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Effect of impeller type and stirring frequency on the behavior of an AnSBBR in the treatment of low-strength wastewater

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A B S T R A C T

The influence of impeller type and stirring frequency on the performance of a mechanically stirred anaerobic sequencing batch reactor containing immobilized biomass on an inert support (AnSBBR – Anaerobic Sequencing Batch Biofilm Reactor) was evaluated. The biomass was immobilized on polyurethane foam cubes placed in a stainless-steel basket inside a glass cylinder. Each 8-h batch run consisted of three stages: feed (10 min), reaction (460 min) and discharge (10 min) at 30 °C. Experiments were performed with four impeller types, i.e., helical, flat-blade, inclined-blade and curved-blade turbines, at stirring frequencies ranging from 100 to 1100 rpm. Synthetic wastewater was used in all experiments with an organic-matter concentration of 530 ± 37 mg/L measured as chemical oxygen demand (COD). The reactor achieved an organic-matter removal efficiency of around 87% under all investigated conditions. Analysis of the four impeller types and the investigated stirring frequencies showed that mass transfer in the liquid phase was affected not only by the applied stirring frequency but also by the agitation mode imposed by each impeller type. The best reactor performance at all stirring frequencies was obtained when agitation was provided by the flat-blade turbine impeller.

1. Introduction

Novel configurations of anaerobic reactors have been investigated for a variety of applications, such as the treatment of different industrial and domestic wastewaters, with a focus on the potential use of anaerobic processes and maximization of their practical application (Zaiat et al., 2001; Rodrigues et al., 2006). All modern configurations are designed to attempt to meet the requirements essential for achieving good treatment efficiency, practical applicability and operational simplicity. These requirements have been met by improving contact between the biomass and the material to be degraded and by retaining a large amount of the biomass in the system.

These configurations include discontinuous anaerobic reactors, or anaerobic sequencing batch reactors (AnSBR – Anaerobic Sequencing Batch Biofilm Reactor), which have been employed by researchers in several applications. This reactor configuration was designed as an alternative to continuous systems to provide improved solids retention, improved process control and easier operation (Canto et al., 2008).

The operation of anaerobic sequencing batch reactors comprises four stages: feed, reaction, decanting and discharge (Sung and Dague, 1995). However, despite the advantages over continuous reactors provided by the intrinsic characteristics of the system, many fundamental and operational aspects remain to be investigated to enable full-scale application, especially for the treatment of low-strength wastes, such as domestic wastewater. Some of the main drawbacks of this configuration include the long operation time required to accomplish autoimmobilization of the biomass in the form of granules or flocks and the decanting time of the autoimmobilized biomass, which further lengthens the total batch time and affects the final quality of the treated effluent.

To overcome some of these drawbacks, Ratusznei et al. (2000) proposed a new configuration for an anaerobic sequencing batch reactor that included immobilized biomass and mechanical stirring to treat low-strength wastewater (AnSBBR). In this reactor, the biomass adheres to an inert support, in this case a polyurethane foam, and mixing is promoted by mechanical stirrers to improve mass transfer, which is fundamental in anaerobic systems using inert material for biomass adherence. Moreover, the utilization of polyurethane foam as a support for immobilization of the biomass promoted good solids retention in the reactor and eliminated the decanting step, which reduced the cycle length and resulted in good organic-matter removal efficiency. However, the utilization

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of immobilized biomass on an inert support evidenced the need for studies regarding aspects related to mass transfer (both solid and liquid phase), including investigations on the effect of agitation on the performance and stability of these bioreactors (Harnby et al., 1997; Nienow, 1998; Vrábel et al., 1998).

Cubas et al. (2007) assessed solid-phase mass transfer using polyurethane foam cubes ranging in size from 0.5 to 3.0 cm and concluded that effluent quality improved with decreasing bioparticle size as a consequence of the decrease in solid-phase mass-transfer resistance. Improvement in liquid-phase mass transfer through mechanical agitation was observed by Cubas et al. (2004), who concluded that the reactor performance and cycle length required for each batch were directly affected by liquid-phase mass transfer. Pinho et al. (2004) showed that stirring in sequencing batch reactors, in addition to promoting mixing in the reactor, increases solid-phase mass transfer and the solubilization of particulate organic matter. Damasceno et al. (2008) and Michelan et al. (2009) both noted that improvement in homogenization, liquid flow and solid–liquid mass transfer were directly related to the type of impeller used.

Although prior authors have evaluated the influence of impeller type in mechanically stirred AnSBBR (Pinho et al., 2006; Michelan et al., 2009; Novaes et al., 2010), no conclusive results have been obtained for low-strength wastewater, and fundamental studies in bench-scale reactors are still required for a deeper understanding of such influence.

In this context, this paper reports on the influence of four types of impellers providing axial and radial agitation at different stirring frequencies on the performance of a mechanically stirred anaerobic sequencing batch reactor containing immobilized biomass on an inert support (AnSBBR) applied to the treatment of a low-strength synthetic wastewater.

2. Methods

2.1. Experimental setup

The bench-scale AnSBBR (Fig. 1) consisted of a glass flask with a total capacity of 5 L. The biomass was immobilized on polyurethane foam particles arranged in an 18-cm high perforated basket with a diameter of 22 cm. Mixing was performed by three impellers, each with a diameter of 3 cm, that were vertically spaced 4 cm apart. The reactor was encased in a water jacket to maintain a constant temperature of 30 ± 1 °C throughout the experiment. Feed and discharge steps were performed with two diaphragm pumps equipped with automatic timers.

2.2. Inoculum and inert support

The sludge used as inoculum came from an upflow anaerobic sludge-blanket reactor that treated wastewater from a poultry slaughterhouse. The immobilization procedure was performed in accordance with the methodology proposed by Zaiat et al. (1994). Approximately 4 L of sludge and 45 g of dry foam were uniformly mixed and maintained for a period of about 12 h to promote adhesion of the biomass. The biomass was immobilized on 1-cm polyurethane foam cubes with an apparent density of 23 kg/m^3, a surface area of 43.8 g/m^2 and a porosity of 95%.

2.3. Synthetic wastewater

All experiments used a low-strength synthetic wastewater containing readily and barely degradable carbohydrates, which were composed of sucrose (35 mg/L), starch (114 mg/L), cellulose (34 mg/L), meat extract (208 mg/L), soybean oil (51 mg/L), NaCl (250 mg/L), $MgCl_2{\cdot}6H_2O$ (7 mg/L), $CaCl_2{\cdot}2H_2O$ (4.5 mg/L), $NaHCO_3$ (200 mg/L), and a commercial detergent for emulsification of soybean oil (three drops/L). Organic-matter concentration in unfiltered samples of the synthetic wastewater was 521 ± 36 mg/L measured as chemical oxygen demand (COD). The total volatile acid concentration was 34 ± 10 mg HAc/L, and the bicarbonate alkalinity was 124 ± 19 mg $CaCO_3$/L. Finally, the pH was between 6.5 and 7.5.

2.4. Experimental procedure

Four impeller types were used (Fig. 2): a helix with three blades, a turbine with four flat blades, a turbine with four inclined blades and a turbine with four curved blades. The agitation frequencies studied were 100, 300, 500, 700, 900 and 1100 rpm. Experiments

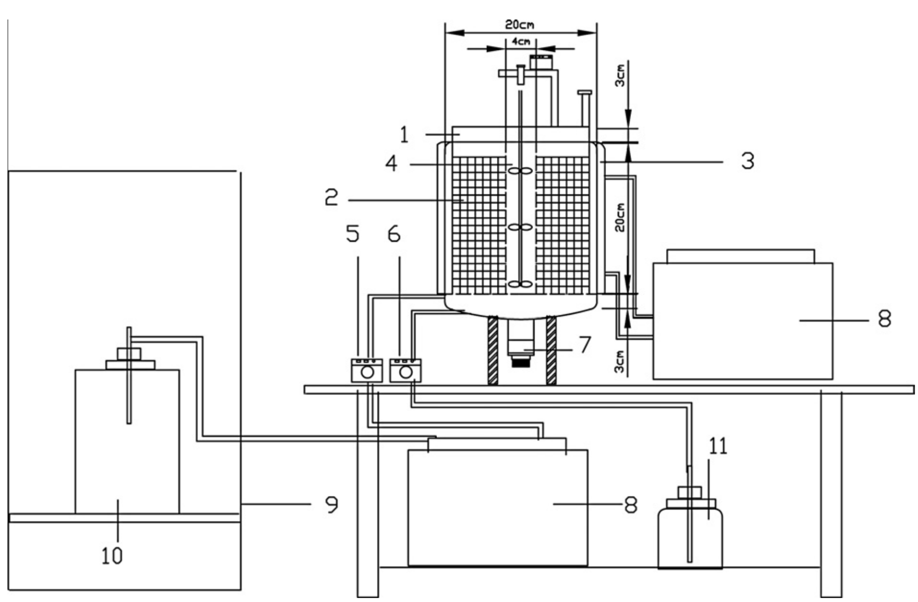

Fig. 1. Experimental setup. (1) Reaction vessel; (2) Basket containing immobilized biomass; (3) Heating jacket; (4) Mechanical stirrer; (5) Diaphragm feed pump; (6) Diaphragm discharge pump; (7) Sludge discharge; (8) BTC-9090 ultrathermostatic bath; (9) Refrigerator; (10) Substrate; (11) Effluent.

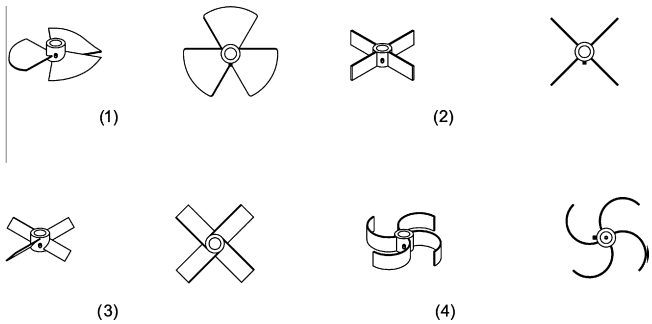

Fig. 2. Impeller types used in the experiments. (1) Helical turbine; (2) Flat-blade turbine; (3) Inclined-blade turbine; (4) Curved-blade turbine.

with the different impellers lasted 31 days (approximately 70 consecutive cycles), at 30 ± 1 °C, with 24-h sequencing cycles in the first eight days of adaptation that changed to 8 h during the monitoring phase (feed: 10 min, reaction: 460 min, and discharge: 10 min). During the 11-day monitoring period (42 consecutive cycles), the stirring frequency was 300 rpm.

Reactor stability was checked by monitoring the organic-matter removal efficiency, i.e., the reactor was considered stable when efficiency did not vary significantly from one cycle to another. Subsequently, time profiles were run for COD and gas composition at stirring frequencies of 100, 300, 500, 700, 900 and 1100 rpm.

2.5. Analytical methods

The operating variables, monitored in accordance with Standard Methods for Examination of Water and Wastewater (1998), were as follows: substrate concentration (measured as COD) for unfiltered (C_{ST}) and filtered samples (C_{SF}), bicarbonate alkalinity (BA), total volatile acids (TVA), total solids (TS), total volatile solids (TVS), total suspended solids (TSS) and volatile suspended solids (VSS).

Methane production (V_{CH_4}) and composition of the biogas $\%_{CH_4} - \%_{CO_2}$ generated by anaerobic degradation were analyzed, respectively, by a gas meter using an NaOH solution (50 g/L) to promote CO_2 absorption and gas chromatography using a Hewlett Packard® 6890 gas chromatograph equipped with a thermal-conductivity detector. The sample volume was 1 mL, and the drag gas was hydrogen with a flow rate of 50 mL/min. The column, injector, and detector temperatures were, respectively, 35, 60 and 160 °C.

2.6. Kinetic model formulation and fitting

In each experiment, when the effluent substrate concentration did not vary significantly from one cycle to the next, temporal profiles of filtered samples of substrate (soluble COD) were taken from the batch every 30 min. These profiles provided a better understanding of the degradation routes across cycles and also enabled us to obtain kinetic parameters for organic-matter degradation by fitting a first-order kinetic model to the experimental filtered organic-matter concentration data.

Analysis of the time profiles was accomplished with nonlinear Levenberg–Marquardt regression using Origin 6.0 software (Microcal®) (Contrera et al., 2007).

Eq. (1) is the modified first-order kinetic model that was used.

$$S = S_R + (S_0 - S_R)e^{-k_1^{app}t} \quad (1)$$

Eq. (1) is analogous to the first-order kinetic model with a residual substrate concentration (S_R), where S is the substrate concentration in the liquid volume, t is the time and S_o is the initial substrate concentration inside the reactor at time $t = 0$. The parameter k_1^{app} is the apparent first-order kinetic constant.

The effect of the stirring frequency, and thus, indirectly, the liquid-phase mass transfer, on reactor performance was also assessed through the initial reaction rate (Rs_0), obtained by Eq. (2).

$$Rs_0 = k_1^{app}(S_0 - S_R) \quad (2)$$

3. Results and discussion

Values obtained for the monitored parameters in the influent and effluent did not indicate that the different impeller operations varied at 300 rpm. Organic-matter removal efficiency for all impeller types was 86 ± 4%, with an effluent total volatile acids concentration of 16 ± 7 mg HAc/L, a bicarbonate alkalinity of 218 ± 11 mg $CaCO_3$/L and a pH between 6.8 and 7.4. Suspended volatile solids concentrations were low under all conditions, indicating that no significant biomass wash-out occurred. All values obtained during the monitoring of each investigated condition are shown in Table 1.

Although the monitored values were similar under all conditions, the worst performance was observed with the curved-blade impellers, which also presented the highest concentration of volatile acids (23 ± 7 mg HAc/L) and the worst final effluent quality. The best performance regarding all monitored parameters was obtained when the flat-blade impellers were used.

The stirring frequency of 1100 rpm was only used with the helical impellers because aeration that caused a high degree of foaming was observed with the other impellers at this speed. Reactor stability under all conditions was confirmed by the low concentration of volatile acids and reduced generation of bicarbonate alkalinity in the effluent. Moreover, under all conditions, the monitored parameters presented low standard deviations.

The effect of stirring frequency on reactor performance could not be assessed from the values obtained by monitoring the influent and the effluent because the global performance with an 8-h cycle was similar for all investigated conditions. A more precise analysis was only possible through the time profiles obtained during a cycle for each operating condition. Thus, to assess the effect of stirring frequency, organic-matter concentration profiles (expressed as COD) of the filtered effluent were obtained. The time profiles were completed during a batch at stirring frequencies (N) of 100 to 1100 rpm depending on impeller type.

The parameters of the kinetic model (S_0, S_R and k_1^{app} in Eq. (1)) for each investigated condition are shown in Table 2. Analysis of the parameters for the different impeller types at each investigated frequency showed that variation of the first-order apparent kinetic constant (k_1^{app}) did not present a well-defined tendency when the following impeller types were used: helical (N = 300–900 rpm),

Table 1
Average values of the monitored parameters in the anaerobic sequencing batch reactor with different impeller types.

Parameter* (N = 300 rpm)	Impeller type			
	Helix	Flat-blade turbine	Inclined-blade turbine	Curved-blade turbine
S_T (mg COD/L)**	79 ± 19	51 ± 10	79 ± 13	81 ± 14
ε_T(%)***	85 ± 4	90 ± 2	85 ± 3	83 ± 3
Effluent BA (mg $CaCO_3$/L)	218 ± 8	221 ± 16	216 ± 7	218 ± 13
Effluent TVA (mg HAc/L)	17 ± 4	11 ± 7	12 ± 3	23 ± 7
Effluent SVS (mg-SSV/L)	48 ± 11	44 ± 17	53 ± 18	50 ± 10
Effluent pH range	6.8–7.4	6.8–7.1	6.8–7.4	6.8–7.1

* Eleven determinations for each parameter.
** S_T Organic-matter concentration of the filtered effluent, in terms of COD.
*** ε_T (%) was calculated from the unfiltered substrate influent concentrations and the filtered substrate effluent concentrations.

Table 2
Parameters S_0, S_R and k_1^{app} of the modified first-order kinetic model (1) obtained for each experiment with different stirring frequencies (N) and their respective coefficient of determination (R^2).

Impeller	Parameter	Stirring frequency N (rpm)					
		100	300	500	700	900	1100
Helix	S_0 (mg/L)	–	370	343	343	324	328
	S_R (mg/L)		82.0 ± 5.1	85.4 ± 5.3	90.7 ± 6.2	82.9 ± 4.9	48.5 ± 4.4
	k_1^{app} (h^{-1})		0.76 ± 0.05	0.69 ± 0.05	0.72 ± 0.06	0.68 ± 0.06	0.99 ± 0.06
	R^2		0.9841	0.9818	0.9722	0.9718	0.9821
Flat-blade turbine	S_0 (mg/L)	–	310	287	279	291	–
	S_R (mg/L)		56.8 ± 6.2	47.4 ± 2.7	55.9 ± 0.24	54.9 ± 1.6	
	k_1^{app} (h^{-1})		0.72 ± 0.06	1.07 ± 0.05	1.09 ± 0.05	1.73 ± 0.06	
	R^2		0.9716	0.9905	0.9915	0.9946	
Curved-blade turbine	S_0 (mg/L)	334	300	311	249	–	–
	S_R (mg/L)	131.9 ± 4.3	114.5 ± 8.6	61.4 ± 6.9	42.3 ± 0.23		
	k_1^{app} (h^{-1})	0.72 ± 0.05	0.58 ± 0.08	0.63 ± 0.06	1.11 ± 0.03		
	R^2	0.9788	0.9332	0.9704	0.9933		
Inclined-blade turbine	S_0 (mg/L)	344	333	309	307	–	–
	S_R (mg/L)	90.9 ± 5.5	72.6 ± 6.5	53.3 ± 3.9	54.1 ± 1.8		
	k_1^{app} (h^{-1})	0.60 ± 0.04	0.56 ± 0.04	0.79 ± 0.04	1.07 ± 0.03		
	R^2	0.9853	0.9822	0.9895	0.9963		

curved blades and inclined blades (N = 100–500 rpm); the values obtained ranged from 0.60 to 0.76 h^{-1}. These values indicate that under these conditions, the time necessary to achieve complete efficiency was not significantly affected by stirring frequency. However, when a stirring frequency of 1100 rpm was used with the helical impellers or 700 rpm with the curved-blade and inclined-blade turbines, k_1^{app} increased, which indicates that the overall conversion rate of organic matter and, importantly, cycle length were affected by stirring frequency.

Different behavior was observed when the flat-blade turbine impellers were used. The kinetic constant k_1^{app} increased when the stirring frequency N was increased from 300 to 900 rpm. According to Bird et al. (2007), this increase is related to the reduction of the stagnant film surrounding the bioparticle, where resistance to external mass transfer is lower. Moreover, resistance to mass transfer in the liquid phase is directly related to the physical properties of the liquid, the geometric characteristics of the particles and primarily to the mixing efficiency in the reactor, which is achieved by the intensity and method of agitation. It should be mentioned that flat-blade turbine impellers impart axial movement and according to Nienow (1998), this impeller type promotes more effective energy transfer to the liquid.

The parameter S_R did not present significant variations when the helical impellers were used with N ranging from 300 to 900 rpm. However, a different behavior was observed at N = 1100 rpm when the final COD concentration was much lower (approximately 41% less) than at the other investigated stirring frequencies, which confirms the results obtained by Cubas et al. (2004).

With the flat-blade turbine impellers at 300–900 rpm, similar behavior was observed as with the helical impellers in the same range of N. However, S_R values were much lower and close to those obtained with the helical impellers at N = 1100 rpm. Aeration and foaming occurred in the system with the flat-blade turbine impellers at N above 900 rpm. The flat-blade and curved-blade turbine impellers both presented a decrease in final effluent concentration (S_R) with increased N. However, for these two conditions, the maximum N studied was 700 rpm, because for higher N, aeration and foaming occurred in the system.

The values of Rs_0 obtained by Eq. (2) for the investigated impellers and at different stirring frequencies (N) are shown in Fig. 3. The values of k_1^{app}, S_0 and S_R used for the calculation are listed in Table 2. The initial reaction rate (Rs_0) generally increased with increasing N when the flat-blade, inclined-blade and curved-blade turbine impellers were used. The helical impellers did not show the same trend; Rs_0 did not vary much at stirring frequencies between 300 and 900 rpm. The initial reaction rate only increased when N was 1100 rpm. Therefore, under this condition, the same atypical behavior was obtained as observed with the other parameters. The highest values of Rs_0 (231.4–505.6 mg/L h) were obtained for the flat-blade turbine impellers, indicating that this impeller type was the best for the entire stirring frequency range used, followed by the inclined-blade impeller.

Analysis of the four impeller types and the investigated stirring frequencies showed that mass transfer in the liquid phase was affected not only by the applied stirring frequency but also by the agitation mode imposed by each impeller type. The best reactor performance at all stirring frequencies was obtained when agitation in the reactor was provided by the flat-blade turbine impellers. Under these conditions, the values of the apparent kinetic constant (k_1^{app}) and of the initial reaction rate (Rs_0) were the highest. Moreover, organic-matter degradation was more effective, with a residual COD concentration (S_R) close to 50 mg/L.

Pinho et al. (2006) employed a similar reactor and the same impeller types to treat wastewater containing particulate organic matter and observed that the impeller type exerted directly affected the final quality of the effluent. The results also showed that the flat-blade turbine impellers presented better performance with no disadvantage when high values of N were used, which caused operational difficulties and had less favorable energy consumption.

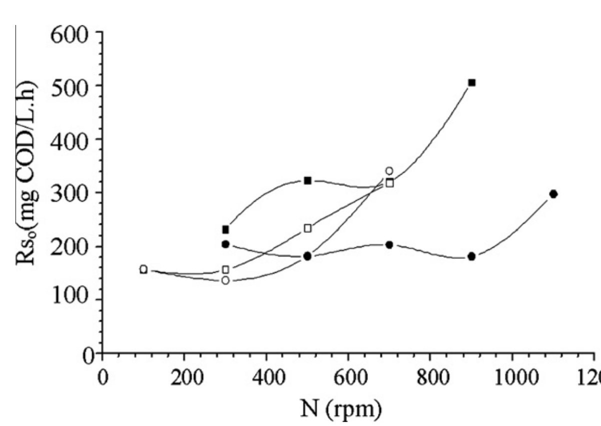

Fig. 3. Initial reaction rate (Rs_0) as a function of N. Impeller types: (●) helical; (■) flat-blade; (□) inclined-blade; (○) curved-blade.

Damasceno et al. (2008) assessed the effects of mixing mode by comparing two impeller types (turbine and helical) and concluded that turbine impellers provide better performance when low stirring frequencies are used. However, the helical impeller shows better homogenization because of the resulting axial flow.

4. Conclusions

Analysis of the parameters obtained with the four impeller types at the investigated stirring frequencies showed that mass transfer in the liquid phase is affected not only by the applied stirring frequency but also by the different mixing efficiencies provided by the different impeller types. The best reactor performance for all investigated stirring frequencies was obtained when agitation of the liquid inside the reactor was supplied by the flat-blade turbine impellers. In these conditions, the values of the apparent kinetic constant (k_1^{app}) and of the initial reaction rate (Rs_0) were the highest. Moreover, organic-matter degradation was more effective, with a residual COD concentration (S_R) close to 50 mg/L.

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