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Influence of operational parameters over biomass growth and decay kinetic constants on membrane bioreactors

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ABSTRACT

In this study, activated sludge from two experimental full-scale membrane bioreactor (MBR) systems (microfiltration and ultrafiltration) working in parallel has been used to determine Y_H and b_H in a batch respirometer. Both systems were equipped with a pre-denitrification stage and followed the same configuration: anoxic bioreactor, aerobic bioreactor and MBR. Nowadays, describing a conventional or MBR biological process cannot be understood without determining the values of several bio-kinetic parameters describing biomass growth and decay. The aim of this study is to evaluate the influence of several operational parameters related to MBR systems such as sludge retention time (SRT), hydraulic retention time, organic load, sludge temperature and aerobic bioreactor height over the heterotrophic decay coefficient (b_H) and the heterotrophic yield (Y_H), whose values ranged from 0.0088 to 0.31 d^{-1} and from 0.40 to 0.88 mgCOD/mgCOD, respectively. Average sludge temperature and SRT have statistically significant effects on b_H, whose value increases as the temperature increases and SRT decreases and related to Y_H, also organic load influences it, getting lower values of Y_H for higher SRT or organic loads and for lower temperatures.

Keywords: Respirometry; Kinetic parameters; MBR

1. Introduction

In the last decades, conventional activated sludge processes are being replaced by systems based on membrane technologies such as membrane bioreactors (MBR), which have a greater capacity to degrade organic matter, due to longer sludge retention times (SRT), are better at producing high-quality effluent that meets water quality regulations [1] and have lower space requirements [2].

Since the beginning of activated sludge processes, one of the most widespread tools for improving our understanding of the biological processes is respirometry, which is also used to ensure the operational

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control of MBR. Respirometric techniques are widely used and standardized for the characterization of wastewater and biomass in conventional urban wastewater treatment plants [3,4], and nowadays, describing a conventional or MBR-activated sludge, biological process cannot be understood without determining the values of several bio-kinetic parameters describing biomass growth and decay, substrate utilization rates, nitrification and denitrification or phosphorous removal. These parameters, whose value need to be known, allow the system being modelled and simulated and knowing the effect of operational parameters over them gives information about the influence of these operational parameters over the global process reducing costs and time that otherwise should be spent to check different conditions.

Robust model-based optimization of wastewater treatment plants necessitates successful calibration of the complex wastewater treatment plant models to ensure the prediction capability of activated sludge models under variable process conditions where the model should describe realistically the plant behaviour [5], so, if these constants are calibrated under specific operational conditions and used as constant values to model the same system working at different conditions, the error in the simulation results may be high. IWA-activated sludge models have been used as a reference to describe activated sludge processes [6], but due to the high SRT, no loss of solids in the effluent, increasing amounts of inert particulate matter and other specific characteristics of the MBR processes, it is necessary to check the values of some of the kinetic and stoichiometric parameters included in these models to fit them to the MBR processes. Due to these differences, several models describing the activated sludge process have been published in recent decades [7] and some modifications to adapt these models to MBR processes have also been suggested [8].

In the recent years, several studies have reported the effects of operational parameters such as load rates [9,10], hydraulic retention time (HRT) [11,12] or SRT [13–15] over the MBR performance and the bio-kinetic constants have also been evaluated for MBR systems [8,16–18]. However, MBR research is mainly focused on the membrane performance and bio-fouling [19–21] and one of the main problems related to the application of MBR technology is the lack of reliable kinetic parameters for process design, so, further works are required in order to improve bio-kinetic constants knowledge and biological modelling on MBR processes.

The bio-kinetic constants that better describe the heterotrophic biomass activity are: heterotrophic biomass yield (Y_H) and decay coefficient (b_H). These constants indicate the ability to generate new biomass from the consumption of biodegradable organic matter and the biomass losses due to the biomass decay, respectively and they can be easily calculated using respirometric assays. Both constants are really important when models that define the biological process need to be calibrated to describe a specific system. Previous studies such as Ruiz et al. [22] show that they do not highly vary based on the membrane technology (microfiltration or ultrafiltration) used in an MBR system, but they are affected by operational parameters. In view of this, the aim of this study is to evaluate the influence of several operational parameters related to MBR systems such as SRT, HRT, organic loading, sludge temperature and aerobic bioreactor height over the kinetic and stoichiometric parameters describing the heterotrophic behaviour of the activated sludge.

2. Materials and methods

2.1. Pilot plants and experimental conditions

The experimental installations used in this study were two full-scale MBR systems running in parallel and configured in pre-denitrification mode following the same configuration: anoxic bioreactor, aerobic bioreactor and MBR where the sludge and the permeate were separated using different membrane technologies (Fig. 1). Both plants were fed with urban wastewater pre-treated in a full-scale plant (Granada Wastewater Treatment Plant) to remove rubbish, sand and oils. Before entering the plants, wastewater passed through a 1-mm pore-size brush sieve in order to remove particles that could clog up the membranes. Dissolved oxygen (DO) concentration inside the aerobic bioreactors was kept in the range 0.5–1.6 mg/L, and the MBRs were also aerated to remove solids from the membrane and to control fouling.

The first experimental plant was equipped with hollow fibre submerged ultrafiltration membranes (0.034-μm nominal pore size) made in polyvinylidene-fluoride (PVDF), and the flow rate between bioreactors was seven times the influent flow rate. Running conditions involved a 5-min production phase (1 m^3/h), followed by 30 s of backwashing (1.5 m^3/h) and chemical cleaning was carried out weekly using NaClO (100 mg/l).

On the other hand, the second plant was equipped with submerged plane microfiltration membranes (0.4-μm nominal pore size) made of chlorine polyethylene (PE), it worked at a constant permeate flow and the flow rate between bioreactors was four times the influent flow rate. Membranes were chemically

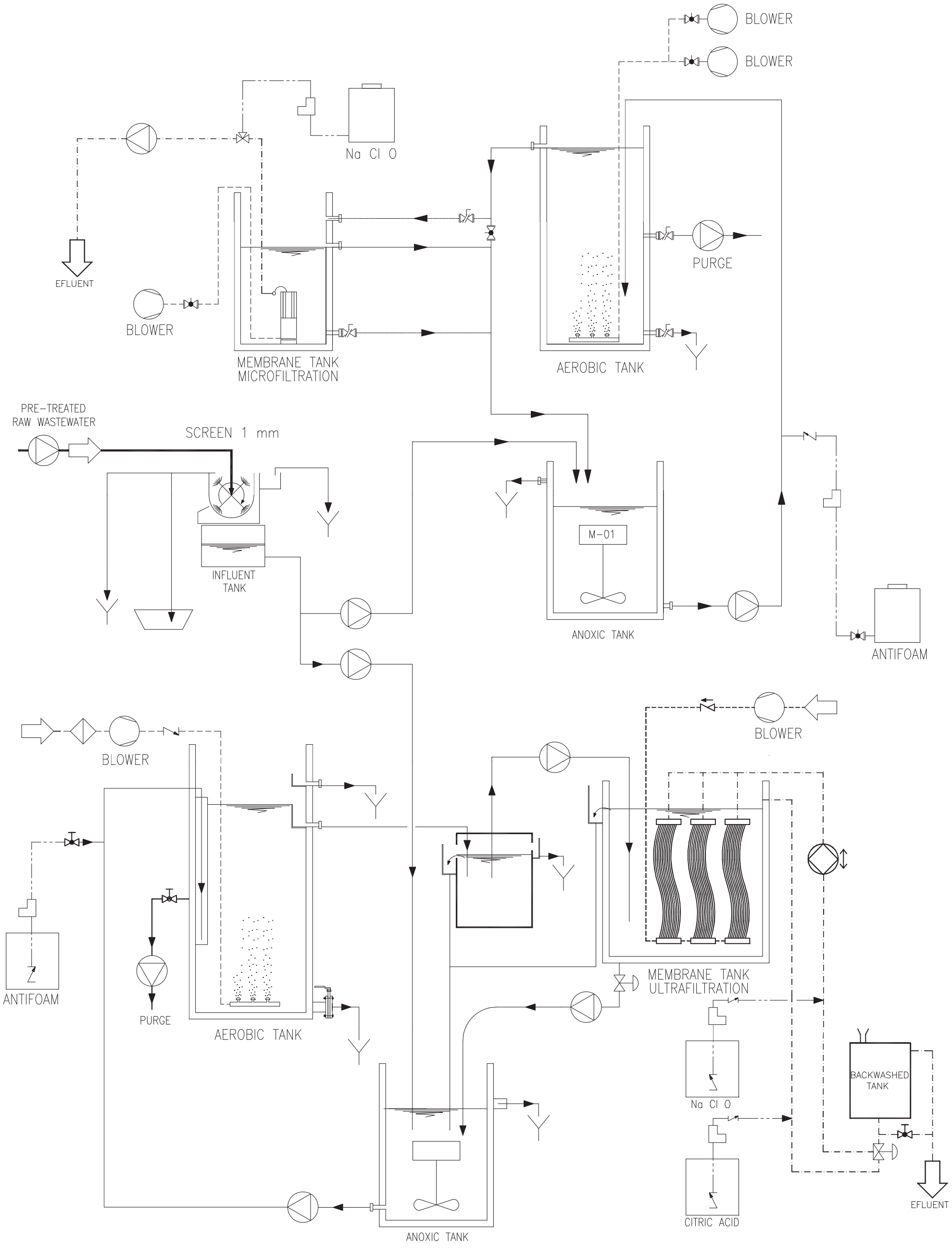

Fig. 1. Layout of pilot-plants.

cleaned using NaClO (100 mg/l) if the transmembrane pressure (TMP) became excessively high.

After checking that the membrane type (ultrafiltration or microfiltration) does not cause differences in the system behaviour [22], different operational conditions have been tested in each plant. Table 1 shows the main characteristics evaluated in each plant in order to compare their influence over the decay and growth heterotrophic constants. The period of this study has been divided in different phases according to the HRT, SRT, average temperature, organic load and bioreactor height at which the plants have been working. In total, 37 phases have been considered.

2.2. Physical and chemical analysis

Activated sludge samples were collected daily directly from each bioreactor to determine TSS by

Table 1
Different operational parameters evaluated in the ultrafiltration and microfiltration MBR plants

Parameter	Ultrafiltration plant	Microfiltration plant
HRT, h	23, 32, 35 and 40	35
SRT, d	16, 20, 35 and 40	20, 25, 30, 35 and 40
Average temperature, ˚C	<15, 15–20, 20–25 and >25	<15, 15–20, 20–25 and >25
Organic load, kg COD/m^3 d	0.4, 0.5, 0.75, 0.9 and 1.1	0.4, 0.5, 0.75 and 1.1
Aerobic bioreactor height, m	2.5 and 3.75	3.75 and 5.0

vacuum filtration, drying at 105˚C and gravimetric determination, using 0.45-μm filters and VSS by incineration at 550˚C according to *Standard Methods* [23]. Influent and effluent samples were collected daily from each pilot plant using a time controller and a peristaltic pump and kept refrigerated at 4˚C until they were taken for analysis. Chemical oxygen demand (COD) was measured using the COD closed reflux micromethod [23] where absorbance of the digestate was measured colorimetrically at 600 nm.

2.3. Respirometer

Fresh sludge samples were taken from the aerobic bioreactors of each plant and kept aerated until it reached an endogenous state. After large particles were removed from the biomass, it was fed into the respirometer where Y_H and b_H were calculated by means of the oxygen consumption rate measurements using a perfectly stirred 1 litre batch respirometer developed by Surcis.

DO concentration and temperature were measured continuously inside the respirometer and recorded online every 2 s, and all experiments were conducted under conditions of controlled temperature, keeping inside the respirometer a temperature similar to biological reactor using a water cooler connected to the respirometer, so that water flowed through the jacket at the desired temperature. pH was also kept constant in the range 7.0–8.0. For the respirometric analysis of heterotrophic biomass parameters, allylthiourea was added to inhibit nitrification.

Two sets of experiments were carried out using the respirometer. Oxygen uptake rate (OUR) experiments using endogenous biomass and inhibiting nitrification were carried out to determine b_H according to the estimation proposed by Henze et al. [24]. The second set of experiments was carried out to determine Y_H according to the procedure devised by Strotmann et al. [25]. For these experiments, an easily biodegradable organic compound such as sodium acetate was used. For b_H calculations, the unbiodegradable endogenous residue fraction, f_p, was assumed to be 0.08 and the stoichiometric formula of $C_5H_7NO_2$ for the biomass was also assumed. In order to evaluate differences in the process parameters but not in the respirometer conditions, for Y_H experiments the amount of sodium acetate added was always constant (50 ml of a solution with a concentration of 213 mg/l).

2.4. Data analysis and statistical methods

In both plants, parameters such as temperature, pH, DO concentration, tank levels, TMP and flow rates were continuously measured and registered in a database every second. The high amount of data collected daily made necessary to use a specific software called *Active Factory 9.2* for the data analysis.

The data obtained throughout this study were analysed using a computer-assisted statistics program called Statgraphics 3.0 (STSC, Rockville, MD, USA). The least significant differences test was used to measure the differences among the obtained results for the different operational conditions studied and the analysis of variance (ANOVA) was used to assess the homogeneity of variance with a significance level of 95% (p-value < 0.05). The results of these statistical tests are represented in Box-and-Whisker plots. Moreover, multifactor analysis of variance (MANOVA) was carried out in order to determine which operational parameters are the most influencing parameters over the decay and growth constants. This test decomposes the variability of the parameter into contributions due to various factors and the contribution of each factor is measured having removed the effects of all other factors. In this case, also a significance level of 95% (p-value < 0.05) was selected.

3. Results and discussion

Previous study [22] showed that the type of membrane used in an MBR system does not influence the values of the decay and growth heterotrophic constants, b_H and Y_H, respectively. In this study, different operational conditions (SRT, HRT, average temperature inside the bioreactor, organic load and height of

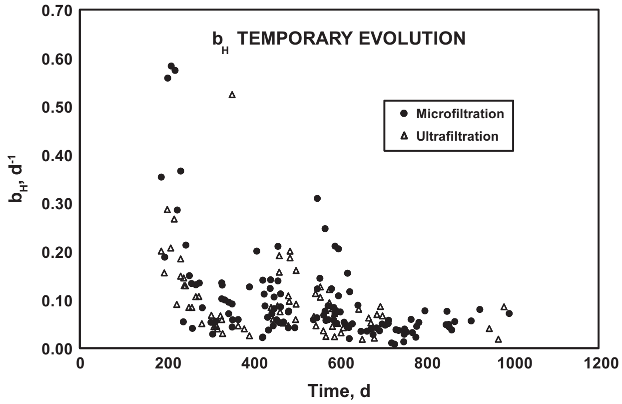

Fig. 2. b_H temporary evolution in the ultrafiltration and microfiltration MBR plants.

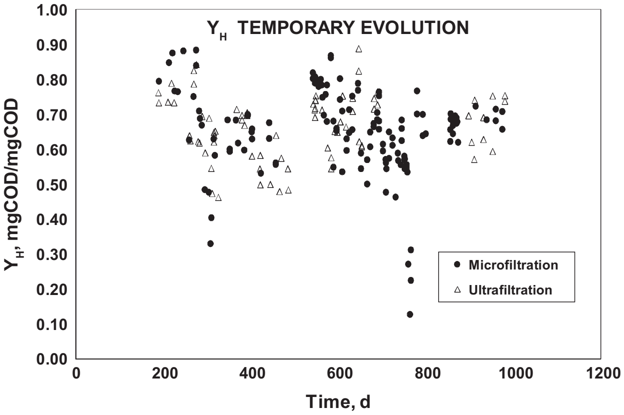

Fig. 3. Y_H temporary evolution in the ultrafiltration and microfiltration MBR plants.

the bioreactor) have been tested in both experimental MBR plants (ultrafiltration and microfiltration) in order to determine how changes in these conditions affect the decay and growth heterotrophic constants.

Figs. 2 and 3 show the temporary evolution of b_H and Y_H, respectively, during the period under study. These results show that during the whole research period, the decay coefficient b_H in the ultrafiltration plant reached values from 0.019 to 0.287 d^{-1} and in the microfiltration plant the values ranged from 0.0088 to 0.31 d^{-1}, with no differences between the results of both plants. These values are similar to those reported in literature for MBR systems [15,17,26,27]. The maximum value for b_H has been obtained for a SRT of 20 d, a HRT of 40 h, an organic load of 0.5 kgCOD/m^3 d and temperatures from 20 to 25°C. At the beginning of the study, systems instability is higher, leading to higher variabilities in the results, but finally, steady state is reached and constant values of these parameters are obtained.

Related to the other evaluated parameter, Y_H values from 0.46 to 0.88 mg COD/mg COD were reached in the ultrafiltration system and from 0.40 to 0.88 mg COD/mg COD in the microfiltration system, with no differences between the values of both systems. Compared with results reported in the literature for MBR systems [3,17,18,27,28], these values are also similar and not lower than those usually used for conventional systems as could be expected. In this case, the highest values were obtained during a period with activated sludge temperature between 20 and 25°C, an organic loading of 0.5 kg COD/m^3 d, HRT of 35 h and SRT of 20 d. On the other hand, the lowest values were obtained for a period with activated sludge temperature above 25°C, an organic load above 1.0 kg COD/m^3 d, HRT of 35 h and SRT of 35 d. Variation of Y_H values in MBR systems are important in function of operational conditions and considering a fixed value for this parameter during a modelling study may lead to significant errors.

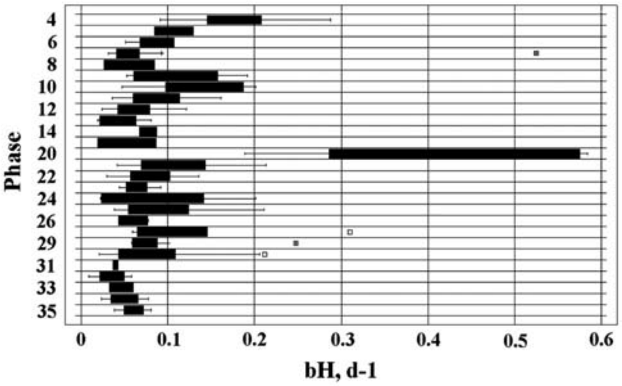

Fig. 4. b_H values obtained during the different phases of the study in the ultrafiltration and microfiltration MBR plants.

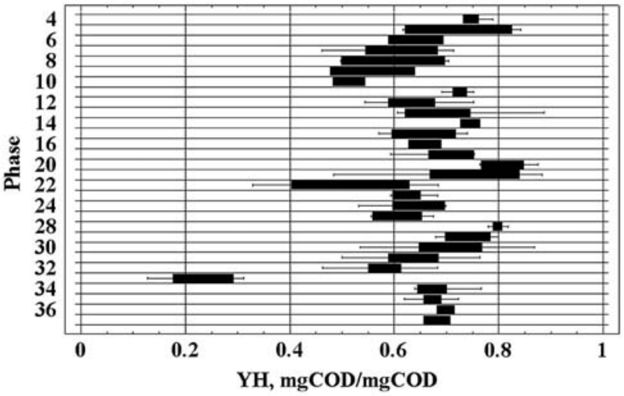

Fig. 5. Y_H values obtained during the different phases of the study in the ultrafiltration and microfiltration MBR plants.

Table 2
p-Values obtained in the multifactorial ANOVA test for b_H and Y_H analysis

Factor	Parameter	
	b_H	Y_H
HRT, h	0.7647	0.4838
SRT, d	0.0000	0.0000
Average temperature, ℃	0.0000	0.0000
Organic load, kg COD/m^3 d	0.9489	0.0000
Aerobic bioreactor height, m	0.1140	0.7238

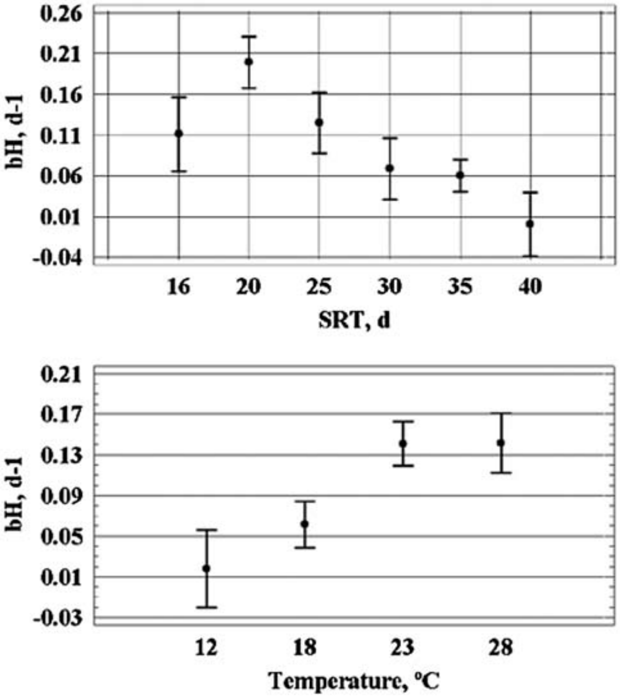

Fig. 6. Influence of SRT (top) and temperature (bottom) over b_H.

An ANOVA statistical test has been carried out for each parameter (b_H and Y_H) in order to determine whether the means of the results obtained in each phase under study are equal or not. Figs. 4 and 5 shows the Box and Whisker plots for b_H and Y_H, respectively.

From the multiple range test results for b_H, it can be concluded that applying a multiple comparison procedure to determine, which means are significantly different from others, 61 pairs show statistically significant differences at the 95.0% confidence level and five homogeneous groups have been identified. Data obtained during phase 20 are significantly different from the results obtained during all the other phases. This is probably due to the fact that this phase matched the first period of the microfiltration plant, that is, when the system started to work, so, its performance was not still stable. Moreover, phases 4, 28 and 32 also show statistical differences with some of the other phases. Phase 4 corresponds to the same period than phase 20, but it is related to the ultrafiltration plant. Daily laboratory COD and mixed liquor suspended solids (MLSS) analysis show that these periods correspond to unstable growth periods where the influent COD concentration is high.

On the other hand, the results for Y_H indicate that a higher number of pairs (191) show statistically significant differences at the 95.0% confidence level and 14 homogeneous groups have been identified. In general, Y_H values show higher variability than b_H values (the standard deviation is higher for Y_H). It seems that parameters such as the organic loading or the HRT does not highly influence the values obtained

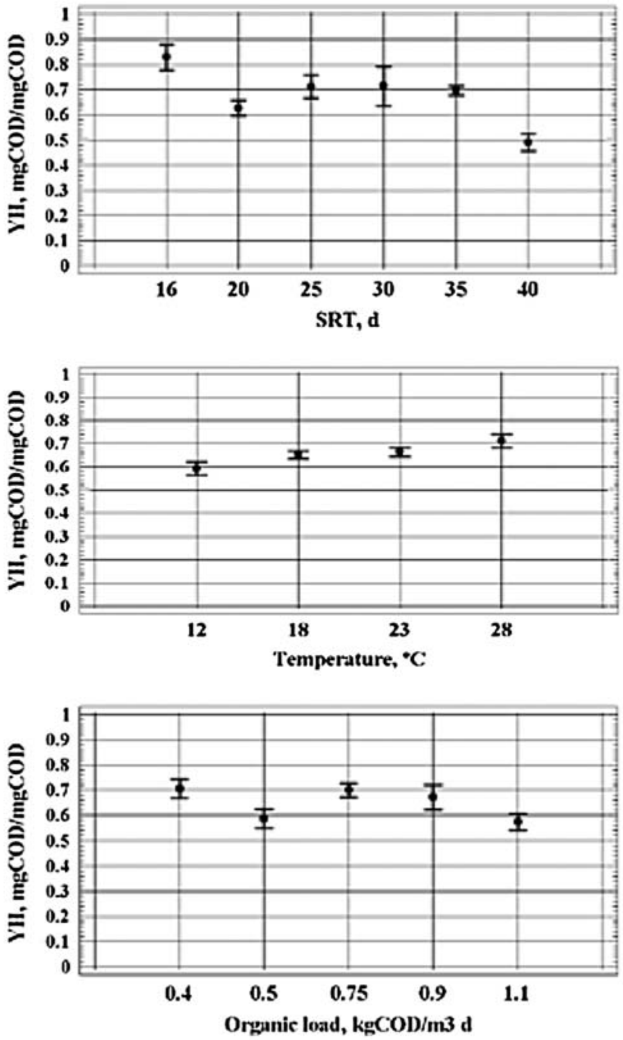

Fig. 7. Influence of SRT (top), average temperature (middle) and organic load (bottom) over Y_H.

for Y_H but other parameters such as the SRT or the activated sludge temperature highly influence the obtained values, getting lower values of Y_H for higher SRT and lower temperatures.

Multifactor ANOVA tests (MANOVA) have also been carried out using Statgraphics 3.0. In both cases, the factors that have been evaluated are the following: average temperature inside the bioreactor, SRT, HRT, organic load and bioreactor height. Table 2 shows the p-values obtained in the MANOVA tests for b_H and Y_H.

Figs. 6 and 7 show the relationship between b_H and Y_H and their respective influencing factors. For b_H, since two p-values are lower than 0.05, these factors (average temperature and SRT) have a statistically significant effect on b_H at the 95% confidence level. For Y_H, the results show that there is another influencing factor, the organic load.

MANOVA b_H results show statistical differences between all the temperature groups except for the two groups with temperatures above 20°C (20–25 and <25°), as the temperature increases, b_H values are also higher and three homogeneous groups are identified. Related to the other influencing parameter, SRT, an increase in SRT lead to lower b_H values and 4 homogeneous groups are identified.

On the other hand, MANOVA Y_H results also show statistical differences between all the temperature groups, as the temperature increases, Y_H values are also higher and three homogeneous groups are identified. Related to SRT, an increase in SRT lead to lower Y_H values and four homogeneous groups are identified. Finally, related to the organic load factor, two homogeneous groups are identified and differences between low organic load (0.4 and 0.5 kg COD/m^3 d phases) and high organic load (0.75, 0.9 and 1.1 kg COD/m^3 d phases) exist. The tendency is that Y_H decreases as the organic load increases.

4. Conclusions

In this study, different operational conditions (SRT, HRT, average temperature inside the bioreactor, organic load and height of the bioreactor) have been tested in two experimental MBR plants (ultrafiltration and microfiltration) in order to determine how these factors affect the decay and growth heterotrophic constants and the following conclusions may be obtained:

- Temporary evolution of the decay coefficient, b_H reached values from 0.0088 to 0.31 $d^{-1,}$ with no differences between the results of both plants.
- Related to the other evaluated parameter, Y_H values ranged from 0.40 to 0.88 mgCOD/mgCOD, with no differences between the values of both plants. Variations of Y_H values in MBR systems are important in function of operational conditions and considering a fixed value for this parameter during a modelling study may lead to significant errors.
- ANOVA statistical tests show that only during the initial phase of the microfiltration plant when the plant did not reached a steady state, b_H results are significantly different from the results obtained during all the other phases and that the average temperature and the SRT have a statistically significant effect on b_H at the 95% confidence level. The value for this constant increases as the temperature increases and related to the other influencing factor, an increase in SRT lead to lower b_H values.
- On the other hand, Y_H values show higher variability than b_H values and changes in the SRT, the activated sludge temperature or the organic load influence the value of this constant, getting lower values of Y_H for higher SRT or organic loads and for lower temperatures.

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