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STUDY OF THE KINETIC MODELING IN HYBRID AND PURE MOVING BED BIOFILM REACTOR-MEMBRANE BIOREACTOR SYSTEMS FOR MUNICIPAL WASTEWATER TREATMENT

Leyva Díaz, Juan Carlos; Muñío Martínez, María del Mar; González-López, Jesús; Poyatos Capilla, José Manuel
Universidad de Granada

The moving bed biofilm reactor-membrane bioreactor (MBBR-MBR) is a novel technology which constitutes a solution to conventional processes. In this study, a membrane bioreactor (MBR), a hybrid MBBR-MBR and a pure MBBR-MBR, working in parallel, were compared under a hydraulic retention time (HRT) of 6 h. The hybrid MBBR-MBR had suspended and attached biomasses and the pure MBBR-MBR mainly contained attached biomass as biofilm. The kinetic parameters for heterotrophic and autotrophic biomasses were evaluated and related to organic matter and nitrogen removals. The pure MBBR-MBR had the highest efficiency of total nitrogen (TN) removal with a value of 63.21±11.01%. The hybrid MBBR-MBR showed the highest chemical oxygen demand (COD) removal efficiency with a value of 84.10±2.25%. The kinetic study supported the efficiencies of COD and TN removals as the hybrid MBBR-MBR and pure MBBR-MBR showed the best kinetic performances for the heterotrophic and autotrophic biomasses, respectively. The presence of the attached biomass improved the organic matter and nitrogen removals in the hybrid and pure MBBR-MBR systems, respectively.

Keywords: *Wastewater treatment; Moving bed biofilm reactor-membrane bioreactor; Nitrogen removal; Biofilm; Autotrophic kinetics.*

ESTUDIO DEL MODELADO CINÉTICO EN BIORREACTOR DE MEMBRANA CON LECHO MÓVIL HÍBRIDO Y PURO PARA TRATAMIENTO DE AGUAS RESIDUALES URBANAS

El biorreactor de membrana con lecho móvil (MBBR-MBR) es una tecnología novedosa que soluciona los problemas de los procesos convencionales. En este estudio, un biorreactor de membrana (MBR), un MBBR-MBR híbrido y un MBBR-MBR puro, operando en paralelo, fueron comparados con un tiempo de retención hidráulico (TRH) de 6 h. El MBBR-MBR híbrido tenía tanto biomasa suspendida como adherida y el MBBR-MBR puro contenía principalmente biomasa adherida en forma de biopelícula. Los parámetros cinéticos para las biomasas heterótrofa y autótrofa se evaluaron y relacionaron con las eliminaciones de materia orgánica y nitrógeno. El MBBR-MBR puro mostraba la mayor eficiencia respecto a la eliminación de nitrógeno total (NT) con un valor de 63.21±11.01%. El MBBR-MBR híbrido tenía el mayor rendimiento en eliminación de demanda química de oxígeno (DQO) con un valor de 84.10±2.25%. Las eficiencias en eliminación de DQO y NT se fundamentaron en el estudio cinético llevado a cabo ya que los sistemas MBBR-MBR híbrido y puro mostraban el mejor funcionamiento cinético para las biomasas heterótrofa y autótrofa, respectivamente. La presencia de la biomasa adherida mejoraba las eliminaciones de materia orgánica y nitrógeno en los sistemas MBBR-MBR híbrido y puro, respectivamente.

Palabras clave: *Tratamiento de aguas residuales; Biorreactor de membrana con lecho móvil; Eliminación de nitrógeno; Biopelícula; Cinética autótrofa*

Correspondencia: Juan Carlos Leyva Díaz jcleyva@ugr.es

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1. Introduction

The growing increase of urbanization, together with the industrial and farming development, has caused a rise in the consumption and deterioration of water resources (Wang et al., 2006). In the last years, the technical and scientific community has shown a growing interest in developing innovative treatment biological processes that, together with very high removal efficiencies concerning organic matter and nutrients, can lead to a very low space and volume request (Di Trapani et al., 2010a).

Among various technologies that have been introduced in the last decades, the moving bed biofilm reactor-membrane bioreactor (MBBR-MBR) constitutes an advanced technology which combines suspended and attached biomass and represents a possible solution to conventional activated sludge processes (Leiknes and Ødegaard, 2007). These systems introduce plastic elements called carriers inside the bioreactor for the growth of attached biomass (Di Trapani et al., 2010a). This technology couples a moving bed biofilm reactor (MBBR) (Ødegaard, 2006) with a membrane bioreactor (MBR) (Visvanathan, Ben Aim and Parameshwaran, 2000), and the resulting process becomes economically attractive when compact technology is required to accommodate space constraints or stringent effluent quality requirements are mandatory regarding organic matter and nutrient removal (Yang, Chen and Zhang, 2006; Leyva-Díaz et al., 2013). Moreover, this process is more resilient to overloading conditions and toxic compounds and has low head loss, high specific biomass activity and large area for colonization (Guo et al., 2010; Feng et al., 2012).

There are two ways of working in an MBBR-MBR system, i.e. a hybrid MBBR-MBR and a pure MBBR-MBR. In a hybrid MBBR-MBR the biomass grows as suspended and attached biomass (Mannina and Viviani, 2009). The difference between the hybrid MBBR-MBR and pure MBBR-MBR resides in the biomass growth, which was mainly developed on carriers as attached biomass in the pure MBBR-MBR since there was no biomass recycling from the membrane tank to the MBBR and the mixed liquor suspended solids (MLSS) concentration in the bioreactor was similar to that in the influent (Falletti, Conte and Milan, 2009).

The analysis of available scientific literature shows a lack of knowledge in terms of heterotrophic and autotrophic kinetics in MBBR-MBR systems used to treat municipal wastewater. In such perspective, respirometry definitively represents a helpful method for kinetic modeling, providing kinetic parameters of heterotrophs and autotrophs under controlled conditions of temperature and pH (Ferrai, Guglielmi and Andreottola, 2010). The principles of respirometry for the characterization of these systems have been described in the literature (Leyva-Díaz et al., 2013). In light of this, kinetic modeling can be an important tool for design and operation of MBBR-MBR plants (Leyva-Díaz et al., 2014).

The kinetics of organic matter and nitrogen removal in the MBBR-MBR was studied based on the Monod first order substrate removal model (Rittmann and McCarty, 1980), taking into account the influence on the kinetics due to the coexistence of two kinds of biomass, suspended and attached (Di Trapani et al., 2010b). The identification and quantification of the heterotrophic and autotrophic microbial population present in the MBR, hybrid MBBR-MBR and pure MBBR-MBR were necessary to evaluate the different kinetic parameters.

2. Objectives

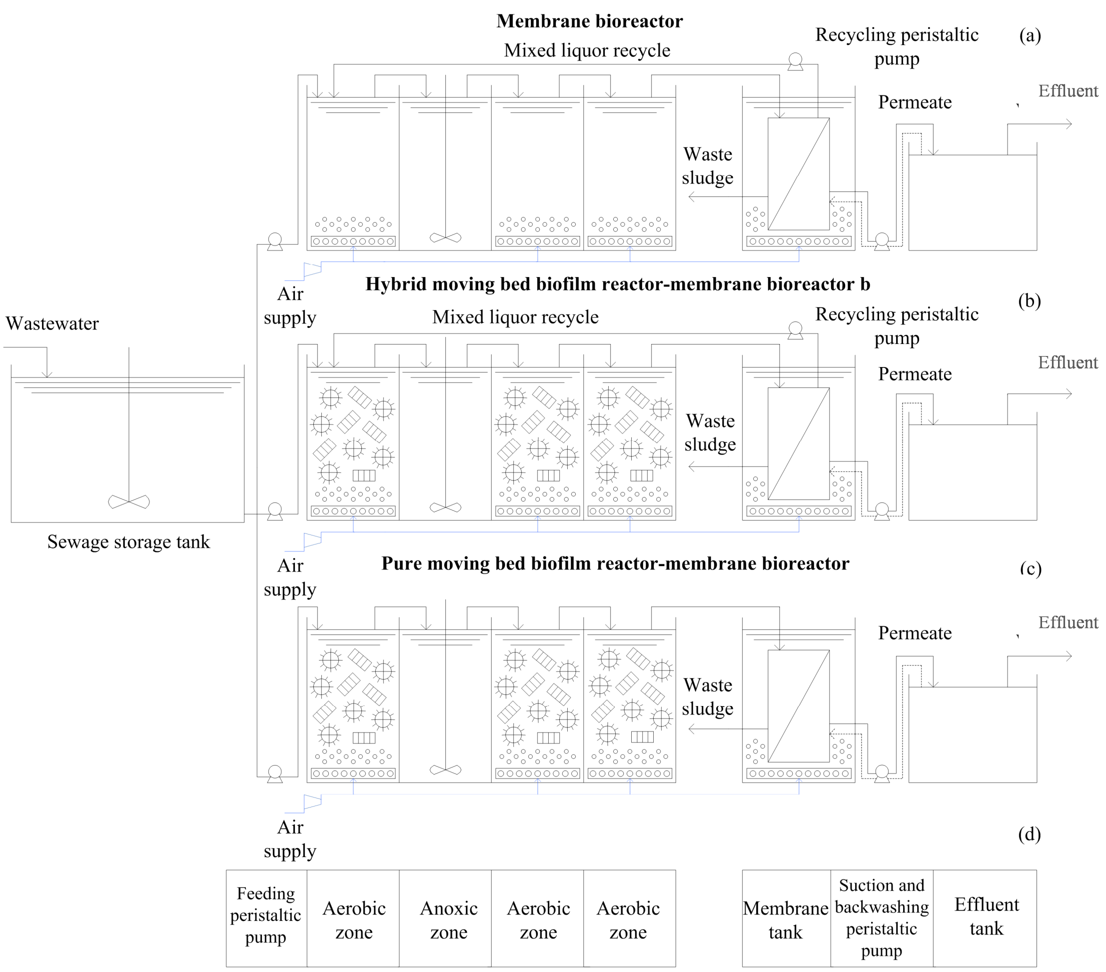
This research work was aimed at the experimental assessment of heterotrophic and autotrophic kinetics in an MBR, a hybrid MBBR-MBR and a pure MBBR-MBR, analyzing its influence on the removal of organic matter and nitrogen.

3. Materials and methods

3.1. Description of the experimental pilot plants and operation conditions

The wastewater treatment plants (WWTPs) consisted of an MBR (Figure 1a), a hybrid MBBR-MBR$_b$ (Figure 1b) and a pure MBBR-MBR (Figure 1c). These systems included a bioreactor divided into four zones: one anoxic zone and three aerobic ones, as well as a membrane tank. The MBR and hybrid MBBR-MBR$_b$ had a biomass recycling from the membrane tank to the bioreactor to get the working MLSS concentration inside the bioreactor and the nitrogen removal. The recycling rate was three times and a half the influent flow rate for the MBR and hybrid MBBR-MBR$_b$. Figure 1d shows the reactor zones, the membrane tank, the effluent tank and some peristaltic pumps.

Figure 1: Diagram of the experimental plants used in the study. (a) Membrane bioreactor (MBR). (b) Hybrid moving bed biofilm reactor-membrane bioreactor b (Hybrid MBBR-MBR$_b$). (c) Pure moving bed biofilm reactor-membrane bioreactor (Pure MBBR-MBR). (d) Nomenclature concerning the reactor zones, membrane tank, effluent tank and some peristaltic pumps.



The three pilot WWTPs, working in parallel, were fed with municipal wastewater from a sewage storage tank. This tank was filled with real wastewater coming from the outlet of the primary settler of a wastewater treatment plant (WWTP) located in Granada (Spain). Municipal wastewater was pumped into the first aerobic chamber of the bioreactor and went through the different chambers by a communicating vessel system. Aerobic zones were equipped with fine bubble disk diffusers at the bottom of the bioreactor; the air flow rate had a value of 30 L h^{-1}. The anoxic zones had mechanical stirrers. Both the diffusers and the stirrers kept the carriers moving inside the bioreactor and homogenized the mixed liquor. The outlet of the bioreactor was led into the membrane tank, which contained a submerged module of hollow-fiber ultrafiltration membranes; the air flow rate was 100 L h^{-1}. The total membrane area was 0.20 m^2. The permeate was extracted through the membrane using a suction-backwashing peristaltic pump to collect it in the effluent tank, with a cyclic mode of operation which consisted of production and backwashing periods of 9 min and 1 min, respectively. A fraction of the retentate was removed from the membrane tank as excess sludge.

The WWTPs operated under a hydraulic retention time (HRT) of 6 h, a flow rate of 4.70 L h^{-1}, a membrane flux of 23.5 L m^{-2} h^{-1}. The working volumes of the bioreactor and the membrane tank were 24 L and 4.32 L, respectively, and the anoxic zone of the bioreactor had a volume of 6 L. The sludge retention time (SRT) was 5.7 days for the MBR, 5.4 days for the hybrid MBBR-MBR_b and 4.5 days for the pure MBBR-MBR. The K1 media filling-fraction had a value of 35% in the aerobic zone; the anoxic zone did not contain carriers.

3.2. Experimental procedure and analytical determinations

Samples were collected every 24 h from the influent, the effluents and the anoxic and aerobic zones of the bioreactors and the membrane tank. Physical and chemical determinations were carried out regarding the pH, conductivity, temperature, dissolved oxygen, chemical oxygen demand (COD), five-day biochemical oxygen demand (BOD_5), total suspended solids (TSS), volatile suspended solids (VSS), total phosphorus (TP), total nitrogen (TN) and the concentrations of ammonium (NH_4^+), nitrite (NO_2^-) and nitrate (NO_3^-) (APHA, 2012).

The kinetic parameters for heterotrophic, autotrophic and nitrite-oxidizing bacteria and the substrate degradation rate (r_{su}) were evaluated according to Leyva-Díaz et al. (2013). The concentrations of heterotrophic and autotrophic bacteria were necessary for the assessment of the different kinetic parameters and were evaluated by supposing the percentages of heterotrophic, autotrophic and nitrite-oxidizing bacteria in the MLSS and biofilm density (BD) attached to the carriers for the MBR and hybrid MBBR-MBR systems studied by Leyva-Díaz et al. (2015).

The evaluation of statistically significant differences between the results concerning COD, BOD_5, TSS, TN, TP and concentrations of NH_4^+, NO_2^- and NO_3^- was carried out using the software SPSS 20.0 for Windows.

4. Results and discussion

4.1. Biomass formation and physical and chemical parameters

The MBR, hybrid MBBR-MBR_b and pure MBBR-MBR worked at average MLSS concentrations of 2,777.78±282.27 mg L^{-1}, 2,243.75±216.95 mg L^{-1} and 258.75±79.99 mg L^{-1}, respectively, in the steady state. The values of BD concerning the steady state were 748.53±111.97 mg L^{-1} and 2,070.00±202.97 mg L^{-1} for the hybrid MBBR-MBR_b and pure MBBR-MBR, respectively. The concentration of MLSS in the MBR was slightly higher than that in the hybrid MBBR-MBR_b although this difference was compensated by the attached biofilm on the carriers contained in the hybrid MBBR-MBR_b. The pure MBBR-MBR mainly had attached BD and the MLSS concentration in the bioreactor was similar to that of the influent. The values of MLSS concentrations and attached BD were similar to those reported by Leyva-Díaz et al. (2014).

Table 1 shows the average values of pH, conductivity, temperature and dissolved oxygen concentration of the influent, effluents and mixed liquors of the different bioreactors. The pure MBBR-MBR showed similar values of conductivity of the influent, mixed liquor and effluent since there was no biomass recycling from the membrane tank to the bioreactor. The temperature was 20.7±1.1ºC. The dissolved oxygen concentrations in the aerobic zone of the bioreactors were around 2.0 mg O_2 L^{-1}, which is recommended to achieve an efficient removal of organic matter and nitrogen, according to Wang et al. (2006).

Table 1: Average values of pH, conductivity, temperature and dissolved oxygen concentration of the influent, effluents and mixed liquors of the biological reactors of the experimental plants.

Parameter	Sampling zone									
	Influent	MBR			Hybrid MBBR-MBR_b			Pure MBBR-MBR		
		Effluent	Anoxic zone	Aerobic zone	Effluent	Anoxic zone	Aerobic zone	Effluent	Anoxic zone	Aerobic zone
pH	8.16±0.15	7.10±0.54	7.39±0.52	7.05±0.59	6.71±0.35	7.17±0.57	6.59±0.73	7.49±0.50	7.80±0.06	7.67±0.08
Conductivity (µS cm^{-1})	1,313±103	1,025±79	1,085±83	1,051±84	1,031±64	1,053±53	1,033±59	1,271±133	1,376±142	1,342±134
Temperature (ºC)	20.2±1.3	20.7±0.8	20.7±0.8	20.7±0.8	20.7±1.0	20.7±0.9	20.7±0.9	20.7±1.3	20.7±1.2	20.7±1.3
Dissolved oxygen (mg O_2 L^{-1})	-	-	0.3±0.2	2.0±1.1	-	0.2±0.1	1.8±0.8	-	0.3±0.1	2.1±0.5

4.2. Organic matter and nutrient removal

The values of COD and BOD_5 obtained from the influent and effluents relating to the MBR, hybrid MBBR-MBR_b and pure MBBR-MBR, as well as the removal percentages of these parameters for the steady state, are shown in Table 2.

Table 2: Average values of COD, BOD_5, TSS, TP, TN, NH_4^+, NO_2^- and NO_3^- of the influent and effluents of the experimental plants and removal percentages of COD, BOD_5, TSS, TP and TN during the steady state. COD (chemical oxygen demand), BOD_5 (five-day biochemical oxygen demand), TSS (total suspended solids), TP (total phosphorus), TN (total nitrogen), NH_4^+ (concentration of ammonium), NO_2^- (concentration of nitrite), NO_3^- (concentration of nitrate).

Parameter	Sampling zone				Removal percentage	Wastewater treatment plant		
	Influent	Effluent MBR	Effluent Hybrid MBBR-MBR_b	Effluent Pure MBBR-MBR		MBR	Hybrid MBBR-MBR_b	Pure MBBR-MBR
COD (mg O_2 L^{-1})	207.61±38.79	33.20±3.76	33.01±6.20	41.99±7.12	COD (%)	84.01±2.15	84.10±2.25	79.78±4.60
BOD_5 (mg O_2 L^{-1})	104.29±15.01	4.79±0.67	4.60±1.23	4.40±0.98	BOD_5 (%)	95.41±0.96	95.58±0.87	95.78±0.82
TSS (mg L^{-1})	83.07±20.26	4.58±2.38	5.41±2.46	3.14±2.62	TSS (%)	94.49±3.65	93.49±3.66	96.21±2.71
TP (mg TP L^{-1})	9.15±1.27	4.98±0.70	5.24±0.72	5.31±1.48	TP (%)	45.55±11.67	42.71±6.91	41.98±9.95
TN (mg TN L^{-1})	80.21±8.50	43.43±8.71	41.28±13.44	29.51±3.93	TN (%)	45.86±10.69	48.53±16.71	63.21±11.01
NH_4^+ (mg NH_4^+ L^{-1})	100.45±31.70	ND	ND	ND				
NO_2^- (mg NO_2^- L^{-1})	0.81±0.02	8.42±5.67	18.16±8.04	28.87±12.26				
NO_3^- (mg NO_3^- L^{-1})	8.14±4.11	180.97±69.88	158.36±47.34	91.77±25.22				

ND: Not Detected

The hybrid MBBR-MBR_b showed a better performance than the MBR and pure MBBR-MBR regarding COD removal, with a value of 84.10±2.25%. The differences between the hybrid MBBR-MBR_b and MBR regarding the COD removal were not statistically significant under an HRT of 6 h. However, these differences were statistically significant between the hybrid MBBR-MBR_b and pure MBBR-MBR with a p-value of 0.00030 (Table 3). The improvement regarding the removal of organic matter in the hybrid MBBR-MBR_b was probably due to the presence of suspended and attached biomass, as the pure MBBR-MBR mainly contained attached biomass, while the MBR only had suspended biomass.

Table 3: P-values of sequential comparison (ANOVA analysis) of removal percentages of COD, BOD_5, TSS, TN and TP between the different experimental plants. COD (chemical oxygen demand), BOD_5 (five-day biochemical oxygen demand), TSS (total suspended solids), TN (total nitrogen). TP (total phosphorus).

Wastewater treatment plants		Parameter				
		COD	BOD_5	TSS	TN	TP
MBR	**Hybrid MBBR-MBR_b**	0.06519	0.79999	0.99110	0.89674	0.99995
MBR	**Pure MBBR-MBR**	**0.00450**	0.22043	0.78543	**0.04478**	0.99956
Hybrid MBBR-MBR_b	**Pure MBBR-MBR**	**0.00030**	0.89992	0.23252	**0.03480**	0.99999

The differences between the pilot plants regarding the removal percentage of TSS were not statistically significant (Table 3) due to the physical process of ultrafiltration.

The concentrations of TP and TN in the influent and the effluents of the WWTPs and the removal percentages of these nutrients are indicated in Table 2. The experimental plants removed a fraction of TP due to the physical process of ultrafiltration and the creation of small anaerobic zones in the anoxic chambers. However, the process of biological phosphorus removal could not be initialized since there was not a strict anaerobic compartment (Kermani et al., 2009), so the differences between the pilot plants were not statistically significant regarding the TP removal (Table 3).

The pure MBBR-MBR showed the best performance concerning TN removal, with a value of 63.21±11.01% (Table 2). The differences between the pure MBBR-MBR and the MBR and hybrid MBBR-MBR_b were statistically significant under an HRT of 6 h as the p-values obtained were lower than $\alpha=0.05$ (Table 3). In light of this, the TN removal was more effective in the pure MBBR-MBR. This was probably due to the biomass growth as it was mainly developed on carriers as attached biomass, with a value of BD of 2,070.00±202.97 mg L^{-1}, involving a better contact between the nitrate and the microorganisms involved in the nitrogen cycle for its removal (Rusten, Hem and Ødegaard, 1995). Nitrification took place in the outer layer of the attached biomass (aerobic layer) and denitrification occurred in the deeper layer (anoxic layer). Consequently, the pure MBBR-MBR showed the highest performance of TN removal (Yang et al., 2009).

4.3. Kinetic modeling of MBR, hybrid MBBR-MBR_b and pure MBBR-MBR

Table 4 shows the parameters that fit the Monod model for the heterotrophic, autotrophic and nitrite-oxidizing bacteria contained in the different bioreactors.

Table 4: Kinetic parameters for the characterization of heterotrophic, autotrophic and nitrite-oxidizing bacteria. Y_H (yield coefficient for heterotrophic biomass), $\mu_{m,H}$ (maximum specific growth rate for heterotrophic biomass), K_M (half-saturation coefficient for organic matter), Y_A (yield coefficient for autotrophic biomass), $\mu_{m,A}$ (maximum specific growth rate for autotrophic biomass), K_{NH} (half-saturation coefficient for ammonia-nitrogen), Y_{NOB} (yield coefficient for nitrite-oxidizing bacteria), $\mu_{m,NOB}$ (maximum specific growth rate for nitrite-oxidizing bacteria), K_{NOB} (half-saturation coefficient for nitrite-nitrogen), k_d (decay coefficient for autotrophic and heterotrophic biomass).

Parameter	Sampling zone		
	MBR	Hybrid MBBR-MBR_b	Pure MBBR-MBR
	Heterotrophic bacteria		
Y_H (mg VSS mg COD^{-1})	0.5632	0.5756	0.5941
$\mu_{m,H}$ (h^{-1})	0.0255	0.0658	0.0292
K_M (mg O_2 L^{-1})	7.0629	18.9121	2.9681
	Autotrophic bacteria		
Y_A (mg O_2 mg N^{-1})	1.9591	2.2366	2.3657
$\mu_{m,A}$ (h^{-1})	0.1607	0.2250	0.3591
K_{NH} (mg N L^{-1})	0.3887	2.4179	3.1582
	Nitrite-oxidizing bacteria		
Y_{NOB} (mg O_2 mg N^{-1})	0.5746	0.4918	0.4989
$\mu_{m,NOB}$ (h^{-1})	0.1482	0.2478	0.1828
K_{NOB} (mg N L^{-1})	0.5809	1.0025	1.2601
	Total bacteria		
k_d (d^{-1})	0.0366	0.0390	0.0982

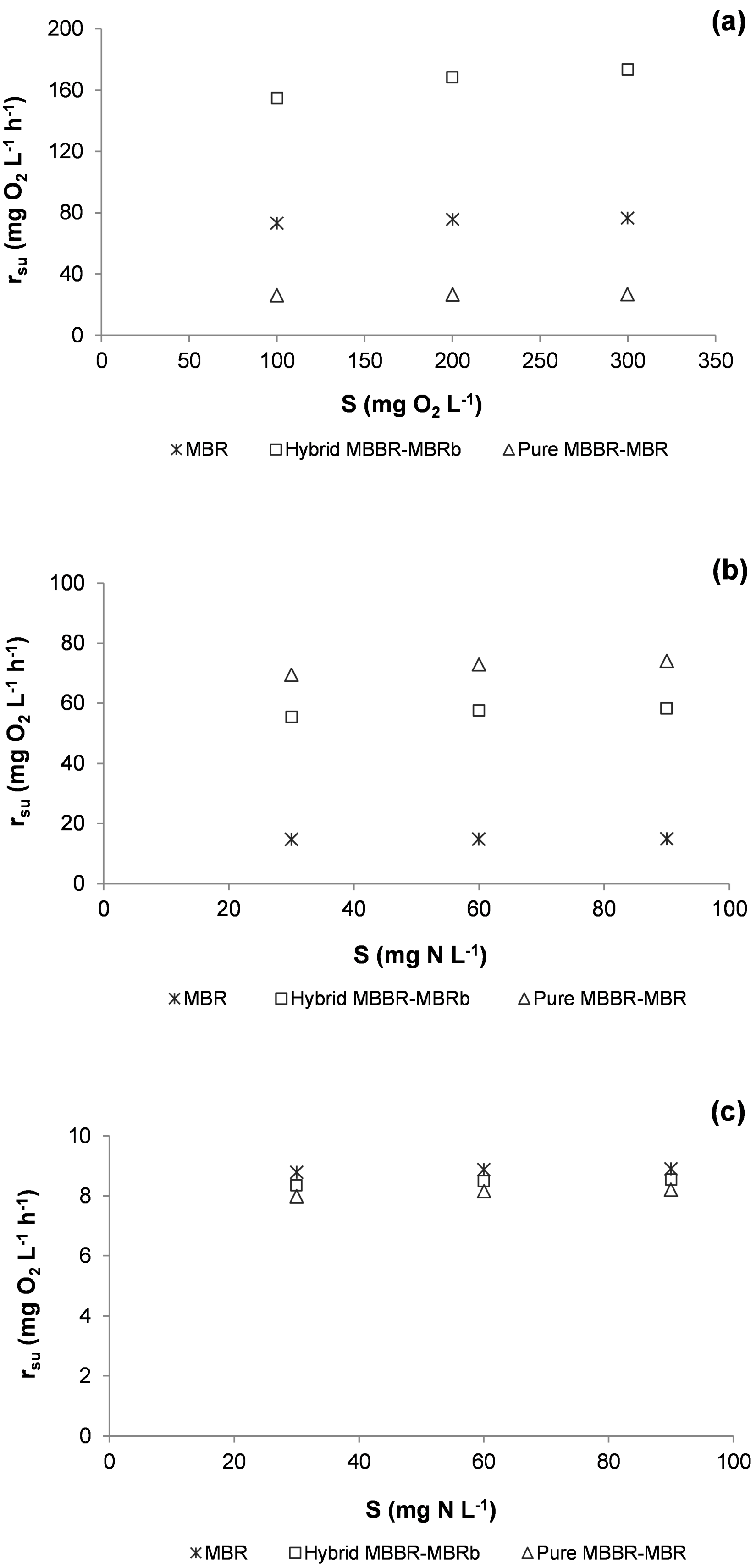
The heterotrophic biomass of the hybrid MBBR-MBR_b showed a kinetic performance that was better than those corresponding to the MBR and pure MBBR-MBR according to the evaluation of the r_{su}, depending on the kinetic parameters and the substrate and biomass concentrations, as shown in Figure 2a. Therefore, the heterotrophic biomass of the hybrid MBBR-MBR_b required less time for organic matter oxidation under the operation conditions of this study. Moreover, the detection of the maximum specific growth rate (μ_m) could be carried out with less available substrate and less time would be required to accomplish a steady state in the hybrid MBBR-MBR_b. This was in accordance with the highest COD removal efficiency of the hybrid MBBR-MBR_b, with a value of 84.10±2.25%, as indicated in Table 2.

The autotrophic biomass of the pure MBBR-MBR showed a kinetic behavior that was better than those corresponding to the MBR and hybrid MBBR-MBR_b (Figure 2b). Thus, the autotrophic biomass of the pure MBBR-MBR needed less time for the oxidation of nitrogen contained in the influent under the operation conditions, the detection of the μ_m was carried out with less available substrate, and less time would be required to accomplish a steady state in the pure MBBR-MBR. This was probably due to the better accessibility to the available substrate by the attached biomass of the pure MBBR-MBR since there was practically no competition between suspended and attached biomass. This supported that the pure MBBR-MBR was the pilot plant with the highest percentage of TN removal, with a value of 63.21±11.01%, as shown in Table 2. The values of Y_A reported by Seifi and Fazaelipoor (2012) and Di Trapani et al. (2008) were slightly lower than those obtained in this study. Henze et al. (1987) and Seifi and Fazaelipoor (2012) obtained similar values regarding K_{NH} and $\mu_{m,\ A}$, respectively, in an MBBR.

From the point of view of the nitrite-oxidizing bacteria (NOB), the MBR showed the best kinetic performance, with values of Y_{NOB} = 0.5746 mg O_2 mg N^{-1}, $\mu_{m,\ NOB}$ = 0.1482 h^{-1} and K_{NOB} = 0.5809 mg N L^{-1} (Henze et al., 2000; Pambrun, Paul and Sperandio, 2006; Iacopozzi, Innocenti and Marsili-Libelli, 2007), as shown in Figure 2c. This supported the fact that the nitrate concentration in the effluent from the MBR was higher than those from the hybrid MBBR-MBR_b and pure MBBR-MBR (Table 2). Consequently, the pure MBBR-MBR could have a better kinetic behavior regarding the ammonium-oxidizing bacteria (AOB) because, on the whole, the kinetics of autotrophic bacteria was better in this system, as previously mentioned, and the pure MBBR-MBR had the highest nitrite concentration in its effluent (Table 2). There were statistically significant differences regarding nitrite and nitrate formations between the MBR and pure MBBR-MBR as the p-values obtained were less than α=0.05, p-value $_{\text{MBR-Pure MBBR-MBR}}$ (NO_2^-) = 0.01315 and p-value $_{\text{MBR-Pure MBBR-MBR}}$ (NO_3^-) = 0.02289.

The values of the decay coefficient for total bacteria (k_d) are also indicated in Table 4. The k_d for the biomass of the pure MBBR-MBR was the highest. The value of SRT in the pure MBBR-MBR was the lowest compared to the MBR and hybrid MBBR-MBR_b, with a value of 4.5 days, as the flow rate of waste sludge was higher than those corresponding to the MBR and hybrid MBBR-MBR_b to keep a low MLSS concentration inside the bioreactor of the pure MBBR-MBR. In light of this, the biomass decay rate will be higher as the organic loading rate was similar in the WWTPs, but the MLSS concentration was lower in the pure MBBR-MBR.

Figure 2: Substrate degradation rate (r_{su}) obtained in the biological kinetic study depending on the substrate concentration for the different bioreactors from the WWTPs. (a) Heterotrophic bacteria. (b) Autotrophic bacteria. (c) Nitrite-oxidizing bacteria.



5. Conclusions

The pure MBBR-MBR had a higher potential to remove TN from municipal wastewater than the MBR or hybrid MBBR-MBR_b, with an efficiency of TN removal of 63.21±11.01%, as the attached biomass had a great quantity of available substrate and a better accessibility to it. The hybrid MBBR-MBR_b showed the best performance of COD removal as this system had a better heterotrophic kinetic performance. Thus, the effect of the attached biomass enhanced the organic matter and nitrogen removal through a hybrid MBBR-MBR_b or pure MBBR-MBR, respectively.

Consequently, the hybrid MBBR-MBR_b and pure MBBR-MBR would enable the rehabilitation of activated sludge plants and membrane bioreactors which, for any reason, did not comply with the Directive 91/271/EEC regarding the organic matter and nitrogen removal.

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