, Germany). A DO probe connected to a data logger (WTW Oxi 3310, Germany) was employed to monitor the DO concentration in the suspension. The reactor was aerated either using air or pure oxygen. The air was provided by a HIBLOW HP 80 air blower (Techno Takatsuki, Japan) for air flow rates (AFRs) from 0.1 to 1 $m^3\ h^{-1}$ and by an AIRMAC air blower (Model number: DB 150, Taiwan) for an AFR of 4 $m^3\ h^{-1}$. Pure oxygen was provided by means of a pure oxygen cylinder (MESSER, Croatia). Both the air and the pure oxygen were supplied to the reactor through the fine bubble diffuser. The air and oxygen gas flow rates were determined as follows: the flow rates ranging from 0.02 to 0.1 $m^3\ h^{-1}$ were measured by a DK 800 series flowmeter (KROHNE Messtechnik GmbH, Germany); the flow rates ranging from 0.5 to 1 $m^3\ h^{-1}$ were measured by a Cole-Parmer flowmeter (EW-32461-44, USA); and the flow rate of 4 $m^3\ h^{-1}$ was measured by a KING flowmeter (KING instrument, USA).

Air intrusion experiments

The K_La due to the air intrusion in clean water was determined by the non-steady-state batch test in clean water (WEF and ASCE 2001). Nitrogen was sparged into the reactor until reaching a DO concentration below approximately 0.5 mg L^{-1}. Then, the mixer was started at an identical mixing intensity as to be used in the oxygen transfer experiments. The DO concentration was continuously monitored and recorded until reaching a DO concentration of approximately the DO atmospheric saturation value. The K_La value was then calculated by a non-linear regression carried out with the Microsoft Excel software add-in SOLVER getting the best fit between the measured and calculated DO.

Oxygen transfer performance experiments in clean water

The K_La in clean water was determined by the non-steady-state batch test in clean water (WEF and ASCE 2001). The K_La in clean water was determined for all the evaluated flow rates and oxygen sources. For all evaluated experimental conditions as described in Table 1, the same experimental procedure was carried out as follows. The reactor was filled with 20 L of tap water. The DO concentration was depleted by sparging nitrogen gas until measuring a DO concentration below 0.5 mg L^{-1}. Then, oxygen was supplied at the desired flow rate by either supplying air or pure oxygen through the fine bubble diffuser. The DO concentration was continuously monitored and recorded until reaching a stable DO concentration. The K_La value was calculated as described in the "Air intrusion experiments" section. The oxygen intrusion from the atmosphere was taken into account for adjusting the K_La values in clean water. The experiments were conducted in triplicate, and an average K_La value at each experimental condition was reported.

Oxygen transfer performance experiments in mixed liquor

The concentrated sludge collected from the WWTP was aerated overnight prior to the experiments. The K_La of the sludge at the evaluated concentrations was determined by the non-steady-state batch test under endogenous respiration conditions (WEF and ASCE 2001). For all the evaluated experimental conditions as described in Table 1, the same experimental procedure was carried out as follows. The reactor was filled with 20 L of mixed liquor at the desired concentration. The DO concentration was depleted by sparging nitrogen gas until the DO concentration was below 0.5 mg L^{-1}. Then, oxygen was supplied at the desired gas flow rate either supplying air or pure oxygen through the fine bubble diffuser. The DO concentration was continuously monitored and recorded until reaching an equilibrium DO concentration. The OURs were determined before and after each evaluation as described in the "Oxygen uptake rate" section. Moreover, samples were taken at the end of each evaluation to determine both the PSD and viscosity. The K_La value was calculated by conducting a non-linear regression with the Microsoft Excel software add-in SOLVER as described in the "Air intrusion experiments" section; the values were corrected considering the oxygen intrusion from the atmosphere through the surface. The experiments were performed in triplicate and the average K_La was reported for each experimental condition. After conducting each test, the sludge was aerated for a period of 24 h, and the experiments previously described were repeated; then this procedure was repeated again. Thereafter, the oxygen transfer performance was evaluated at a range of MLSS from 4 to 40 g L^{-1} using different oxygen sources (air or pure oxygen) at different gas flow rates (from 0.02 to 4 $m^3\ h^{-1}$) and at different degrees of sludge stabilization (after aerating the sludge for 24, 48, and 72 h). All the determined K_La were corrected to 20 °C temperature, and the alpha factors were calculated and reported. A summary of the entire evaluated experimental conditions is presented in Table 1.

Table 1 Evaluated experimental conditions

Experiment		Gas flow rates ($m^3\ h^{-1}$)		Oxygenation time before measurements (hours)
		Air	Oxygen	
Clean water		0.1, 0.5, 1, 4	0.02, 0.1	–
Sludge MLSS ($g\ L^{-1}$)	4			24, 48, 72
	10			
	20			
	30			
	40	0.5, 1, 4	0.1	

Results and discussion

To evaluate the current limitations imposed by conventional bubble diffusers on the HL-MBR, the effect of the MLSS concentration on the alpha factor was evaluated on municipal sludge obtained from a WWTP operated at an SRT of approximately 5 days. The evaluation was carried out at different operational conditions including different oxygen sources (air and pure oxygen) and at different volumetric air/oxygen flow rates. In addition, the impact of the MLSS concentration on the alpha factor was determined at different levels of sludge stabilization indicated by the sludge specific OUR (SOUR). The results and discussion first introduce the impact of the MLSS concentration on the alpha factor at the evaluated oxygen sources and at the different air/oxygen flow rates. Then, the effect of the sludge stabilization on the alpha factor is introduced. Finally, a discussion is presented on the current limitations imposed by the bubble diffusers and possibilities for designing and operating the HL-MBR.

Impact of the MLSS concentration on the alpha factor at different air/oxygen flow rates

Figure 1 shows the effect of the MLSS concentration on the alpha factor when supplying either air (Fig. 1a) or pure oxygen (Fig. 1b) at different air/pure oxygen flow rates. Regardless of the specific AFR, the alpha factor decreased as the MLSS concentration increased. Particularly, at an MLSS concentration of approximately 20 g L^{-1}, non-detectable alpha factors were reported at a flow rate of 0.1 $m^3\ h^{-1}$. Similarly, at an MLSS concentration of approximately 30 g L^{-1}, non-detectable alpha factors were reported at AFRs of 0.1, 0.5, and 1 $m^3\ h^{-1}$. In addition, at an MLSS concentration of approximately 40 g L^{-1}, non-detectable alpha factors were reported for the entire range of evaluated AFRs. Figure 1b indicates the effect of the MLSS on the alpha factor at the evaluated pure oxygen flow rates (POFRs) of 0.02 and 0.1 $m^3\ h^{-1}$. As observed as when supplying air (Fig. 1a), the alpha factor decreased as the MLSS increased, regardless the POFR. However, at an MLSS concentration of approximately 20 g L^{-1}, the alpha factors were detected at all the evaluated POFRs. At an MLSS concentration of 30 g L^{-1}, non-detectable alpha factors were observed at the POFR of 0.02 $m^3\ h^{-1}$. In addition, as observed when supplying air, at an MLSS concentration of approximately 40 g L^{-1}, non-detectable alpha factors were reported for the entire evaluated POFR range.

The overall trends in Fig. 1a and b showed that the alpha factor decreased as the MLSS concentration increased. The higher the MLSS concentration, the more noticeable the effect of the suspended solids limiting the oxygen diffusion from the fine bubbles into the liquid phase. This observation is in accordance with previously reported studies investigating the relationship between the alpha factor and the MLSS concentration (Cornel et al. 2003; Germain et al. 2007; Günder 2000; Henkel et al. 2009b; Krampe and Krauth 2003; Muller et al. 1995; Rosenberger 2003). These studies reported wide ranges of alpha factors at specific MLSS concentrations; alpha factors from approximately 0.5 to 1.0 were reported at an MLSS concentration of 5 g L^{-1}, while alpha factors from non-detectable to 0.3 were reported at an MLSS concentration of 40 g L^{-1}. The alpha factors obtained in the present work as indicated in Fig. 1 fitted well within the ranges previously reported in the literature at MLSS concentrations below 30 g L^{-1}. However, at MLSS concentrations higher than approximately 30 g L^{-1}, the alpha factors obtained in this research (mostly non-detectable) dropped below the previously reported values (Cornel et al. 2003; Germain et al. 2007; Günder 2000; Henkel et al. 2009b; Krampe and Krauth 2003; Muller et al. 1995; Rosenberger 2003). This means that a stronger negative impact of the MLSS concentration on the alpha factor was observed in this research compared to the literature. A linear regression analysis was carried out for determining the best expression that relates the alpha factor to the MLSS concentration; the linear regression results when supplying either air or pure oxygen are shown in Fig. 1a and b, respectively. Günder (2000) and Muller et al. (1995) also carried out linear regression analyses to determine the best expression to relate the alpha factor to the MLSS concentration when supplying air; their main findings are reported below in Eqs. 1 and 2, respectively. Particularly, when operating at high MLSS concentrations of approximately 40 g L^{-1} (aim of this research), alpha factors of 0.036 and 0.25 are calculated when using the expressions reported by Günder (2000) and Muller et al. (1995), respectively. When using the expression obtained in this research, an alpha factor of 0.014 is obtained.

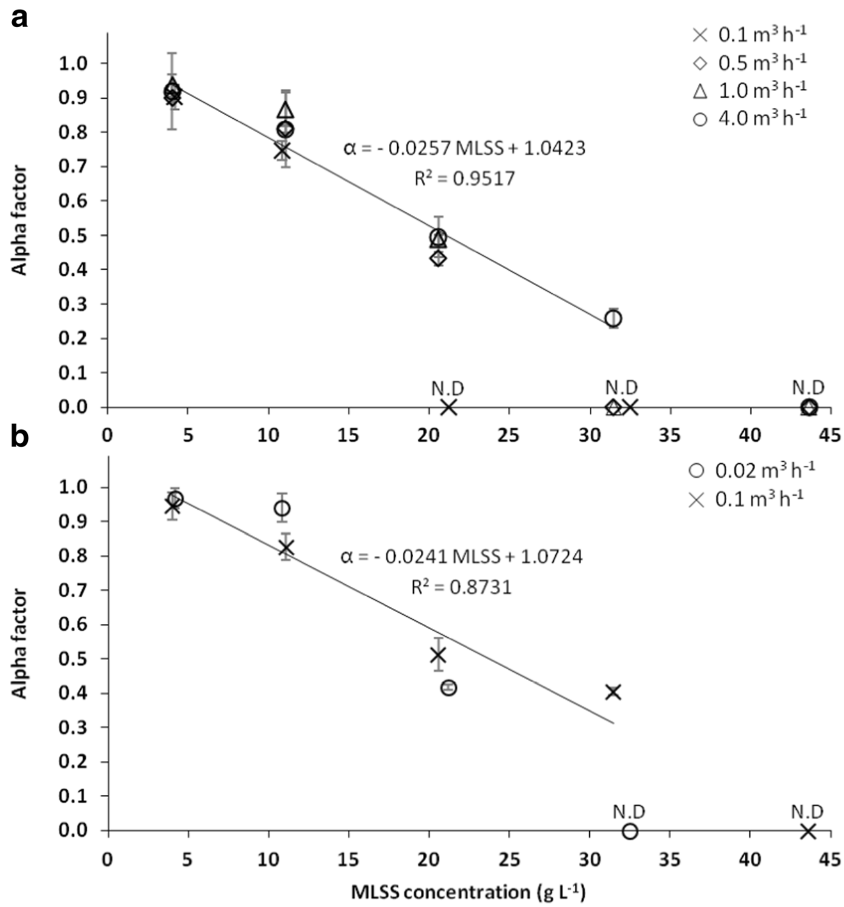


Fig. 1 **a** Impact of the MLSS concentration on the alpha factor at different AFRs; the linear regression analysis corresponds to the average values of alpha factors determined at the evaluated AFRs of 0.1, 0.5, 1.0, and 4.0 m^3 h^{-1}; **b** impact of the MLSS concentration on the alpha factors at different POFRs; the linear regression analysis corresponds to the average values of alpha factors determined at the evaluated POFRs of 0.02 and 0.1 m^3 h^{-1}

That is, at high MLSS concentrations (that is, higher than approximately 30 g L^{-1}), lower alpha factors were obtained in this research compared to the values reported by other authors such as Günder (2000) and Muller et al. (1995). This research was conducted with sludge obtained from a WWTP working at a short SRT of approximately 5 days, while most of the research reported in the literature were carried out at very high (even infinite) SRTs. The negative effect of short SRTs on the alpha factor was reported by several authors (Gillot and Héduit 2008; Groves et al. 1992; Henkel et al. 2009a, 2011; Rieth et al. 1995; Rodríguez et al. 2012; Rosso and Stenstrom 2005, 2007; US EPA 1989). However, previous studies were all conducted at low (CAS relevant) MLSS concentrations in the range from 3 to 6 g L^{-1} rather than at the high MLSS concentration range carried out in this research.

$$\alpha = e^{-0.083\ MLSS} \tag{1}$$

$$\alpha = 1.507e^{-0.0446\ MLSS} \tag{2}$$

α Alpha factor (unitless)
MLSS Mixed Liquor Suspended Solids (g L^{-1})

Moreover, most of the authors reported a negative exponential relationship between the alpha factor and the MLSS concentration (Cornel et al. 2003; Günder 2000; Krampe and Krauth 2003). However, the results from this research indicated a negative linear relationship between the alpha factor and the MLSS concentration, as observed in Fig. 1. A similar negative linear relationship was observed by Henkel et al. (2009b) who reported higher alpha factors compared to the literature at the evaluated MLSS concentrations. The authors claimed that since they were working with gray water sludge, the sludge MLVSS/MLSS ratios were much lower compared to municipal sludge. Consequently, when reporting the alpha factors as a function of the MLVSS concentration rather than at the MLSS concentration, similar (lower) alpha factors as reported by other authors were obtained; in addition, probably the most important finding reported by Henkel et al. (2009b), a negative linear relationship between the alpha factor and the MLVSS concentration was observed. As such, the MLVSS, and not the MLSS, exhibited a direct impact on the oxygen transfer performance. Henkel (2010) reported that correlating the alpha factors to the MLSS led to a wide spread of the reported alpha factor at specific MLSS concentrations. In addition, the author correlated the alpha factors reported by others (Cornel et al. 2003; Germain et al. 2007; Krampe 2001; Rosenberger 2003) to the MLVSS concentrations (rather than to the MLSS concentrations) and obtained a negative direct linear relationship regardless the operational conditions (such as the SRT) at which these previous experiments were conducted. As observed in Fig. 1, a similar negative linear trend was observed in the present study as reported by Henkel et al. (2009b); however, Fig. 1 relates the alpha factor to the MLSS concentration rather than to the MLVSS concentration. The present work was conducted with fresh sludge obtained from a WWTP operated at an SRT of approximately 5 days; therefore, and as indicated in Table 2, the sludge exhibited relatively high MLVSS/MLSS ratios at the entire evaluated MLSS range. As such, most of the sludge consisted of MLVSS with a similar MLVSS/MLSS ratio for the entire evaluated MLSS range. This may eventually explain the negative linear relationship between the alpha factor and the MLSS concentration, as observed in Fig. 1. The alpha factors in this research were also reported as a function of the MLVSS concentration (Fig. 2). As expected, a similar negative linear trend was also obtained as both shown in Fig. 1 and reported by Henkel et al. (2009b). Our results support the findings drawn by Henkel et al. (2009b), suggesting a direct negative relationship between the MLVSS and the alpha factor.

Henkel (2010) indicated that the dependence of the alpha factor on the MLVSS rather than on the MLSS may be due to the following: (i) the reduction of the available gas/liquid interfacial area for the oxygen transfer due to the accumulation of sludge flocs (mostly MLVSS) on the surface of the gas bubbles; and (ii) the direct dependence of the sludge floc volume (determining the free water content of the solution) on the MLVSS content. Henkel et al. (2009b) investigated the specific effect of the MLVSS on the gas/liquid bubble interface. Because of the partial hydrophobic surface of the sludge flocs and the hydrophobicity of the gas/liquid bubble interface, the sludge flocs tend to get attracted and accumulate on the gas bubble surface reducing the available gas/liquid interfacial area; this observation is regardless of the bubble size. Henkel et al. (2009b) observed a larger fraction of the bubble surface area covered with solids when working at an MLVSS concentration of 6.8 g L^{-1} compared to when working at an MLVSS concentration of 2.4 g L^{-1}. As the MLVSS increased, the surface area of the air bubbles was consistently more covered with flocs; therefore, reducing the net interfacial area available for the oxygen transfer, and increasing the difficulty for the oxygen molecules to diffuse into the liquid phase. Moreover, the MLVSS fraction directly correlates to the bacteria and extracellular polymeric substances (EPS) content of the sludge, which to a large extent consists primarily of water (Raszka et al. 2006). The more water bound in the sludge by the organic matter, the larger the volume that the floc occupies; therefore, the less free water is available for an undisturbed mass transfer from the gas to the liquid phase. The MLSS and MLVSS concentrations only describe the sludge content in its dried form without considering the water bound in the sludge. The MLVSS concentration (not the MLSS) directly correlates with the free water content and the floc volume; an increase on the floc volume, decreases the free water content reducing the alpha factor in a linear way (Henkel 2010). The MLVSS component of the sludge not only directly interacts with the bubble (getting in contact with the bubble surface reducing the interfacial area between the liquid and the bubble), but also significantly contributes to the floc volume. The MLSS concentration is not the correct parameter to explain mechanisms that are related to floc volume phenomena. The MLVSS concentration better reproduces the free water content and floc volume than the MLSS concentration.

Most of the studies evaluating the impact of the MLSS concentrations on the alpha factors were carried out at long SRTs (Cornel et al. 2003; Günder 2000; Henkel et al. 2009b; Muller et al. 1995); the higher the SRT, the lower the MLVSS/MLSS ratio due to the aerobic stabilization of the sludge. However, our research was conducted with sludge obtained from a WWTP operated at a short SRT of approximately 5 days; therefore, relatively high MLVSS/MLSS ratios were reported as described in Table 2. The higher the fraction of MLVSS in the sludge, both the higher the amount of sludge flocs accumulating in the surface of the bubbles, and the larger the floc volume decreasing the free water content of the suspension. Thus, the combination of these two effects has a negative impact on the oxygen transfer process explaining

Table 2 Sludge properties at the evaluated MLSS concentration range

Target MLSS concentration (g L^{-1})	Sludge characteristics						
	MLSS (g L^{-1})	MLVSS (g L^{-1})	MLVSS/MLSS	PSD (μm)			Viscosity (mPa s)
				Dv 10	Dv 50	Dv 90	
4	4.0	3.3	0.83	48.6	122.6	257.0	4.0
10	11.1	8.8	0.79	52.9	140.4	332.2	6.0
20	20.5	15.6	0.76	46.2	123.0	280.9	7.0
30	31.5	23.2	0.74	35.1	109.6	207.8	17.5
40	43.6	34.9	0.8	34.8	116.0	277.9	74.0

Dv, volumetric particle diameter

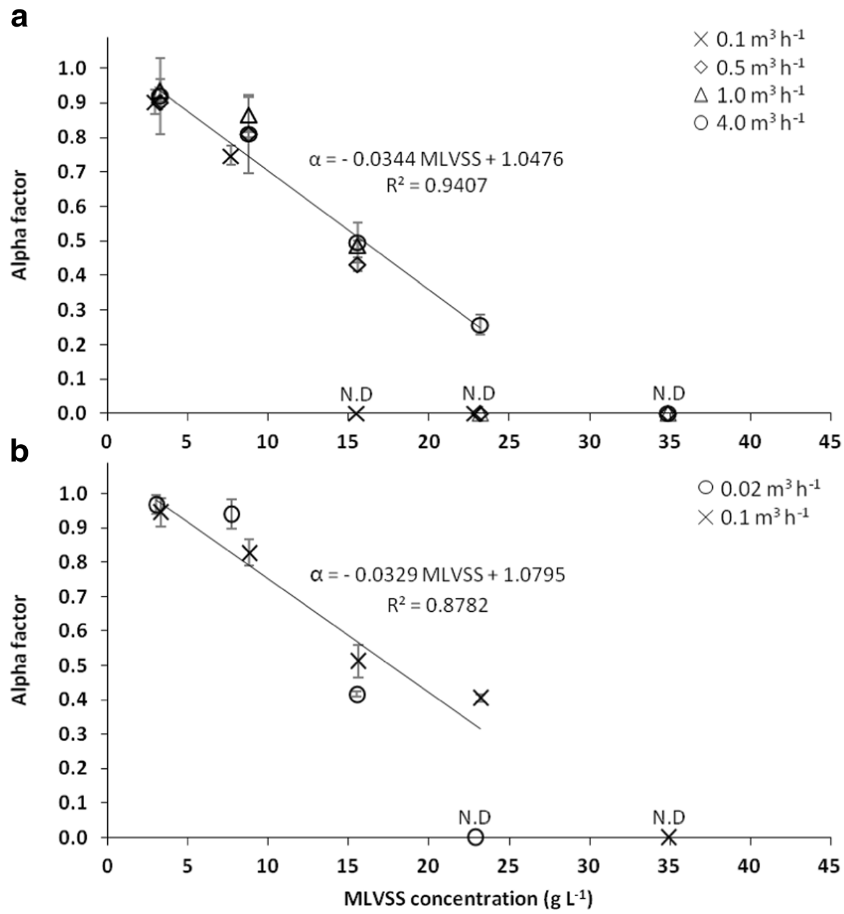


Fig. 2 **a** Impact of the MLVSS concentration on the alpha factor at different AFRs; the linear regression analysis corresponds to the average values of alpha factors determined at the evaluated AFRs of 0.1, 0.5, 1.0, and 4.0 m^3 h^{-1}; **b** impact of the MLVSS concentration on the alpha factors at different POFRs; the linear regression analysis corresponds to the average values of alpha factors determined at the evaluated POFRs of 0.02 and 0.1 m^3 h^{-1}

the low alpha factors determined in this research (conducted with sludge obtained from a WWTP operated at a short SRT of approximately 5 days) compared to the values reported on the literature (at high SRT) at similar MLSS concentrations. Therefore, under similar conditions, the lower the SRT, the higher the sludge floc concentration and MLVSS fraction on the sludge, and this contributes to a decrease in the alpha factor (as reported in this research). Consequently, operating an MBR system at high MLSS concentrations and short SRTs (HL-MBR concept) seems to be detrimental for the oxygen transfer process when using conventional bubble diffusers.

Zhang et al. (2015) reported higher concentrations of EPS when operating an MBR at a relatively short SRT of 10 days compared to when operating at SRTs of 30 and 90 days. Both the higher expected EPS concentrations, most likely to occur when working at short SRTs, together with the effect of operating a reactor at high MLSS concentrations may promote the agglomeration of sludge particles. This may probably modify the nature and structure of the flocs with a potential impact on both the accumulation of the flocs on the surface of the bubble, as well as on the floc volume; this has a residual effect on the oxygen transfer and alpha factor. However, as shown in Table 2 and Fig. 3, relatively standard floc sizes were reported on this research of approximately 120 μm, and non-significant changes on the PSD were observed for the entire evaluated MLSS concentration range. These observations indicated the absence of agglomeration of flocs within the evaluated MLSS concentration range. Therefore, even though operating with sludge obtained from a WWTP operated at a short SRT of approximately 5 days and high MLSS concentrations may introduce a large amount of EPS (not measured in this research), agglomeration of the sludge was not observed that could have probably altered the effect of the MLSS concentrations on the oxygen transfer.

The viscosity of the sludge was also determined at the evaluated MLSS concentrations and reported in Table 2. The viscosity exponentially increased with the MLSS concentration; similar trends were reported by Sato and Ishii (1991) and Itonaga et al. (2004). The adverse effects of the viscosity on the oxygen mass transfer performance were reported by several authors (Cornel et al. 2003; Germain and Stephenson 2005; Günder 2000; Krampe and Krauth 2003). Iorhemen et al. (2016) reported an additional increase of the viscosity when operating WWTPs at long SRTs due to the accumulation of non-biodegradable substances which contributed significantly to the overall viscosity. Pollice et al. (2008) reported similar findings when operating a bench-scale MBR treating municipal wastewater at different MLSS

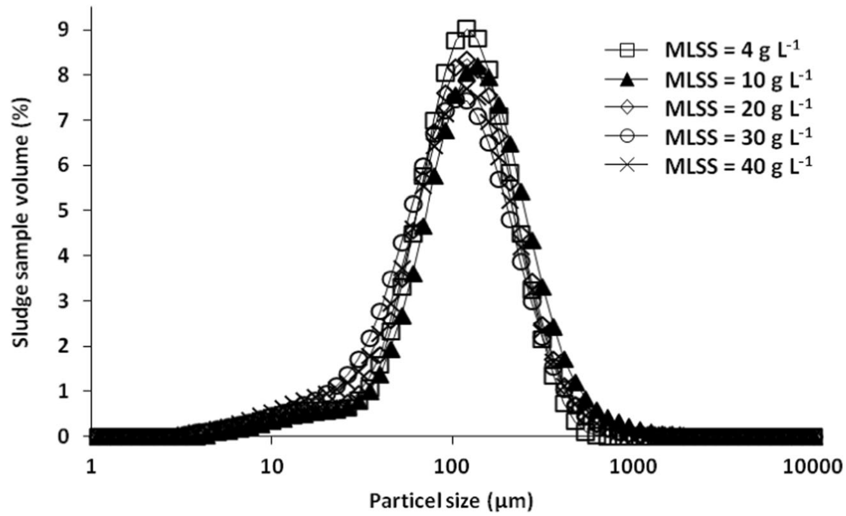


Fig. 3 PSD of sludge at each MLSS concentration after 24 h of oxygenation

concentrations (from 4 to 23 g L^{-1}) and SRTs (from 20 days to infinite). They observed a significant increase on the viscosity as the SRT increased from 20 days to infinite SRT. Consequently, operating at short SRTs seems to be beneficial in terms of lowering the viscosity with a positive impact on the oxygen mass transfer. However, short SRTs also increase the MLVSS/MLSS sludge ratio eventually overruling the positive effects of the reduced viscosity.

Figure 4 describes more precisely the impact of air (Fig. 4a) and pure oxygen (Fig. 4b) flow rates on the alpha factor at the specific assessed MLSS concentrations. The alpha factor exhibited a much higher dependence on the MLSS concentration than on the air/oxygen flow rates. Similar alpha factors were reported at the specific MLSS concentrations, regardless of the evaluated air/oxygen flow rate. At the largest flow rates for air and pure oxygen of 4 and 0.1 m^3 h^{-1}, respectively, alpha factors were detected even at an MLSS concentration as high as 30 g L^{-1}. However, alpha factors were not detected at the largest evaluated MLSS concentration of 40 g L^{-1}.

The flow rate has a direct impact on the mixing intensity. As reported by Benjamin and Lawler (2013), other factors being equal, the larger the mixing intensity, the larger the liquid exchange frequency in the proximity of the interfacial gas/liquid transfer layer, and the smaller the thickness of that interfacial layer. These effects cause an increase on the K_La. However, the K_La could have proportionally increased both in clean water and in process water at the evaluated flow rates; therefore, the alpha factors did not considerably change as the air/oxygen flow rate increased as observed in Fig. 4. Similar findings were reported by Germain et al. (2007). The authors could not find any particular clear relationship between the alpha factor and the AFRs.

Similar alpha factors were reported when supplying either air or pure oxygen. When supplying pure oxygen, the gas bubbles consisted entirely of oxygen molecules, providing larger gas-transfer interfacial areas per unit of volume and larger K_La values compared to when supplying air. However, the K_La could have proportionally increased both in clean and process water; therefore, the alpha factor remains unchanged regardless of the supplied oxygen source (air or pure oxygen). Most of the literature describing the effects of the MLSS concentrations on the alpha factor in the context of high MLSS concentrations was reported supplying air rather than pure oxygen. To our knowledge, Rodríguez et al. (2011) were the only research reporting alpha factors working at MLSS concentrations relevant for an MBR while supplying pure oxygen rather than air. The authors reported an alpha factor of approximately 0.03 at an MLSS concentration of 12.6 g L^{-1} in an MBR operated at an SRT of 40 days. This is a relatively low alpha factor compared to other authors working at similar MLSS concentrations that supplied air rather than pure oxygen. Although the oxygen transfer process strongly depends on the operational conditions, the only research reported where oxygen was supplied rather than air at a relatively high MLSS concentration did not show a significant advantage in terms of the oxygen transfer and alpha factor.

Effect of the sludge stabilization on the alpha factor

This particular phase aimed at evaluating the impact of the different MLSS concentrations at different degrees of sludge stabilization/activity (aerobically stabilized) as indicated by the sludge SOUR. The sludge at MLSS concentrations from 4 to 40 g L^{-1} was further oxygenated for periods of 24, 48, and 72 h, and the alpha factors were determined. Figure 5 describes the alpha factors at the evaluated sludge samples expressed as a function of the MLVSS concentration when supplying air at a flow rate of 4 m^3 h^{-1}.

The alpha factor followed a similar trend as previously described in Figs. 1 and 2, regardless of the degree of sludge stabilization. The alpha factors were determined at the entire range of MLVSS concentrations, and degrees of sludge stabilization, except at the largest evaluated MLSS concentration

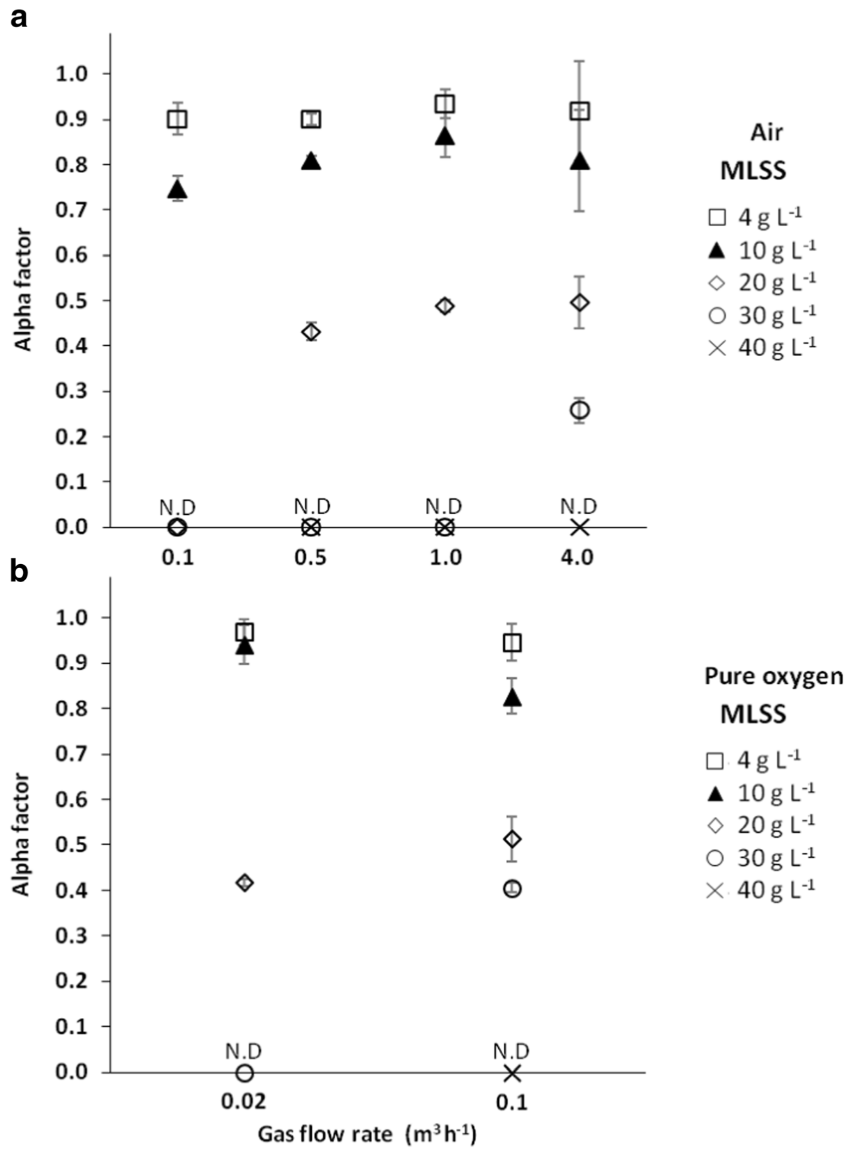


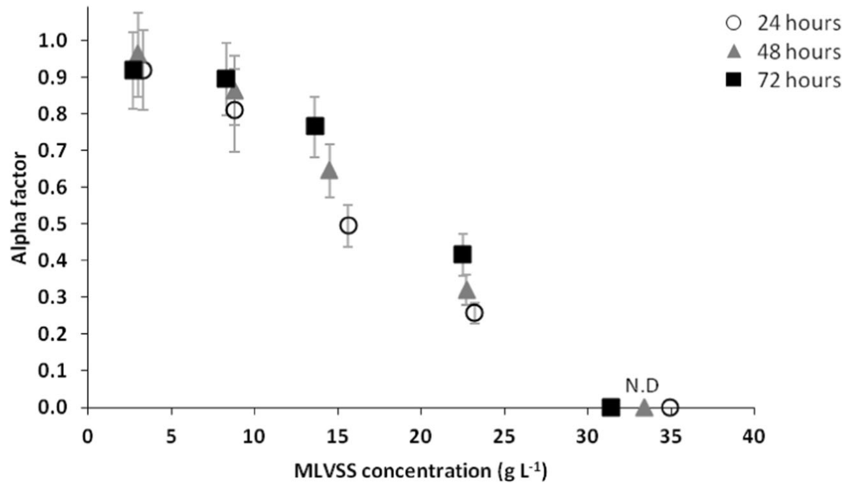
Fig. 4 **a** Impact of the AFRs on the alpha factors at different MLSS concentrations; **b** impact of the POFRs on the alpha factors at different MLSS concentrations

of approximately 40 g L^{-1} where negligible alpha factors were reported. As indicated in Fig. 5, the larger the degree of sludge stabilization at the specific evaluated MLVSS concentrations, the higher the alpha factor. Particularly, this trend is more pronounced at the highest used MLVSS concentrations. Table 3 indicates the precise MLVSS concentrations reported at each specific target MLSS concentration, as well as the overall sludge properties at which the sludge samples were evaluated.

The results observed in Fig. 5 clearly indicate considerable differences on the reported alpha factors at similar MLVSS concentrations. Particularly, at the target MLSS concentration of 30 g L^{-1} (with an MLVSS concentration of approximately 23 g L^{-1}), the alpha factors ranged from 0.26 to 0.46. Similarly, at the target MLSS concentration of 20 g L^{-1} (and an MLVSS concentration of approximately 15 g L^{-1}), the alpha factors ranged from 0.47 to 0.64. The differences were not that evident when working at the lowest range of the target MLSS concentration (4 g L^{-1}). Therefore, the results clearly indicated that in addition to the negative effects exerted directly by the MLVSS on the oxygen transfer and alpha factors (reported in the "Impact of the MLSS concentration on the alpha factor at different air/oxygen flow rates" section), there are other causes strongly influencing the oxygen transfer that may not depend directly on the MLVSS concentration.

Henkel (2010) reported that the presence of surfactants such as surface-active long-chain fatty acids (LCFAs) may also negatively affect the oxygen transfer performance; particularly, when these substances are adsorbed to the sludge (not on their soluble form). Rosso and Stenstrom (2006) have also reported on the adverse effects of surfactants on the oxygen transfer. Dignac et al. (2000) and Quéméneur and Marty 1994 reported that the surface-active substances commonly found in municipal wastewater are due to the presence of fatty acids

Fig. 5 Alpha factor as a function of the MLVSS concentration evaluated at an AFR of 4 $m^3 h^{-1}$; unfilled symbols = 24-h oxygenation; gray symbols = 48-h oxygenation; black symbols = 72-h oxygenation



in lipids. Lipids may count for approximately 20 to 25% of the organic material in domestic wastewater (Quéméneur and Marty 1994). Activated sludge flocs are able to trap (adsorb) low water-soluble organic compounds such as LCFA surfactants (Struijs et al. 1991). Henkel (2010) reported the presence of LCFA surfactants adsorbed to the sludge when working at short SRTs (as short as 2 days) and low oxygen transfer efficiencies most likely due to the presence of these compounds adsorbed to the sludge. Since surfactants are mostly biodegradable, their accumulation on the sludge (and their negative effect on the oxygen transfer) is more noticeable at short SRTs. As the SRT increases, these compounds are prone to be biodegraded, and their effects on the oxygen transfer should be less noticeable. The trends observed in our research might be eventually explained by the presence of biodegradable surfactants. As observed in Fig. 5, when increasing the sludge oxygenation time from 24 to 72 h, the alpha factor (and the oxygen transfer performance) increased at the specific evaluated target MLSS concentrations. The larger the sludge oxygenation time, the higher the possibilities for the biodegradable surfactants to be removed out of the sludge alleviating the negative effects on the oxygen transfer.

The analytical determination of surfactants was not carried out in this research; however, the OUR of the sludge was determined at the different stages of sludge stabilization at the evaluated MLSS concentrations. Figure 6 describes the alpha factor as a function of the SOUR at the evaluated range of MLSS concentrations. The OUR values as well as the overall

Table 3 Sludge properties at the evaluated MLSS concentrations at different sludge stabilization times

Target MLSS concentration ($g L^{-1}$)	Sludge stabilization (h)	Sludge characteristics: MLSS ($g L^{-1}$)	MLVSS ($g L^{-1}$)	MLVSS/MLSS	OUR (mg O_2 L^{-1} h^{-1})	SOUR (mg O_2 g $MLVSS^{-1}$ h^{-1})
4	24	4.0	3.3	0.83	29.4	7.61
	48	3.8	3.0	0.79	26.4	7.31
	72	3.6	2.7	0.75	20.4	6.21
10	24	11.1	8.8	0.79	72.0	7.97
	48	10.8	8.6	0.80	51.0	5.87
	72	10.4	8.3	0.80	42.6	4.91
20	24	20.6	15.6	0.76	76.2	4.88
	48	19.2	14.5	0.76	50.4	3.54
	72	19.1	13.6	0.71	37.2	2.79
30	24	31.5	23.2	0.74	108.6	4.83
	48	31.4	22.7	0.72	72.6	3.40
	72	31.7	22.5	0.71	54.6	2.58
40	24	43.6	34.9	0.80	198.0	5.70
	48	44.3	33.4	0.75	153.0	4.62
	72	43.9	31.4	0.72	87.0	2.82

evaluated sludge parameters are presented in Table 3. Similarly, as reported in Fig. 5, at the low range of evaluated MLSS concentrations (4 and 10 g L^{-1}), similar alpha factors were reported regardless the SOUR. However, at MLSS concentrations of 20 and 30 g L^{-1}, the alpha factor significantly increased as the SOUR decreased. The MLVSS concentrations did not significantly vary at each target MLSS concentration at the different sludge stabilization stages (24, 48, and 72 h), as shown in Fig. 5. Therefore, the decrease on the reported SOUR could have been due to the removal of biodegradable substances (e.g., biodegradable surfactants). This implies that the increase on the alpha factor as the SOUR decreased was not in this case due to the effects of the MLVSS concentration (as reported in the "Impact of the MLSS concentration on the alpha factor at different air/oxygen flow rates" section), but due to the removal of biodegradable compounds present in the sludge mixture. As the sludge aerobic stabilization progressed, the reduction of the SOUR indicated the biodegradation of organic compounds alleviating their negative impact on the oxygen transfer. Therefore, other factors being equal, the larger the sludge aerobic stabilization time (usually provided when working at large SRTs), the better the oxygen transfer performance.

Based on the results obtained in this research, the most significant negative effect to the oxygen transfer is probably still be given by the MLVSS concentration. As observed in Fig. 6 at the same SOUR of approximately 4.5 mg O_2 g $MLVSS^{-1}$ h^{-1}, the alpha factors are significantly reduced when going from an MLSS concentration of 4 to 40 g L^{-1}. However, not only should the effects of the MLVSS concentration be considered when evaluating the potential impact on the oxygen transfer, but also the presence of specific organic substances (such as surfactants) which may also hinder the oxygen transfer performance. The SOUR seems like a promising good indicator together with the MLVSS concentration to better assess and predict the oxygen transfer performance of a biological wastewater treatment system.

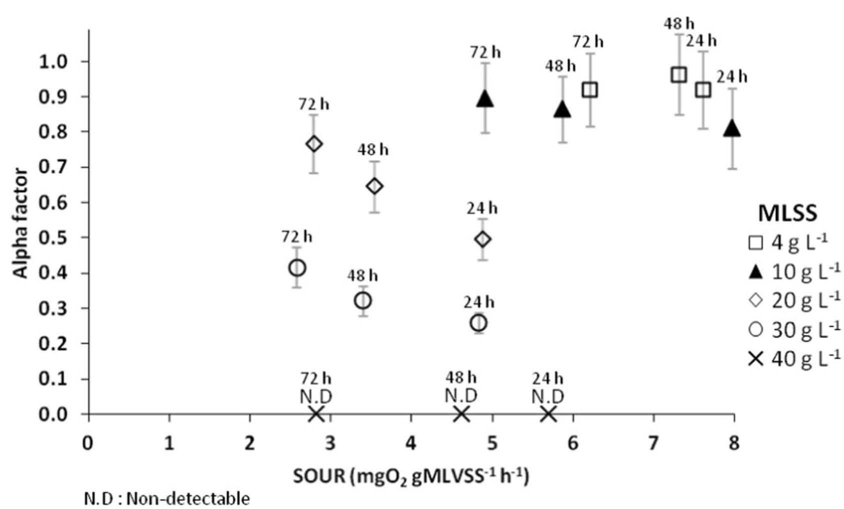
The goal of this research was to assess the limitations imposed by conventional bubble diffusers in the context of the HL-MBR. The concept of a HL-MBR for maximizing the treatment capacity while minimizing the system footprint requires operating the system at the highest achievable biologically active MLSS concentration obtained by operating the system at high loading rates and low SRTs. Our results indicated a negative impact of both high MLSS concentrations and short SRTs (emulated by taking and concentrating municipal sludge from a WWTP operated at a short SRT of approximately 5 days) on the oxygen transfer performance of conventional bubble diffusers. This may limit the design and operation conditions of the HL-MBR provided with conventional bubble diffusers.

Current limitations imposed by conventional diffused aeration on the HL-MBR

This section aims at both presenting the advantages of designing and operating a HL-MBR, as well as providing guidelines on the current limitations imposed by conventional diffused aeration on this system. Figure 7a describes some of the advantages of a HL-MBR system, while Fig. 7b describes the limitations of these systems imposed by the conventional aeration systems.

Figure 7a captures the most relevant design advantages of a hypothetical HL-MBR designed and operated at the conditions described in Table 4. Figure 7a shows the volume requirements and treatment capacities of the hypothetical system when operated at an MLSS concentration that ranges from 3 to 40 g L^{-1} and at an SRT of 10 days. As the MLSS concentration increases from 3 to 40 g L^{-1}, the volume requirements of the system dramatically decrease from approximately 2500 to 190 m^3, while the volumetric organic loading rates (Vol OLRs) to the system considerably increase from approximately 1.5 to 14 kg bCOD m^{-3} d^{-1}. Moreover, the sludge wastage flow rates

Fig. 6 Alpha factors as a function of the SOUR at each MLSS concentration at an AFR of 4 m^3 h^{-1}



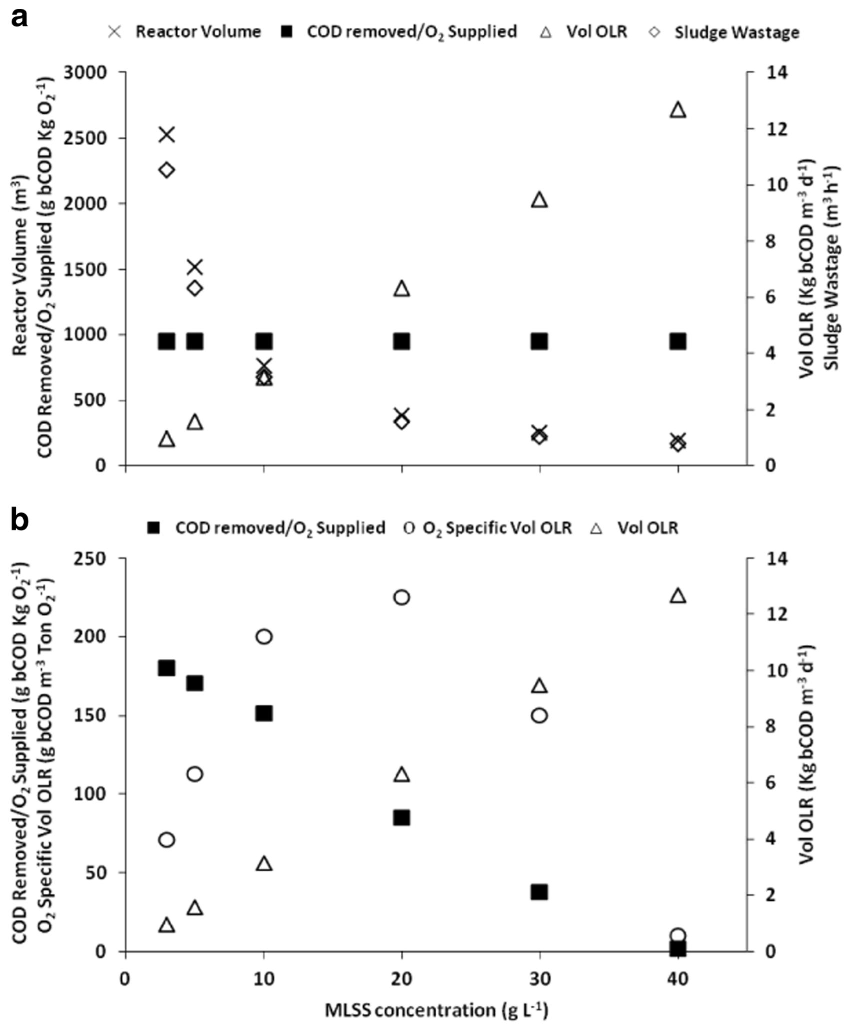


Fig. 7 **a** Most relevant design advantages of a HL-MBR as a function of the MLSS concentration without considering oxygen transfer inefficiencies introduced by fine bubble diffusers; **b** HL-MBR performance as a function of the MLSS concentration considering the process water SOTE introduced by conventional fine bubble diffusers as investigated in this research

decrease from approximately 10 to 0.8 m^3 h^{-1} at MLSS concentrations of 3 and 40 g L^{-1}, respectively. That is, Fig. 7a describes the operational unique advantages of the HL-MBR. When operating at high MLSS concentrations and relatively standard (short) SRTs, high loading rates can be treated while minimizing the footprint needed by the system. Moreover, the sludge wastage flow can also be considerably decreased. The hypothetical system exhibits a biological oxygen demand of 2530 kg O_2 d^{-1}; which indicates that approximately 950 g bCOD can be removed per kilogram of oxygen consumed by the system without considering the oxygen transfer inefficiencies introduced by the bubble diffused aeration systems. This implies that in the example presented in Fig. 7a, a standard oxygen transfer efficiency (SOTE) of 100% in process water was considered. Moreover, the hypothetical example assumed both complete biodegradation of the influent biodegradable COD (bCOD) and a full nitrification of the influent total nitrogen at the selected SRT of 10 days.

Figure 7b describes the treatment capacities of the hypothetical HL-MBR, but now adding the oxygen transfer inefficiencies imposed by the conventional diffused aeration on the HL-MBR operational conditions as investigated in this research. Both the high concentration of MLVSS and the potential accumulation of surfactants, most likely to occur at the designed operational conditions of the HL-MBR (high loading rate and short SRT), introduce a serious limitation on the oxygen transfer performance. The hypothetical example presented in Fig. 7b considered a SOTE of 5% per meter of submergence in clean water for a 4-m depth reactor (equivalent to a total SOTE in clean water of 20%). In addition, the alpha factors obtained in the present work were selected when working in wastewater. Overall SOTEs in process water of 19, 18, 16, 9, 4, and 0% were selected for MLSS concentrations of 3, 5, 10, 20, 30, and 40 g L^{-1}, respectively. As observed in Fig. 7a, Fig. 7b also shows the Vol OLR, as well as the amount of bCOD removed per amount of oxygen at an MLSS concentration range from 3 to 40 g L^{-1} and SRT of 10 days. Moreover, Fig. 7b also introduces the oxygen specific Vol OLR parameter describing the amount of COD that can be removed per volume occupied by the system and per oxygen consumed by the system. The same volume requirements (not shown in Fig. 7b) and sludge wastage as described in Fig. 7a apply to the HL-MBR system

Table 4 Wastewater characteristics and bio-kinetic designed parameters

Wastewater characteristics		
Influent flow rate	(m^3 d^{-1})	2000
Influent biodegradable COD	(g COD m^{-3})	1200
Influent unbiodegradable particulate COD	(g COD m^{-3})	20
Influent total suspended solids	(g TSS m^{-3})	500
Influent volatile suspended solids	(g VSS m^{-3})	400
Influent total Kjeldahl nitrogen	(g TKN m^{-3})	120
Bio-kinetic design parameters		
Substrate half saturation constant (*Ks*)	(g COD m^{-3})	20
True yield (*Y*)	(g VSS g COD^{-1})	0.45
Specific biomass decay rate (*b*)	(g VSS g VSS^{-1} d^{-1})	0.24
COD to VSS ratio of the sludge (*fcv*)	(g COD g VSS^{-1})	1.48
Inorganic content of active biomass (f_{iOHO})	(g ISS g VSS^{-1})	0.15
Endogenous residue fraction (f_H)	(Unitless)	0.20

when considering the oxygen transfer inefficiencies. The first main difference on the performance of the HL-MBR system when considering the oxygen transfer inefficiencies (as reported in Fig. 1) is that the system cannot be operated at MLSS concentrations higher than 30 g L^{-1}, since negligible alpha factors were reported at those MLSS concentrations; therefore, it is not possible to supply DO at those operational conditions when using conventional diffused aeration systems. Moreover, even though the biological oxygen demand of the system remained identical as presented in Fig. 7a (of 2530 kg O_2 d^{-1} and 950 g bCOD removed per kilogram of oxygen consumed), the amount of oxygen that needs to be supplied increased dramatically considering the oxygen transfer inefficiencies of the bubble diffusers at the reported MLSS concentrations. As seen in Fig. 7b, the amount of COD removed per oxygen supplied considerably decreased as compared to Fig. 7a following a direct linear negative relationship with the MLSS concentration; even reaching a value of zero at an MLSS concentration of 40 g L^{-1}. This implies that the hypothetical system can handle the same volumetric treatment loads as presented in Fig. 7a. However, the aeration system introduces such enormous inefficiencies on the oxygen transfer performance requiring the supply of extremely large amounts of oxygen to satisfy the oxygen biological needs of the systems to maintain aerobic conditions in the reactor.

Moreover, Fig. 7b introduces another parameter aiming at finding the optimal operational set point of the HL-MBR considering the oxygen transfer inefficiencies introduced by the diffused aeration systems. The oxygen specific Vol OLR parameter is introduced describing the amount of COD that can be removed per volume occupied by the system and per oxygen consumed by the system. The higher the value of this indicator, the higher the treatment capacity of the system at the lower footprint and oxygen consumption. As observed in Fig. 7b, a maximum value is reached at an MLSS concentration of 20 g L^{-1} corresponding to 225 g COD removed per cubic meter of the reactor and per ton of oxygen supplied.

The fine bubble diffused aeration system introduces a severe limitation on the design conditions of a HL-MBR. MLSS concentrations higher than 30 g L^{-1} cannot be achieved since it would not be technically feasible to introduce DO; moreover, an optimum design MLSS concentration of 20 g L^{-1} was calculated considering maximizing the amount of COD that can be treated per unit of system footprint and per unit of oxygen consumption.

This research was carried out using fine bubble diffusers for supplying DO into the system. The current evaluation did not consider the performance of coarse bubble diffusers on the HL-MBR system. Coarse bubble diffusers would eventually yield higher alpha factors compared to fine bubble diffusers; however, coarse bubble diffusers experienced overall low SOTEs than fine bubble diffusers. Therefore, even though coarse bubble diffusers could have performed better compared to fine bubble diffusers in terms of alpha factors, the overall SOTE in activated sludge would not considerably change and similar results can be expected.

This research evaluated the current limitations imposed by fine bubble diffused aeration on the HL-MBR; however, there may be other technological options for supplying DO at much more efficient SOTEs that may eventually uncap the current limitations imposed by fine bubble diffused aeration systems. Concentrated oxygen delivery systems (superoxygenation systems) are able to deliver DO at approximately 100% SOTEs (Barreto et al. 2018); however, the precise performance of these systems still needs to be properly evaluated at the operational conditions required by the HL-MBR (like high MLSS concentrations and short SRTs).

Moreover, this research did not evaluate the impact of such high MLSS concentrations on the membrane filtration performance. However, Barreto et al. (2017) reported no significant additional sludge filterability difficulties when operating an MBR at an MLSS concentration of 30 g L^{-1} compared to when operating at a lower MLSS concentration of approximately 8 g L^{-1}. Moreover, ceramic membranes can be used instead of polymeric membranes increasing the conventional standard fluxes allowed through the membranes when operating at higher than usual MLSS concentrations.

This research was conducted in the framework of exploring the limitations of conventional diffusers on the design of a HL-MBR; however, the experiments were conducted in batch reactors without considering the dynamic effects of the membrane filtration process on the sludge. The characteristics of the biomass may eventually differ from what was observed in this research, and the results may not be linearly extrapolated to MBR systems.

Conclusions

The impact of the MLSS concentration on the alpha factors is more pronounced when working at short SRTs (evaluated in this research by using sludge obtained from a WWTP operated at a short SRT of approximately 5 days). At short SRTs, a direct negative linear relationship between the alpha factor and the MLSS concentration can be observed. Other factors being equal, the shorter the SRT, the higher the MLVSS fraction and the lower the alpha factor. The gas flow rate and oxygen source (either air or pure oxygen) have just a marginal effect on the alpha factor at the evaluated operational conditions. The more stabilized the sludge, the lower the potential presence of biodegradable substances such as surfactants; thus, having a positive impact on the oxygen transfer (and alpha factor). The provision of fine bubble diffusers limits the maximum MLSS concentration that can be achieved on the HL-MBR concept at 30 g L^{-1}; beyond that point is either not technically or not economically feasible to supply DO. An optimum MLSS concentration of 20 g L^{-1} is suggested for designing the HL-MBR, maximizing the treatment capacity while minimizing both the footprint needs as well as the oxygen consumption.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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