Influence of temperature on the start-up of membrane bioreactor: kinetic study

J. C. Leyva-Díaz, J. Martín-Pascual, G. Calero-Díaz, J. C. Torres and J. M. Poyatos

ABSTRACT

The start-up phase of a membrane bioreactor (MBR) for municipal wastewater treatment was studied to determine the effect of temperature on the organic matter removal and heterotrophic kinetics. The MBR system was analyzed during four start-up phases with values of hydraulic retention time (HRT) of 6 h and 10 h, mixed liquor suspended solids (MLSS) concentrations of 4,000 mg L^{-1} and 7,000 mg L^{-1} in the steady state, and temperature values of 11.5, 14.2, 22.9 and 30.1 °C. The influence of temperature on the biological process of organic matter removal was determined through the Arrhenius equation and Monod model. At the most favorable operation conditions of HRT (10 h) and MLSS (7,000 mg L^{-1}) corresponding to phase 4, the effect of these variables dominated over the temperature. Heterotrophic biomass from phase 2 (HRT = 10 h, MLSS = 4,000 mg L^{-1} and T = 30.1 °C) had the highest values of chemical oxygen demand (COD) degradation rate ($r_{su,H}$), implying less time to remove organic matter and shorter duration of the start-up phase.

Key words | heterotrophic kinetics, membrane bioreactor, temperature

J. C. Leyva-Díaz (corresponding author)
J. Martín-Pascual
J. M. Poyatos
Department of Civil Engineering,
University of Granada,
Granada,
Spain
and
Institute of Water Research,
University of Granada,
Granada,
Spain
E-mail: *jcleyva@ugr.es*

G. Calero-Díaz
J. C. Torres
Department of I + D + I of HiDRALiA,
HiDRALiA,
Sevilla,
Spain

NOMENCLATURE

A	pre-exponential factor (–)
b_H	decay coefficient for heterotrophic biomass (day^{-1})
E_a	activation energy (J mol^{-1})
f_{cv}	conversion factor (1.48) (mgCOD $mgVSS^{-1}$)
$1\text{-}f_p$	fraction of volatile biomass (mgVSS $mgTSS^{-1}$)
$K_{M,H}$	half-saturation coefficient for organic matter (mgO_2 L^{-1})
OC	oxygen consumption (mgO_2 L^{-1})
OUR_{end}	endogenous oxygen uptake rate (mgO_2 L^{-1} h^{-1})
R	gas constant (J mol^{-1} K^{-1})
r_{su}	substrate degradation rate (mgO_2 L^{-1} h^{-1})
$r_{su,H}$	COD degradation rate (mgO_2 L^{-1} h^{-1})
R_s	dynamic oxygen uptake rate (mgO_2 L^{-1} h^{-1})
r_T	kinetic parameter at working temperature (–)
r_{20}	kinetic parameter at 20 °C (–)
S	substrate concentration (mgO_2 L^{-1})
T	temperature (°C)
X_H	concentration of heterotrophic biomass (mgVSS L^{-1})
X_T	total biomass concentration (mgTSS L^{-1})
Y_H	yield coefficient for heterotrophic biomass (mgVSS $mgCOD^{-1}$)
μ_{emp}	empirical specific growth rate (h^{-1})
$\mu_{m,\ H}$	maximum specific growth rate for heterotrophic biomass (h^{-1})

doi: 10.2166/wst.2017.554

INTRODUCTION

Membrane bioreactor (MBR) systems have been widely used for the treatment of municipal and industrial wastewater (Wintgens *et al.* 2005). MBR technology has emerged as an alternative solution for overloaded conventional wastewater treatment plants (WWTPs) through the replacement of the secondary settling tank by a membrane separation (Gunder & Krauth 1998; Van der Roest *et al.* 2002). These systems improve the conventional activated sludge processes due to their higher effluent quality, smaller space and reactor requirements, increased volumetric

Downloaded from https://iwaponline.com/wst/article-pdf/77/2/448/242756/wst077020448.pdf
by guest

loadings and lower sludge production rates (Oppenheimer *et al.* 2001; Poyatos *et al.* 2008; Wang *et al.* 2009). Moreover, the MBR shows better control of sludge retention time (SRT) and a higher operational reliability, stability and compactness (Jang *et al.* 2013). According to Vyrides & Stuckey (2011), MBR systems can be acclimated to specific wastewater at higher rates. Moreover, this technology can treat high strength wastewater and toxic compounds (Guo *et al.* 2012).

Among the operational factors in the MBR process, such as mixed liquor suspended solids (MLSS), temperature, dissolved oxygen (DO), pH, SRT, and hydraulic retention time (HRT), temperature is one of the most important (Judd 2011). The temperature of mixed liquor varies due to seasonal and diurnal temperature changes, as well as the mixing of hot industrial effluents with municipal wastewater (Arévalo *et al.* 2014; Grandclément *et al.* 2017). These changes can affect the MBR performance through the influence on the concentration of MLSS and microbial kinetics (Huang *et al.* 2001). In light of this, microbial activity, the reaction rate of the biological process occurring in MBR and other physicochemical properties could be influenced by temperature conditions (Calderón *et al.* 2012; Grandclément *et al.* 2017). The influence of temperature on the heterotrophic bacteria kinetics and reaction rate of the biological process of organic matter removal was evaluated through the Monod model (Monod 1949) and the Arrhenius equation (Grandclément *et al.* 2017). Thus, the stability of an MBR system depends on temperature variability, which is related to sludge deflocculation and reduction of sludge metabolic activity (Van den Brink *et al.* 2011).

The aim of this study was to determine the influence of seasonal temperature variations on the performance of a pilot-scale MBR in relation to its heterotrophic kinetics in the start-up phase at HRT values of 6 h and 10 h, and MLSS concentrations for the steady state of 4,000 mg L^{-1} and 7,000 mg L^{-1}.

MATERIALS AND METHODS

Description of the WWTP

In this study, an MBR system was analyzed during the start-up periods corresponding to four operation phases, which are characterized in Table 1.

The choice of these values for HRT and MLSS concentration is based on the intention of simulating a medium-loading process, with values of sludge loading (F/M) of 0.38, 0.35, 0.33 and 0.29 $kgBOD_5\ kgMLVSS^{-1}\ day^{-1}$ for phases 1, 2, 3 and 4, respectively.

Figure 1 shows the diagram of the MBR system analyzed in this research. The bioreactor was fed with municipal wastewater coming from the primary settler of the WWTP of Puente de Los Vados, located in Granada (Spain). The MBR system was designed as an aerated cylindrical bioreactor of 272 L, as well as an external rectangular unit of 78 L containing four vertically oriented submerged modules of hollow-fiber ultrafiltration membranes (ZW-10, ZENON®). The membrane flow was from the outside to the inner side by suction. The total membrane area was 3.72 m^2 (0.93 m^2 per module), with a nominal pore size of 0.04 μm and an absolute pore size of 0.1 μm.

Kinetic modeling

The influence of temperature was assessed during the start-up of the four phases. In light of this, heterotrophic kinetics were evaluated for each one of the start-up phases of MBR operation.

Kinetic parameters for heterotrophic bacteria and the substrate degradation rate (r_{su}) were evaluated through a respirometric method according to Leyva-Díaz *et al.* (2013a). One liter of mixed liquor was withdrawn from the MBR, aerated for 18–24 h to reach endogenous conditions and transferred to the BM-Advance respirometer

Table 1 | Operation conditions and heterotrophic kinetic parameters, $\mu_{m,H}$, $K_{M,H}$, Y_H, b_H, for the different phases of start-up of the MBR system

Phase	HRT (h)	MLSS (mg L^{-1})	T (°C)	Y_H (mgVSS mg COD^{-1})	$\mu_{m,H}$ (h^{-1})	$K_{M,H}$ (mgO_2 L^{-1})	b_H (day^{-1})
1	6	4,000	14.2	0.4100 ± 0.0502	0.0101 ± 0.0024	8.0652 ± 0.7662	0.0494 ± 0.0074
2	10	4,000	30.1	0.9076 ± 0.0976	0.1075 ± 0.0205	30.7323 ± 3.3806	0.2361 ± 0.0307
3	6	7,000	22.9	0.6216 ± 0.0784	0.0182 ± 0.0020	13.6928 ± 1.4377	0.1405 ± 0.0139
4	10	7,000	11.5	0.4356 ± 0.0314	0.0336 ± 0.0040	24.5231 ± 2.8202	0.0828 ± 0.0091

Y_H (yield coefficient for heterotrophic biomass), $\mu_{m,H}$ (maximum specific growth rate for heterotrophic biomass), $K_{M,H}$ (half-saturation coefficient for organic matter), b_H (decay coefficient for heterotrophic biomass)

Downloaded from https://iwaponline.com/wst/article-pdf/77/2/448/242756/wst077020448.pdf
by guest

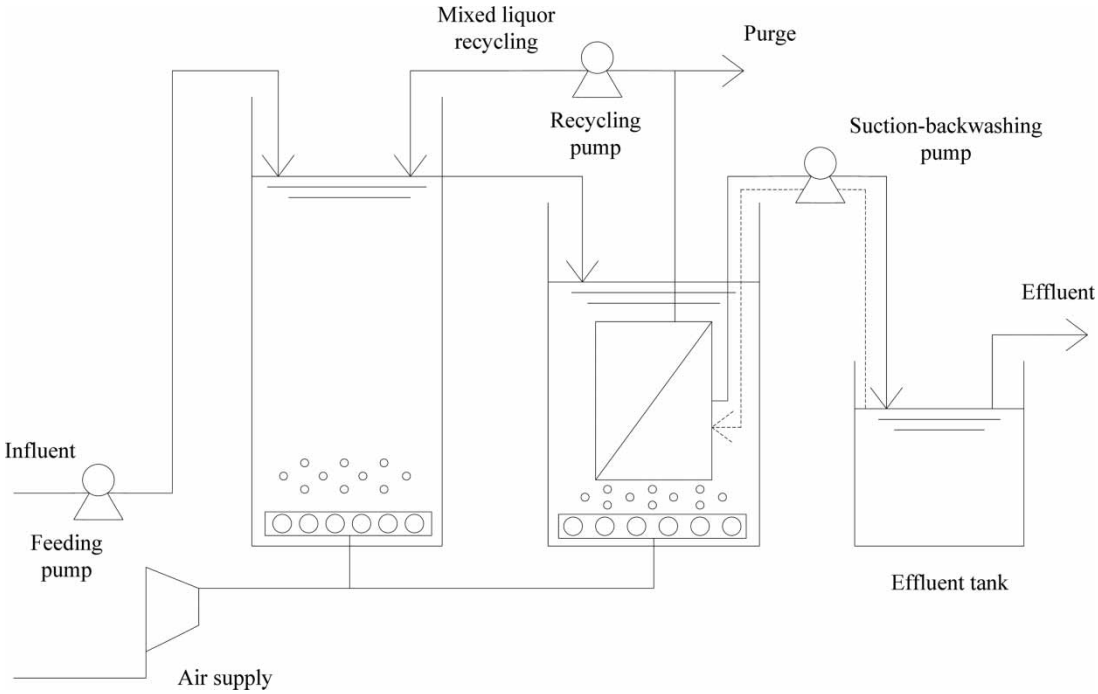

Figure 1 | Diagram of the pilot-scale MBR used in the study.

(Leyva-Díaz *et al.* 2013a, 2013b). Temperature was maintained at 20.0 ± 0.1 °C and the stirring rate was 2,000 rpm. Oxygen was supplied through an air pump, with an air flow rate of 0.906 ± 0.001 L min^{-1}. The value of pH was kept at 7.25 ± 0.50 by using sulphuric acid and/or sodium hydroxide. Moreover, a peristaltic pump allowed for homogenizing the mixed liquor through recycling from the bottom to the top of the respirometer. A stock solution of sodium acetate (500 mg L^{-1}) was prepared and three dilutions (50, 80 and 100%) were used to evaluate the heterotrophic kinetic parameters. The values of chemical oxygen demand (COD) for the three dilutions and the concentrations of MLSS were calculated from *Standard Methods* (APHA 2012). The evolution of the DO and the dynamic oxygen uptake rate (R_s) were registered for the three additions of substrate (Leyva-Díaz *et al.* 2013a), constituting an indirect measurement of the substrate concentration.

After this respirometric assay, the mixed liquor was left without aeration to carry out an endogenous respiration experiment. The decay coefficient was evaluated from this test (Leyva-Díaz *et al.* 2013a).

Therefore, both respirometric experiments facilitated the estimation of the maximum specific growth rate ($\mu_{m,H}$), substrate half-saturation coefficient ($K_{M,H}$), yield coefficient (Y_H) and decay coefficient (b_H) for heterotrophic biomass. The estimation of these parameters was carried out in six steps, whose equations are shown in Table 2:

(1) Assessment of the oxygen consumption (OC) through the integration of R_s, as indicated in Equation (1).
(2) Estimation of Y_H according to Equation (2) described by Helle (1999), where S is the substrate concentration ($mgO_2\ L^{-1}$) and f_{cv} is a conversion factor (1.48 mgCOD mgVSS^{-1}).
(3) Evaluation of the substrate degradation rate (r_{su}) from R_s, as shown in Equation (3).
(4) Determination of the empirical specific growth rate (μ_{emp}) from the relation between the cell growth rate and r_{su} through Equation (4), where X_H is the concentration of heterotrophic biomass (mgVSS L^{-1}).
(5) Estimation of $\mu_{m,H}$ and $K_{M,H}$ through the linearization of the Monod model, as observed in Equation (5).
(6) Estimation of b_H according to Equation (6) described by Ekama *et al.* (1986), where OUR_{end} is the endogenous oxygen uptake rate ($mgO_2\ L^{-1}\ h^{-1}$), X_T is the total biomass concentration (mgTSS L^{-1}) and (1-f_p) is the fraction of volatile biomass (mgVSS mgTSS^{-1}).

The kinetic parameters were evaluated at working temperature through Equation (7), proposed by Metcalf & Eddy (2003) and indicated in Table 2, where r_T and r_{20} symbolize

Downloaded from https://iwaponline.com/wst/article-pdf/77/2/448/242756/wst077020448.pdf
by guest

Table 2 | Equations of the different calculation steps

Calculation	Equation	
Estimation of heterotrophic kinetic parameters	$OC = \int_{t_i}^{t_f} R_s\,dt \quad (mgO_2\,L^{-1})$	(1)
	$Y_H = \frac{S - OC}{S \cdot f_{cv}} \quad (mgVSS\,mgCOD^{-1})$	(2)
	$r_{su} = \frac{R_s}{1 - Y_H \cdot f_{cv}} \quad (mgO_2\,L^{-1}\,h^{-1})$	(3)
	$\mu_{emp} = \frac{Y_H \cdot R_s}{(1 - Y_H \cdot f_{cv}) \cdot X_H} \quad (h^{-1})$	(4)
	$\frac{1}{\mu_{emp}} = \frac{1}{\mu_{m,H}} + \frac{K_{M,H}}{\mu_{m,H}} \cdot \frac{1}{S} \quad (h)$	(5)
	$b_H = \frac{OUR_{end}}{1.42 \cdot X_T \cdot [1 - Y_H(1 - f_p)]} \quad (day^{-1})$	(6)
Fitting of heterotrophic kinetics according to Arrhenius equation	$r_T = r_{20} \cdot \theta^{(T-20)}$	(7)
	$\ln(r_T) = \ln(A) - \frac{E_a}{R} \cdot \frac{1}{T}$	(8)
Evaluation of COD degradation rate	$r_{su,H} = \frac{\mu_{m,H} \cdot S \cdot X_H}{Y_H \cdot (K_{M,H} + S)}$	(9)

the kinetic parameters at working temperature and 20 °C, respectively, θ is a fitting parameter with a value of 1.04 for the MBR, and T is the working temperature.

Moreover, the heterotrophic kinetic parameters were fitted as a function of temperature according to the Arrhenius equation, as indicated in Equation (8) (Table 2), where A is the pre-exponential factor, R is the gas constant and E_a is the activation energy of the biological process.

Thus, the COD degradation rate ($r_{su,H}$) can be expressed as a function of the temperature through the heterotrophic kinetic parameters, as well as the substrate and biomass concentrations, as shown in Equation (9), which is shown in Table 2.

RESULTS AND DISCUSSION

The values of Y_H, $\mu_{m,H}$, $K_{M,H}$ and b_H are reported in Table 1. According to Table 1, the values of Y_H and b_H increased with temperature. This trend was also observed by Arévalo *et al.* (2014), which worked with an MBR system under an HRT of 35 h and temperatures from 9 °C to 33 °C.

In this regard, the temperature of the mixed liquor had an effect on the growth and decay of the biomass. Regarding Y_H, this trend was in accordance with the necessity of biomass to satisfy its maintenance energy requirements previous to using oxygen for biomass growth (Hao *et al.* 2010). In relation to b_H, the decay increased with the temperature since the microbial activity also rose (Pollice *et al.* 2007). Moreover, the b_H values obtained in this study were lower than those reported by Marais & Ekama (1976) for conventional activated sludge systems (0.24 day^{-1}), so the fraction of biomass oxidized per day was lower for the MBR.

Rodríguez *et al.* (2011) worked with a similar MBR to that used in this research. These authors used pure oxygen to supply the aerobic conditions, operating at an HRT of 12 h and temperature of 15.5 °C. The heterotrophic kinetic parameters were estimated during the start-up of the MBR, with values of MLSS concentration varying between 3,420 and 12,600 mg L^{-1}. Rodríguez *et al.* (2011) obtained values of $K_{M,H}$ of 73.954 $mgO_2\,L^{-1}$ for 3,420 mg L^{-1} and 68.002 $mgO_2\,L^{-1}$ for 5,200 mg L^{-1}, which were higher than the value obtained in the present research (8.0652 $mgO_2\,L^{-1}$) at similar temperature (14.2 °C) and MLSS concentration (Table 1). Regarding the maximum specific growth rate, Rodríguez *et al.* (2011) found values of $\mu_{m,H}$ ranging from 0.045 day^{-1} to 0.184 day^{-1}, which were lower than the value obtained for the heterotrophic biomass from the MBR of this study (0.0101 h^{-1}). In relation to the Y_H, the yield coefficients obtained by Rodríguez *et al.* (2011) (0.931–0.935 mgMLSS $mgCOD^{-1}$) practically doubled those obtained in this study (0.4100 mg VSS mg COD^{-1}) at similar MLSS concentrations. Having considered the previous values of the heterotrophic kinetic parameters, it should be highlighted that the $r_{su,H}$ was higher for the MBR analyzed in this study than that from Rodríguez *et al.* (2011), according to Equation (9). This was probably due to a decrease in the efficiency of the aeration system. However, the cell decay rate was higher for the MBR studied by Rodríguez *et al.* (2011) due to the higher

Downloaded from https://iwaponline.com/wst/article-pdf/77/2/448/242756/wst077020448.pdf
by guest

values of b_H (0.1040–0.0520 day^{-1}), implying a higher quantity of biomass oxidized per day (Leyva-Díaz *et al.* 2013a).

Figure 2 shows that the Napierian logarithm of the heterotrophic kinetic parameters was correlated with the inverse of temperature, except for the values of phase 4, characterized by the lowest temperature (11.5 °C).

Table 3 shows the fitting parameters, A and E_a/R, as well as the correlation coefficient (R^2) of the Arrhenius model (Equation (8)) for expressing the heterotrophic kinetics as a function of temperature.

The deviation of the values corresponding to phase 4 in relation to the general trend was probably due to the more favorable operation conditions of HRT and MLSS that characterized it (HRT = 10 h and MLSS = 7,000 mg L^{-1}), cancelling out the effect of temperature. This was supported by Figure 3 as $\mu_{m,H}$, $K_{M,H}$, b_H were more positively correlated with the variables HRT and mixed liquor volatile suspended solids (MLVSS) than temperature.

This effect was also observed when the $r_{su,H}$ and COD removal were analyzed (Figure 4). Considering Equation (9) and the fitting of heterotrophic kinetics as a function of temperature according to the Arrhenius model (Table 3), Equation (10) was obtained to describe the evolution of $r_{su,H}$ depending on temperature, substrate concentration and heterotrophic biomass concentration for the start-up periods of the different phases:

$$r_{su,H} = \frac{1.16 \cdot 10^3 \cdot e^{-2{,}939/T} \cdot S \cdot X_H}{1.08 \cdot 10^5 \cdot e^{-2{,}563/T} + S} \quad (10)$$

Equation (10) could be applied for temperature varying between 11.5 and 30.1 °C, X_H fluctuating between 4,000 and 7,000 mg L^{-1}, and HRT ranging between 6 and 10 h, as validity domain.

Figure 4(a) shows that heterotrophic biomass from phases 2 and 3 had the highest values for $r_{su,H}$, which could be due to their higher working temperatures, 30.1 °C and 22.9 °C, respectively. Nevertheless, heterotrophic biomass corresponding to phase 4 had higher values of $r_{su,H}$ than heterotrophic bacteria from phase 1 despite its lower value of temperature (11.5 °C). This could be explained as a result of the higher influence of HRT and MLSS compared with temperature, which were higher for the heterotrophic biomass from phase 4, with values of 10 h and 7,000 mg L^{-1}, respectively. Finally, the operational conditions of phase 1 were the most unfavorable regarding HRT and MLSS, with values of

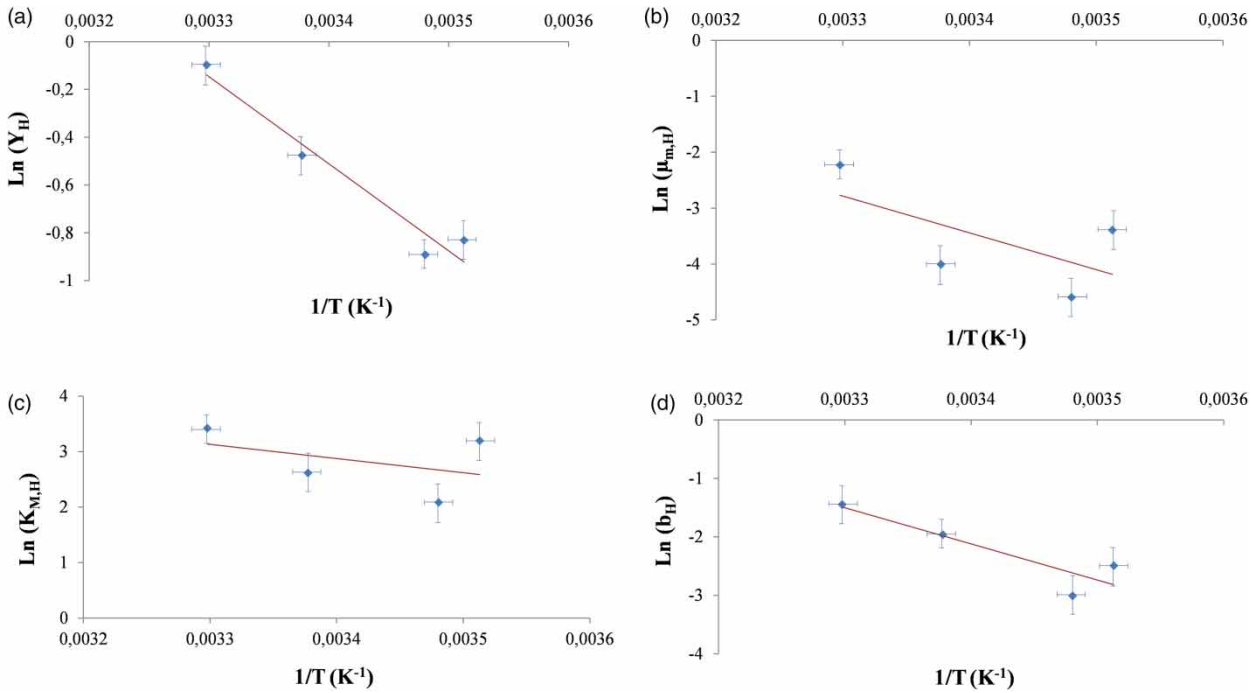

Figure 2 | Linear regression of the Napierian logarithm of heterotrophic kinetic parameters, (a) Y_H, (b) $\mu_{m,H}$, (c) $K_{M,H}$, and (d) b_H, depending on the inverse of temperature using the Arrhenius equation. Y_H (yield coefficient for heterotrophic biomass), $\mu_{m,H}$ (maximum specific growth rate for heterotrophic biomass), $K_{M,H}$ (half-saturation coefficient for organic matter), b_H (decay coefficient for heterotrophic biomass).

Downloaded from https://iwaponline.com/wst/article-pdf/77/2/448/242756/wst077020448.pdf
by guest

Table 3 | Fitting of the heterotrophic kinetics depending on temperature according to the Arrhenius equation

	Heterotrophic kinetic parameter			
Fitting parameter	**Y_H (mgVSS mgCOD^{-1})**	**$\mu_{m,H}$ (h^{-1})**	**$K_{M,H}$ ($mgO_2\ L^{-1}$)**	**b_H (day^{-1})**
A[a]	$1.44{\cdot}10^5$	$1.67{\cdot}10^8$	$1.08{\cdot}10^5$	$1.55{\cdot}10^8$
E_a/R (K)	3,643	6,582	2,563	6,171
R^2	0.9509	0.4086	0.1749	0.8084

[a]The units for A are equivalent to those from the different heterotrophic kinetic parameters

Y_H (yield coefficient for heterotrophic biomass), $\mu_{m,H}$ (maximum specific growth rate for heterotrophic biomass), $K_{M,H}$ (half-saturation coefficient for organic matter), b_H (decay coefficient for heterotrophic biomass), A (pre-exponential factor for Arrhenius model), E_a/R (activation energy divided into gas constant for Arrhenius model).

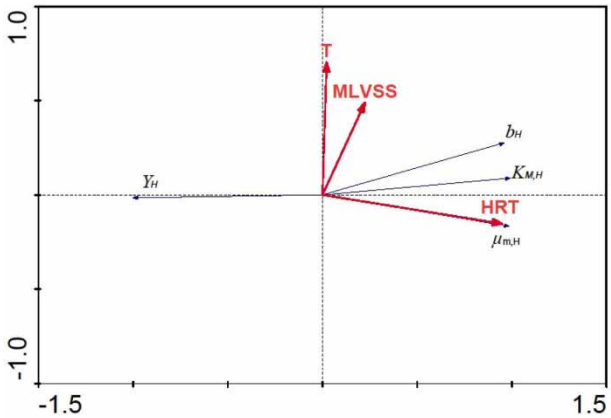

Figure 3 | Triplot diagram for RDA of the heterotrophic kinetic parameters, $\mu_{m,H}$, $K_{M,H}$, Y_H, b_H, in relation to the variables HRT, MLVSS and T. RDA (redundancy analysis), $\mu_{m,H}$ (maximum specific growth rate for heterotrophic biomass), $K_{M,H}$ (half-saturation coefficient for organic matter), Y_H (yield coefficient for heterotrophic biomass), b_H (decay coefficient for heterotrophic biomass), HRT (hydraulic retention time), MLVSS (mixed liquor volatile suspended solids), T (temperature).

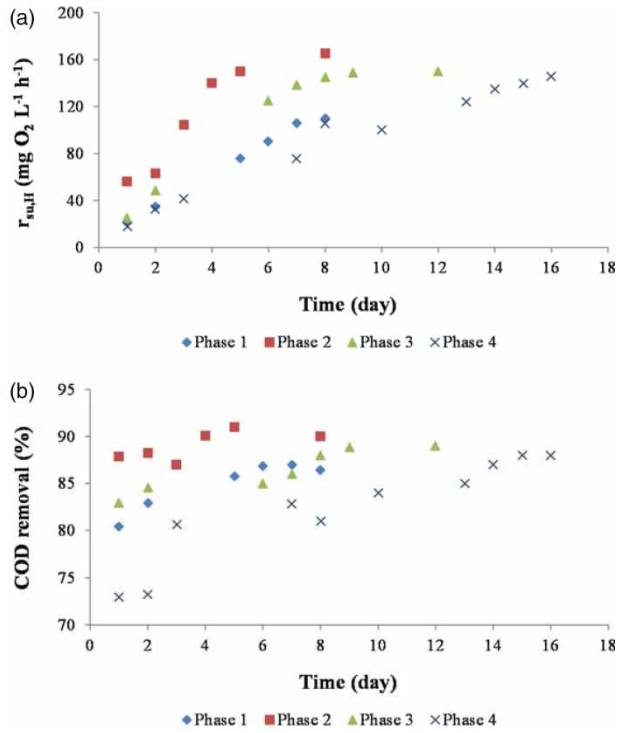

Figure 4 | (a) Evolution of COD degradation rate ($r_{su,H}$) obtained for heterotrophic biomass from MBR, and (b) COD removal during the four start-up phases. Phase 1: HRT = 6 h and MLSS = 4,000 mg L^{-1}; Phase 2: HRT = 10 h and MLSS = 4,000 mg L^{-1}; Phase 3: HRT = 6 h and MLSS = 7,000 mg L^{-1}; Phase 4: HRT = 10 h and MLSS = 7,000 mg L^{-1}. COD (chemical oxygen demand), HRT (hydraulic retention time), MLSS (mixed liquor suspended solids).

6 h and 4,000 mg L^{-1}, respectively, as well as a low value of temperature (14.2 °C), which implied the lowest values for $r_{su,H}$.

Regarding the influence of HRT on the kinetic performance of the heterotrophic biomass, it should be pointed out that phases 2 and 4, which had the greatest values of HRT (Table 1), showed the highest values for the maximum specific growth rate, as observed in Table 1. In particular, phase 2 had a value of $\mu_{m,H}$ of 0.1075 h^{-1} that was higher than that obtained for phase 1 (0.0101 h^{-1}) at an MLSS concentration of 4,000 mg L^{-1}, and phase 4 showed a value of $\mu_{m,H}$ of 0.0336 h^{-1} that was also higher than the corresponding value for phase 3 (0.0182 h^{-1}) at 7,000 mg L^{-1} of MLSS concentration. This is also supported by Figure 3 since HRT had a strongly positive correlation with $\mu_{m,H}$. This could also explain the higher value of $r_{su,H}$ for phase 2 compared with the value corresponding to phase 1 (Figure 4(a)) as $r_{su,H}$ is directly proportional to $\mu_{m,H}$ according to Equation (9) from Table 2. This trend is not clearly observed between phases 3 and 4 due to the higher effect of temperature, which almost doubled its value for phase 3 (22.9 °C) compared with phase 4 (11.5 °C), as explained previously.

Furthermore, it should be highlighted that heterotrophic biomass required less time for organic matter oxidation during the start-up of phase 2 due to its higher $r_{su,H}$ (Figure 4(a)). In light of this, less time would be required to accomplish the steady state in the operational conditions of the start-up of phase 2.

This was supported by the COD removal efficiencies obtained in the four operation phases (Figure 4(b)). Heterotrophic biomass from phase 2 had the highest COD removal, followed by the biomass from phases 3 and 4. Results obtained concerning COD removal for phase 4 also highlighted the higher influence of HRT and MLSS in relation to temperature. During phase 1, the lowest values of COD removal performance were obtained due to their less

Downloaded from https://iwaponline.com/wst/article-pdf/77/2/448/242756/wst077020448.pdf
by guest

advantageous operation conditions. In this regard, Arévalo *et al.* (2014) achieved COD removal rates varying between 98.0% and 98.9% at a higher HRT of 35 h and temperature fluctuations from 9 °C to 33 °C, which were higher than those obtained in this research (Figure 4(b)). Poyatos *et al.* (2008) worked with an MBR at HRT values of 8.05 h and 11.71 h and temperature variations from 8.3 °C to 23.9 °C, obtaining COD removal efficiencies similar to those obtained in this study (84–94%).

CONCLUSIONS

The effect of temperature on the heterotrophic biomass from an MBR was modelled by considering the Arrhenius equation and Monod model. For this, four different start-up phases were analyzed at HRT values of 6 h and 10 h, MLSS concentrations in the steady state of 4,000 mg L^{-1} and 7,000 mg L^{-1}, and temperatures of 11.5, 14.2, 22.9 and 30.1 °C.

In light of this, the COD degradation rate ($r_{su,H}$) was expressed as a function of temperature (T), substrate concentration (S) and heterotrophic biomass concentration (X_H), according to the following equation:

$$r_{su,H} = \frac{1.16 \cdot 10^3 \cdot e^{-2{,}939/T} \cdot S \cdot X_H}{1.08 \cdot 10^5 \cdot e^{-2{,}563/T} + S}$$

The kinetic behavior of heterotrophic biomass corresponding to phase 4 did not follow the general trend for Arrhenius fitting. This was probably due to the fact that the MBR worked at the most favorable operation conditions of HRT (10 h) and MLSS (7,000 mg L^{-1}), and the effect of temperature (11.5 °C) was cancelled out. This was confirmed by the higher values of $r_{su,H}$ and COD removal for phase 4 compared with those from phase 1 (HRT = 6 h, MLSS = 4,000 mg L^{-1} and T = 14.2 °C).

Under the operation conditions of phase 2 (HRT = 10 h, MLSS = 4,000 mg L^{-1} and T = 30.1 °C), heterotrophic biomass had the highest $r_{su,H}$, which implied less time to oxidize organic matter during the start-up phase and less time to reach the steady state. In light of this, the effect of HRT was stated in phase 2, but it was attenuated in phase 4 due to its low temperature.

ACKNOWLEDGEMENTS

The authors would like to express their most sincere gratitude to EMASAGRA, which supported this research.

REFERENCES

APHA 2012 *Standard Methods for the Examination of Water and Wastewater*, 22nd edn. American Public Health Association, Washington, DC.

Arévalo, J., Ruiz, L. M., Pérez, J. & Gómez, M. A. 2014 Effect of temperature on membrane bioreactor performance working with high hydraulic and sludge retention time. *Biochem. Eng. J.* **88**, 42–49.

Calderón, K., González-Martínez, A., Montero-Puente, C., Reboleiro-Rivas, P., Poyatos, J. M., Juarez-Jiménez, B., Martínez-Toledo, M. V. & Rodelas, B. 2012 Bacterial community structure and enzyme activities in a membrane bioreactor (MBR) using pure oxygen as an aeration source. *Bioresour. Technol.* **103**, 87–94.

Ekama, G. A., Dold, P. L. & Marais, G. V. R. 1986 Procedures for determining influent COD fractions and the maximum specific growth rate of heterotrophs in activated sludge systems. *Water Sci. Technol.* **18** (6), 91–114.

Grandclément, C., Seyssiecq, I., Piram, A., Wong-Wah-Chung, P., Vanot, G., Tiliacos, N., Roche, N. & Doumenq, P. 2017 From the conventional biological wastewater treatment to hybrid processes, the evaluation of organic micropollutant removal: a review. *Water Res.* **111**, 297–317.

Gunder, B. & Krauth, K. 1998 Replacement of secondary clarification by membrane separation – results with plate and hollow fibre modules. *Water Sci. Technol.* **38** (4/5), 383–393.

Guo, W., Ngo, H. H. & Li, J. 2012 A mini-review on membrane fouling. *Bioresour. Technol.* **122**, 27–34.

Hao, X. D., Wang, Q. L., Zhu, J. Y. & Van Loosdrecht, M. C. M. 2010 Microbiological endogenous processes in biological wastewater treatment systems. *Crit. Rev. Environ. Sci. Technol.* **40**, 239–265.

Helle, S. 1999 *A Respirometric Investigation of the Activated Sludge Treatment of BKME During Steady State and Transient Operating Conditions*. Thesis, University of British Columbia.

Huang, X., Gui, P. & Qian, Y. 2001 Effect of sludge retention time on microbial behaviour in a submerged membrane bioreactor. *Process Biochem.* **36**, 1001–1006.

Jang, D., Hwang, Y., Shin, H. & Lee, W. 2013 Effects of salinity on the characteristics of biomass and membrane fouling in membrane bioreactors. *Bioresour. Technol.* **141**, 50–56.

Judd, S. 2011 *The MBR Book. Principles and Applications of Membrane Bioreactors for Water and Wastewater Treatment.* 2nd edn. Elsevier, London.

Leyva-Díaz, J. C., Calderón, K., Rodríguez, F. A., González-López, J., Hontoria, E. & Poyatos, J. M. 2013a Comparative kinetic study between moving bed biofilm reactor-membrane bioreactor and membrane bioreactor systems and their influence on organic matter and nutrients removal. *Biochem. Eng. J.* **77**, 28–40.

Leyva-Díaz, J. C., Martín-Pascual, J., González-López, J., Hontoria, E. & Poyatos, J. M. 2013b Effects of scale-up on a hybrid moving bed biofilm reactor-membrane bioreactor for treating urban wastewater. *Chem. Eng. Sci.* **104**, 808–816.

Marais, G. V. R. & Ekama, G. A. 1976 The activated sludge process. Part 1 – steady state behaviour. *Water SA* **2**, 163–200.

Downloaded from https://iwaponline.com/wst/article-pdf/77/2/448/242756/wst077020448.pdf
by guest

Metcalf & Eddy 2003 *Wastewater Engineering Treatment and Reuse*. McGraw-Hill, New York, NY.

Monod, J. 1949 The growth of bacterial cultures. *Annu. Rev. Microbiol.* **3**, 371–394.

Oppenheimer, J., Trussell, R., Boulos, L., Adham, S. & Gagliardo, P. 2001 Feasibility of the membrane bioreactor process for water reclamation. *Water Sci. Technol.* **43** (10), 203–209.

Pollice, A., Giordano, C., Laera, G., Saturno, D. & Mininni, G. 2007 Physical characteristics of the sludge in a complete retention membrane bioreactor. *Water Res.* **41**, 1832–1840.

Poyatos, J. M., Molina-Muñoz, M., González-López, J. & Hontoria, E. 2008 Effects of hydraulic retention time, temperature, and MLSS concentration on the effluent quality of a membrane bioreactor. *Environ. Toxicol. II* **110**, 109–116.

Rodríguez, F. A., Poyatos, J. M., Reboleiro-Rivas, P., Osorio, F., González-López, J. & Hontoria, E. 2011 Kinetic study and oxygen transfer efficiency evaluation using respirometric methods in a submerged membrane bioreactor using pure oxygen to supply the aerobic conditions. *Bioresour. Technol.* **102**, 6013–6018.

Van den Brink, P., Satpradit, O. A., Van Bentem, A., Zwijnenburg, A., Temmink, H. & van Loosdrecht, M. 2011 Effect of temperature shocks on membrane fouling in membrane bioreactors. *Water Res.* **45**, 4491–4500.

Van der Roest, H. F., Lawrence, D. P. & Van Bentem, A. G. N. 2002 *Membrane Bioreactors for Municipal Wastewater Treatment*. IWAI Publishing, Cornwall.

Vyrides, I. & Stuckey, D. C. 2011 Fouling cake layer in a submerged anaerobic membrane bioreactor treating saline wastewaters: curse or a blessing? *Water Sci. Technol.* **63** (12), 2902–2908.

Wang, Z., Chu, J., Song, Y., Cui, Y., Zhang, H., Zhao, X., Li, Z. & Yao, J. 2009 Influence of operating conditions on the efficiency of domestic wastewater treatment in membrane bioreactors. *Desalination* **245**, 73–81.

Wintgens, T., Melin, T., Schafer, A., Khan, S., Muston, M., Bixio, D. & Thoeye, C. 2005 The role of membrane processes in municipal wastewater reclamation and reuse. *Desalination* **178**, 1–11.

First received 6 July 2017; accepted in revised form 19 October 2017. Available online 2 November 2017

Downloaded from https://iwaponline.com/wst/article-pdf/77/2/448/242756/wst077020448.pdf
by guest