Hybrid moving bed biofilm reactors: an effective solution for upgrading a large wastewater treatment plant

Giorgio Mannina and Gaspare Viviani

ABSTRACT

Over the last few years there has been a growing attention regarding the receiving water body quality state. As a matter of a fact, the Directive 91/271 of the European Union (EU) replaced the "emission standard" concept that fixes discharge limits depending on polluting emission characteristics, with the "stream standard" concept that fixes discharge limits for each polluting substance depending on self-depurative characteristics of the RWB. In this context, several WWTPs need to be upgraded in order to meet stricter effluent limits. The need of WWTP upgrading was also emphasized by the growing urbanization that have led, in most cases, to get overloaded WWTP due to an overcoming of the maximum WWTP capacity. In order to upgrade existing WWTP basically two main possibilities can be chosen: building new tanks or modify the WWTP by introducing new technologies such as the HMBBR systems. In this paper, such latter possibility was explored and as a case study an existing Italian WWTP (Acqua dei Corsari) located in Palermo (IT) was analysed. The main goal was to test the effectiveness of HMBBR systems with respect to the WWTP upgrading. The survey was carried out by means of model simulation and an HMBBR pilot plant. This latter was employed for the evaluation of the model parameters as well as kinetic coefficients for the HMBBR. The model results are encouraging towards the WWTP upgrading by means of HMBBR. As a matter of fact, the model simulation results showed that the WWTP maximum capacity can be upgraded from 480,000 up to one million PE.

Key words | GPS-X, IFAS, moving bed biofilm reactors, pilot plant, trickling filters

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INTRODUCTION

Throughout the world, there has been increasing interest in WWTPs (Wastewater Treatment Plant) modelling due to a need to evaluate different solutions prior to their effective realization. Indeed, the dynamic models are increasingly used for scenario evaluations aiming at the optimisation of wastewater treatment processes (Stokes *et al.* 1993; de la Sota *et al.* 1994; Coen *et al.* 1997). In this light, the WWTP design, maintenance and operation can be supported by the mathematical process models, by which simulation experiments can be performed over a wide range of process operating conditions.

Concerning the upgrading of WWTP, new technologies are emerging in order to cope with the stricter effluent limits. More specifically, the idea to combine two different processes (attached and suspended biomass) by adding biofilm carriers, usually plastic carriers, into the aeration tank for biofilm attachment and growth has been proposed. This kind of system is usually referred as IFAS (Integrated Fixed-film Activated Sludge) process (Randall & Sen 1996; Sriwiriyarat & Randall 2005; Sriwiriyarat *et al.* 2005). In these systems the biomass grows both as suspended flocs and as attached biofilm. In this way, it is possible to obtain a higher biomass concentration in the aerobic reactor, but without any significant load increase to the final clarifier. Therefore, the up-grading of overloaded existing plants, no longer able to meet the effluent limits, can be easily

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obtainable without the construction of new tanks. Furthermore, the increase of the overall sludge age in the system leads to a favourable environment for the growth of nitrifying bacteria (Randall & Sen 1996). As a matter of fact, several studies have demonstrated that IFAS process can be an alternative design for biological nitrogen removal and as a cost-effect option for retrofitting WWTPs to sustain nitrification throughout the winter (Sriwiriyarat & Randall 2005).

In the last years many studies have been carried out on hybrid systems, with the aim of investigating the process performances and also to compare different carrier media, obtaining very interesting results and highlighting the effectiveness of such systems both for carbon and nitrogen removal (Morper & Wildmoser 1990; Müller 1998; Gebara 1999; Hamoda & Al-Sharekh 2000; Münch *et al.* 2000; Germain *et al.* 2007).

Concerning the carrier media that is added for the growth of the attached biomass it can be fixed or freely moving inside the reactor. In this latter case, when the media is used on its own, the process is usually called moving bed biofilm reactor (MBBR) (Ødegaard 2006; Germain *et al.* 2007). More specifically, in the MBBR process the biofilm grows attached on small carrier elements, kept in constant motion throughout the entire volume of the reactor (Ødegaard *et al.* 1994; Rusten *et al.* 1995*a*,*b*; Ødegaard 2006). The carriers are kept within the reactor through a sieve arrangement at the reactor outlet. The typical advantages of MBBR systems is the low head loss, no filter channelling and no need of periodic backwashing (Pastorelli *et al.* 1999). The MBBR, also known as suspended carrier biofilm process (Welander *et al.* 1997; Suvilampi *et al.* 2003; Wang *et al.* 2005) has been found suitable for treatment of various wastewaters, such as dairy wastewater (Rusten *et al.* 1994; Andreottola *et al.* 2002), and municipal wastewater (Ødegaard *et al.* 1994; Rusten *et al.* 1994, 1995*a*,*b*, 1997). They have also been applied at low temperatures (3–20°C) with little temperature dependency (Ødegaard *et al.* 1994; Welander *et al.* 1997; Welander & Mattiasson 2003). Moreover, sequencing batch operation of MBBR has been attempted (Pastorelli *et al.* 1997, 1999; Helness & Ødegaard 2001). When used in a hybrid process, the suspended carriers can be kept in the whole or in a part of the activated sludge volume, depending on the main aim of treatment.

The difference between MBBR and IFAS relies on the presence of the return activated sludge (RAS). More specifically, whenever the RAS is returned to the tank with the carriers the system is referred as IFAS otherwise is addressed as MBBR. Nevertheless, recently in the case of moveable carrier media, IFASs have been addressed as HMBBR (Hybrid Moving Bed Biofilm Reactors) process (Mannina *et al.* 2007; Di Trapani *et al.* 2008*a*,*b*) or also HYBAS (AnoxKaldnes 2009).

HMBBRs can be adopted to upgrade existing overloaded activated sludge plants without building new tanks. This aspect can be extremely relevant in case of lack of land space that, in many cases, is quite common due to a high urbanization.

Due to the fact that HMBBR systems are characterized by both suspended and attached biomass, a bacteria specialization generally takes place. More specifically, different species of bacteria, particularly the slow growers (such as nitrifiers), are able to grow in the biofilm (Chen *et al.* 1997).

However, despite the advantages that HMBBRs seem to provide, these systems are more complex compared with the biofilm or the pure suspended growth reactors. Analysis of the system is difficult due to some factors: the need for biofilm analysis, differentiation between suspended and attached growth behaviour, and the complexity of the combined system.

Conventional treatment technologies, such as activated sludge process, have been employed for many years and are routinely employed effectively for treating domestic or industrial wastewater. In contrast, the history of new emerging technologies such as HMBBRs is relatively short. Indeed, studies reported from the technical literature are piecemeal with reference to HMBBR systems and such a fact contributes to a not full knowledge about their design as well as management (Gambaretto & Falletti 2005; Germain *et al.* 2006; Di Trapani *et al.* 2007). Indeed, many doubts still arise regarding the kinetic parameters of hybrid reactors and that are probably quite different from pure MBBR and activated sludge ones, and where furthermore experimental surveys are lacking.

Bearing in mind the considerations discussed above, the aim of this paper is to assess the effectiveness of the HMBBR systems for WWTP upgrading and hence verify the reliability of such new technology. To accomplish such an object, a mathematical modelling of the WWTP was performed by means of GPS-X (Hydromantis 1999). The mathematical model was applied to the case study of Acqua dei Corsari WWTP. Furthermore, in order to evaluate the model stoichiometric as well as kinetic parameters for the HMBBR system, a pilot plant was worked out. This aspect was relevant due to the uncertainty of the HMBBR parameters caused, as aforementioned, by limited well documented case studies reported in the literature.

METHODS

Description of the case study

Acqua dei Corsari WWTP was constructed in 1,970 for a design capacity of 440,000 population equivalent (PE). The WWTP was designed mainly for organic matter removal from the wastewater. The design average flow rate is 152,000 m^3/day and the maximum wet-weather flow that can be processed through the activated sludge plant is 380,000 m^3/day. The plant influent consists of 75% municipal and 25% industrial wastewater. The BOD_5 loading is about 30,800 kg/day while NH_4-N loading is 5,720 kg/day.

A schematic overview of the plant layout for the wastewater processing is shown in Figure 1.

The influent is divided over four parallel rectangular primary clarifiers, of about 3,600 m^3 each, after the pretreatment step (coarse grit removal, fine grit removal, sand and grease removal). The effluent of the primary clarifier flows to the biological units which are based of a first step of four trickling filters (each with a volume of 1,500 m^3) and a following one with eight biological activated sludge tanks (each with a volume of 4,500 m^3). The mixed liquor flows to eight secondary clarifiers through an open aerated channel. The clarifiers are rectangular with a volume of 3,100 m^3 each. The Returned Activated Sludge (RAS) from the secondary settler to the aerobic tank is equivalent to 100% of the influent flow. The air is supplied to the aeration zone by means of a diffused aeration system whose set point for dissolved oxygen concentration is 2 mgO_2/L. The primary and secondary sludge are disposed to the sludge processing units where the sludge is thickened by a circular gravity thickener, stabilized by anaerobic digestion and dewatered by belt press filter.

The WWTP although was designed for 440,000 PE, up to day it is underloaded and operates approximately for 120,000 PE due to incomplete connections to the sewer network. As a matter of fact, only some units are in operation. In particular the units in operations are: one grit chamber, one primary settler, four activated aeration tanks and three secondary settlers; with reference to the trickling filters no one is in operation. Furthermore, since the actual WWTP inflow rate is approximately correspondent only to 1/4 of the effective design capacity, the plant is in operation employing some of the activated sludge tanks as aerobic digesters and bypassing the anaerobic units.

However, the sewer connections are nearly complete and the resulting PE load will be greater than the design load. Therefore, the plant will be overloaded. To cope with this overload a plant upgrade will shortly be needed.

In the light of the considerations discussed above, the study was characterized by the following sequential steps:

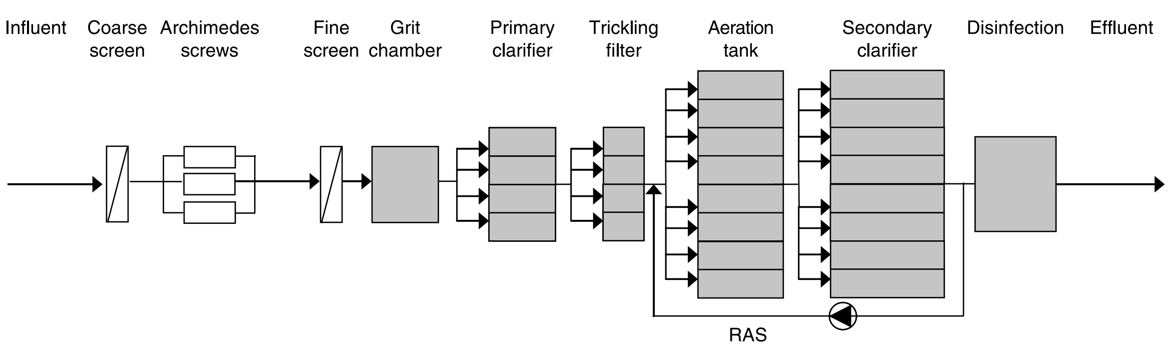

Figure 1 | Layout of Acqua dei Corsari wastewater processing.

1. Acqua dei Corsari WWTP model calibration considering the actual inflow rate and hence the effective units in operation;
2. evaluation of the maximum WWTP capacity considering the operation of the all exiting units;
3. calibration/validation of a HMBBR pilot plant in order to evaluate the stoichiometric as well as kinetic parameters for such kind of system;
4. evaluation of the maximum WWTP capacity considering the Acqua dei Corsari WWTP upgrading by introducing the HMBBR systems.

Mathematical modeling

The WWTP was simulated by means of the GPS-X software (Hydromantis 1999). More specifically, such a software is designed to simulate several WWTP units. The software is made by packages each implementing different mathematical models for the simulation of the WWTP units.

The major models employed to simulate the Acqua dei Corsari WWTP were mainly the Activated Sludge Model No. 1 (ASM1) for the suspended biomass (Henze *et al.* 2000), the attached-growth (biofilm) model (Hydromantis 1999; Henze *et al.* 2000) for the HMBBR system and the secondary clarifier model proposed by Takács *et al.* (1991). Regarding the HMBBR model the contents of the reactor are represented by six fixed layers, the first layer representing the bulk liquid, while the remaining five layers represent that the biofilm formed on the carriers. The first biofilm layer (second model layer) represents the conditions in the outer part of the biofilm, while the sixth layer represents the conditions close to the carriers. The transfer of soluble components between the layers is modelled considering only the diffusion process. The diffusion between the biofilm and the tank liquid is modelled as an empirical relation, while the diffusion within the biofilm is modelled using the second Fick law (Heath *et al.* 1990). The transfer of particulate components between the layers is modelled empirically. The attachment/detachment biofilm model has been build according to Spengel & Dzombak (1992) theory. More specifically, attachment of particulate components to the biofilm is modelled with an attachment rate, while detachment of particulate components from the biofilm to the liquid is represented with a detachment rate. Within the biofilm, particulate component concentrations in the layers change because of the conversion processes. This also affects the biofilm thickness. This phenomena is modelled in such a way that the number of active biofilm layers and therefore the biofilm thickness change dynamically.

In order to carry out the WWTP simulation with GPS-X, a continuous input series in terms of quantity and quality data is needed. Therefore, in order to dispose such series starting from the discrete input measured data, the Fourier series was employed. Indeed such series, after the evaluation of the input parameters on the basis of the measured data, enables to simulate a continuous WWTP inflow. According to the Fourier series the generic input variable, Y, can be modelled by the following equation:

$$Y = \mu \cdot \left(-\beta \cdot \mathrm{Sin}(\omega \cdot (t+\alpha) + \varphi_1) - \frac{1}{2} \cdot \beta \cdot \mathrm{Sin}(2 \cdot \omega \cdot (t+\alpha) + \varphi_2) - \frac{1}{3} \cdot \beta \cdot \mathrm{Sin}(3 \cdot \omega \cdot (t+\alpha) + \varphi_3) \right) + \mu \quad (1)$$

where β, ω, α, φ_1, φ_2, φ_3 are the series parameters, μ the average value of the simulated variable, and t is the time.

The Fourier series moves throughout a line that generally coincides with the horizontal line whose value is the average one of the parameter to be performed. Since from one day to the following one such a value is generally not constant, an oblique line has been considered in order to avoid discontinuities. More specifically, the line that goes from the first average parameter value to the following one has been considered.

The models were first calibrated/validated using an extensive data base of 2 years (from 1/01/2005 to 1/10/2006) and a 15-days field campaign, respectively, for the Acqua dei Corsari WWTP and for the HMBBR pilot plant. Once evaluated the model stoichiometric as well as kinetic parameters, the maximum Acqua dei Corsari WWTP capacity has been evaluated for different configuration systems (CSs). More specifically, three CSs have been compared: CS 1 where the all WWTP units were simulated (four primary settlers, eight activated sludge tanks and eight secondary settlers) except the trickling filters, CS 2 where the trickling filters were also considered in operation and CS 3 where the activated sludge tanks were substituted by HMBBR systems (Figure 2). To accomplish the object,

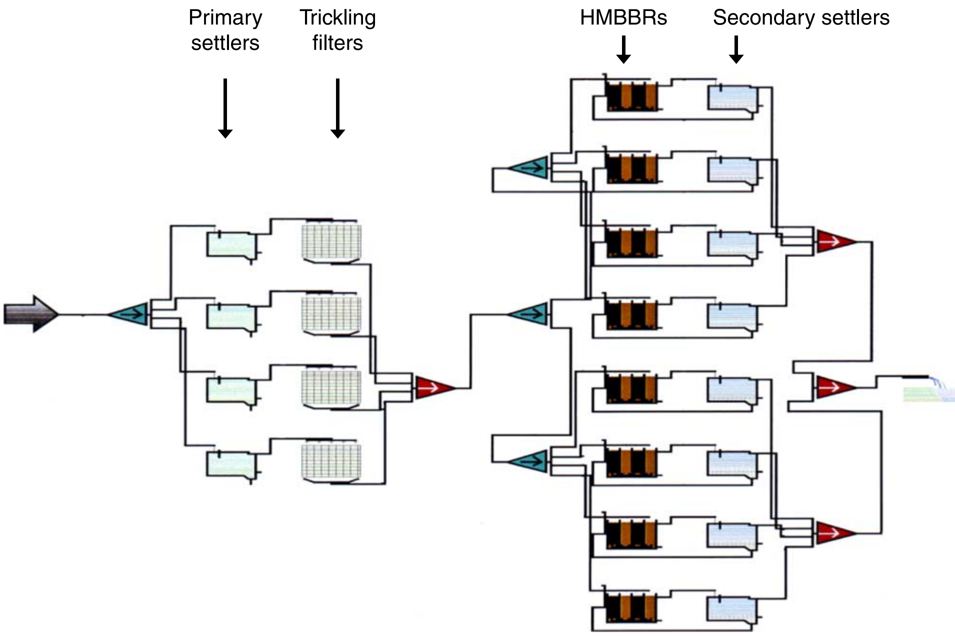

Figure 2 | Model layout for the CS 3.

a simulation analysis has been made where several dynamic simulations have been considered changing the influent series employed for the calibration of the WWTP.

Acqua dei Corsari model calibration

As discussed above, the simulations were carried out adopting an extended WWTP data base. More specifically, such data base includes several process variables, i.e. total COD (COD), and soluble COD (solCOD), total BOD_5 (BOD_5), soluble BOD_5 (solBOD_5) total suspended solids (TSS), volatile suspended solids (VSS), total TKN (TKN), NH_4-N, temperature, pH and different flows (inflow, internal recycle flow, external recycle flow and waste sludge flow). The analyses were performed according to Standard Methods for examination of wastewater (APHA 1996). The information obtained through the sampling program was combined with the data routinely collected by the staff of the plant. In Table 1, the average values of both wastewater and operational characteristics have been reported. The listed values in Table 1 regard the used available data that concerns grab samples taken once a day at the inlet and at the outlet of the WWTP.

Starting from the discrete measured data continuous series was evaluated by means of a Fourier series. The employed approach considers the influent characteristics as a periodic behaviour. In order to proper simulate the daily pattern of the modelled parameters an "ad hoc" field campaign was carried out where data with a two hours frequency were sampled. By employing the gathered data base, the series parameters have been evaluated by minimizing an objective function calculated as the root square of the error variance (Table 2). In Figure 3 a typical pattern

Table 1 | Characteristics of average wastewater and operational parameters at the Acqua dei Corsari WWTP

	Unit	Raw sewage	Final sewage
Wastewater			
COD	mg/L	450	60
BOD_5	mg/L	320	24
TSS	mg/L	375	30
TKN	mg/L	32	21
NH_4-N	mg/L	22	16
pH	–	7.2	7.8
Operation			
Influent flowrate	m^3/d	31,700	
Returned activated sludge	%	100	
MLSS concentration	g/L	3	
Sludge retention time	d	21–30	

Table 2 | Fourier series parameter values

Variables	β	ω	α	φ_1	φ_2	φ_3
COD, NH_4-N	0.58	0.26	11.30	4.27	5.59	5.97
Q	0.52	0.20	11.30	5.62	7.99	4.99

of the input series for the flow rate, COD and NH_4-N measured and simulated are showed. The good agreement between measured and simulated data reported in Figure 3 confirms the suitability of the Fourier series. It has to be stressed that the results are not referred to the whole simulated period. Nevertheless, the Fourier series showed a similar satisfactory behaviour for the other days behaving a correlation coefficient between measured and modelled of $R^2 = 0.88$.

Regarding the modelling process, several different approaches are possible (Andrews 1992); nevertheless, the most crucial step in the entire process is model calibration. Indeed, this latter can be viewed from different perspectives (system engineering vs. process engineering) as presented by Van Veldhuizen *et al.* (1999). In the first case, parameters for calibration are selected based on sensitivity analysis, whereas the second approach involves the process knowledge and professional experience of the modeller (Makinia *et al.* 2002). Cinar *et al.* (1998) used the term "human expert" for this method and an example referring to a model of the activated sludge process (Henze *et al.* 1995) was provided. Coen *et al.* (1997) proposed a procedure for calibrating a general model of WWTP from the process engineering perspective. For the purpose of this study, it was assumed for the calibration phase that the least possible number of parameters would be adjusted to obtain reasonable fits.

As discussed early, the simulation study was accomplished using ASM1 (Henze *et al.* 2000) implemented in the GPS-X simulation package. In accordance with ASM1 concept, different fractions of the COD and TKN are identified. In particular, in the present study literature values (Table 3) have been employed for the wastewater influent (Henze *et al.* 2000). As common practice, X_{BH}, X_{BA} and X_P (heterotrophic and autotrophic biomass and particulate products of decay) and S_O have been set to zero. Simulations were initially run with the model default values; however, the obtained predictions were inaccurate and the model required further calibration. Consequently, the model parameters were manually adjusted (trial and error) so that a satisfactory agreement between the process and the model was achieved.

Modelling the HMBBR pilot plant

In order to evaluate the stoichiometric and the kinetic parameters for the HMBBR system a pilot plant was set up at the Acqua dei Corsari and an extensive gathering field campaign was carried out (Mannina *et al.* 2006).

The plant was basically made up of two parallel lines with the same reactors but with different filling ratios. Each treatment line consisted in a 6.5 litres anoxic reactor, a 6.5 litres aerobic one and a 3.5 litres final settler.

The pilot plant has been operated for a period of approximately three months whose first one was necessary for achieving good working conditions. The plant was continuously fed with a constant flow rate of 1 L/h of primary settled wastewater and an organic load up to 1.2 kg COD/m^3d. Return sludge was pumped from the clarifier to the anoxic tank considering a recycling rate equal to the influent flow rate. Nitrate recycling was operated from the aeration tank outlet to the anoxic tank with a 4 L/h flow rate.

The aerobic reactors were characterised by two different filling ratios of 35% (line 1) and 66% (line 2), corresponding to a theoretical specific surface area of 190 m^2/m^3

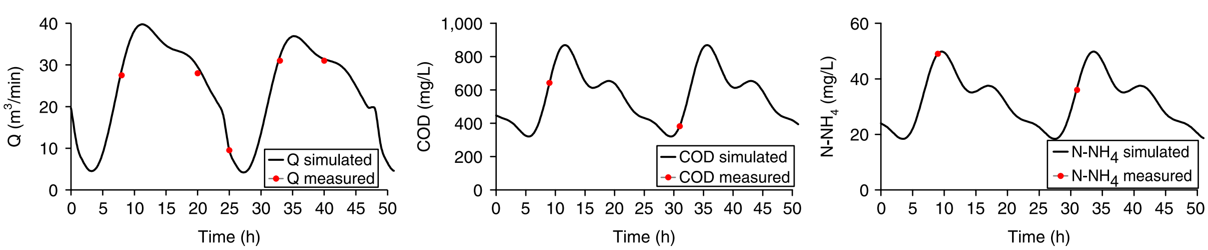

Figure 3 | Example of Acqua dei Corsari continuous input data.

Table 3 | Influent fractions

Description	Symbol	% of COD	% of TKN
Inert non biodegradable soluble COD	S_I	8	–
Soluble degradable COD	S_S	21	–
Inert particulate COD	X_I	14	–
Degradable particulate COD	X_S	57	–
Ammonium	S_{NH}	–	64
Soluble organic nitrogen	S_{ND}	–	16
Particulate organic nitrogen	X_{ND}	–	20

and 330 m^2/m^3 respectively. Mixing was guaranteed in the anoxic tanks by mechanical stirrers, while in the aerobic ones by the aeration systems, a coarse-bubble ones, installed at the bottom of each reactor. Special sieve arrangements, to retain the carriers within the aerobic reactors, have been adopted. The used support material was the Kaldnes Miljøteknology K1, whose characteristics are summarized in Table 4 (Ødegaard 2006).

During the field campaign TSS and Volatile Suspended Solids VSS referring to the fixed and suspended biomass, COD, soluble flocculated COD (CODsol), readily biodegradable COD, NH_4-N, NO_3-N dissolved oxygen, temperature, pH and air flow rate were monitored.

RESULTS AND DISCUSSION

Acqua dei Corsari calibration results

Tables 5 and 6 contain a list of model coefficients adjusted during the model calibration. Therefore, the calibrated parameter values referrer to the actual WWTP units in operation. More specifically, as discussed in the previous paragraph, the actual WWTP units in operation regards one grit chamber, one primary settler, four activated aeration tanks and three secondary settlers. From the suggested values of kinetic and stoichiometric parameters in GPS-X the following parameters were modified: maximum heterotrophic growth rate μ_H was increased from 3.2 to 5 d^{-1},

Table 4 | Characteristics of media carriers

Diameter mm	Height mm	Density kg/m³	Filling ratio %	Total surface m²/m³	Internal surface m²/m³
9.1	7.2	0.98	70	800	500

Table 5 | Diffusion coefficients for HMBBR

Substances	Symbol	Value (10^{-5} m²/s)
Readily biodegradable substrate	S_S	1
Dissolved oxygen	S_O	2.5
Nitrate and nitrite N	S_{NO}	2
Ammonia N	S_{NH}	2.5
Soluble biodegradable organic N	S_{ND}	1

heterotrophic decay rate b_H was lowered from 0.6 to 0.2 d^{-1}, heterotrophic yield was increased from 0.66 to 0.71 g CODbiomass/g CODremoved. Such variations of model parameters values are most likely caused by discharges of relatively high content of the industrial wastewater. Nevertheless, the values of the parameters remained within the range reported in the literature (Henze *et al.* 2000; Dold *et al.* 2005; Choubert *et al.* 2008). Further, these modified values of the kinetic as well as stoichiometric parameters caused an increase of the sludge production that has been checked in order to be sure about the correctness of the calibrated parameter values. Regarding the settler the following parameters were modified (Table 7): maximum settling velocity was increased from 274 to 320 m/d, maximum Vesilind settling was decreased from 480 to 410 m/d and flocculant zone settling was increased from 0.0025 to 0.001 m^3/gTSS.

COD, TSS and BOD effluent concentrations were considered for the model application over the two years simulated period. The first year was considered for model calibration and the second one for model validation. The agreement between predicted and observed values was regarded as satisfactory if the calculated values were in the range of 50%.

The simulation of WWTP effluent concentrations were of similar accuracy, as presented in Figure 4a and b, respectively, for model calibration and validation. The number of data used for model calibration were, 24, 28 and 16 respectively for COD, TSS and BOD; conversely for model validation the data were 14, 19 and 13 respectively for COD, TSS and BOD.

The correlation coefficient between measured and modelled ranged from $R^2 = 0.74$ to 0.83, and the Nash & Sutcliff (1970) coefficient of model efficiency, calculated as a function of the error variance of the model simulations

Table 6 | Model parameter values employed for biological reactions

Parameters	Symbol	Unit	Default value in GPS-X at 20°C	Calibrated for Acqua dei Corsari at 16°C	Calibrated for HMBBR at 16°C
Stoichiometric					
Heterotrophic yield	Y_H	g CODbiomass/g CODremoved	0.666	0.71	0.71
N content of active het. Biomass	i_{BH}	gN/g COD	0.068		
N content of products from het. Biomass	i_{PH}	gN/g COD	0.068		
Fraction of het. biomass yielding particulate products	f_{PH}	–	0.08		
Autotrophic yield	Y_A	g CODbiomass/gNnitrified	0.24		0.19
N content of active aut. Biomass	i_{BA}	gN/g COD	0.068		
N content of products from het. Biomass	i_{PA}	gN/g COD	0.068		
Fraction of aut. biomass yielding particulate products	f_{PA}	–	0.08		
Kinetic					
Max. het. growth rate	μ_H	1/d	3.2	5	5
Half saturation coefficient	K_{SH}	g COD/m^3	5		
Het. decay rate	b_H	1/d	0.62	0.2	
Anoxic hydrolysis factor	η_h	–	0.37		
Anoxic growth factor	η_g	–	1		
Max. hydrolysis rate	k_h	1/d	2.81		
Hydrolysis half sat. coeff.	K_x	–	0.15		
Ammonification rate	k_a	m^3/g COD/d	0.016		
Max. aut. growth rate	μ_A	1/d	0.75		
Half saturation coefficient	K_{NA}	gN/m^3	1		
Aut. decay rate	b_A	1/d	0.04		0.075
Switching functions					
Aerobic/anoxic growth	K_{OH}	g O_2/m^3	0.2		
Ammonia limit	K_{NH}	gN/m^3	0.05		
Nitrate limit	K_{NO}	gN/m^3	1		

and the observed variance for the period under consideration, ranged from $E = 0.76$ to 0.81, respectively, model calibration and validation.

HMBBR model calibration results

Figure 5 shows the input files employed for the COD and NH_4-N for the dynamic simulations. Such series have been estimated with an analogous procedure discussed above for the Acqua dei Corsari input long term series.

Regarding the model parameters, as for the Acqua dei Corsari WWTP modelling, from the suggested values of kinetic and stoichiometric parameters in GPS-X only some parameters were modified: maximum heterotrophic growth rate μ_H was increased from 3.2 to 5 d^{-1}, autotrophic decay rate b_A was increased from 0.04 to 0.075 d^{-1}, heterotrophic yield Y_H was increased from 0.66 to 0.71 g CODbiomass/g CODremoved, autotrophic yield Y_A was lowered from 0.15 to 0.12 g CODbiomass/gNnitrified. Regarding the settler the following parameters were modified: maximum settling velocity was increased from 274 to 310 m/d, maximum Vesilind settling was lowered from 480 to 410 m/d and hindered zone settling was lowered from 0.0004 to 0.0003 m^3/gTSS.

Table 7 | Settler parameters

Parameters	Symbol	Unit	Default value in GPS-X	Calibrated for Acqua dei Corsari	Calibrated for HMBBR
Maximum settling function	ν'_{o}	m d^{-1}	274	320	310
Maximum Vesilind settling function	ν_{o}	m d^{-1}	480	410	410
Hindered zone settling parameter	r_h	m^3 (g SS)$^{-1}$	0.000576		
Flocculant zone settling parameter	r_p	m^3 (g SS)$^{-1}$	0.0025	0.001	
Non-settleable fraction	f_{ns}	–	0.00228		

The model has been applied to a period of fifteen days considering dynamic conditions regarding the influent concentrations and constant ones for the flow rate. Figure 6 shows the model results, respectively, for the 35% and 66% HMBBR plant. More specifically, NH_4-N, NO_3-N COD_{tot}, COD_{sol}, Mixed Liquor Suspended Solids (MLSS), heterotrophic biomass X_h, autotrophic biomass X_a, are shown for the two simulated reactors. The average efficiencies for totCOD removal were 91.35% and 84.51% for the 35% and 66% filling ratios respectively, underlying a very high removal efficiency for both reactors. The maximum influent COD concentration resulted 632 mg/L, while the average inflow concentration was of 437 mg COD/L and an average outflow COD of 37 and 38 mg COD/L for 35% and 66% filling ratio.

The COD effluent showed lower results compared to normal values of conventional treatment (activated sludge). This fact was justified due to the presence of the biofilm that enabled a better settleability of the sludge. Indeed, the Sludge Volumetric Index (SVI) values of the HMBBR were always lower respect to the conventional activated sludge ones highlighting a better sludge settleability. Such results are in agreement with previous studies (Martinez & Luciano 1992; Lessel 1994; Tizghadam *et al.* 2008), showing that the sludge from the HMBBR reactor shows good settling properties and no bulking due to the excessive growth of filamentous bacteria.

Comparing the results obtained with the two parallel lines, it can be observed that 35% HMBBR CODtot removal efficiency were slightly higher than the other one. On the contrary, the soluble COD removal resulted quite similar. Such aspects should be related to the different biomass specie concentrations, as addressed by other authors (Andreottola *et al.* 2000; Di Trapani *et al.* 2007). In fact, in the 35% filling reactor, suspended growth concentration was higher than the 66% one (see Figure 6b and e).

Regarding the nitrogen removal efficiency analogous results have been registered. More specifically, the average nitrification efficiency of both reactors were very high resulting 98.8% for 35% filling HMBBR and 97.2% for 66% filling HMBBR.

The model agreement level between predicted and measured data is acceptable furthermore it shows a good ability to reproduce different filling ratios. Indeed, the model agreement for the 66% HMBBR system demonstrates a good model predictive capacity since no

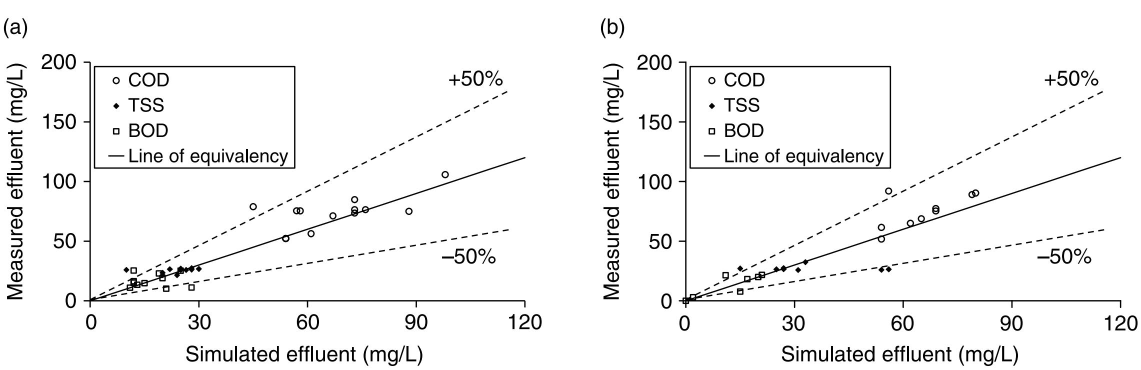

Figure 4 | Results of model calibration (a) and validation (b) in terms of COD, TSS, BOD concentrations at the WWTP outflow.

change of the model parameters value was considered. Since the two systems with different filling ratios showed analogous performance and the 35% filling ratio is more economic, this latter was chosen for Acqua dei Corsari upgrading.

Comparison of the different configuration systems

As discussed above, the new connections to the sewer network will require the need to upgrade the WWTP due to an overcome of the WWTP maximum capacity. With this

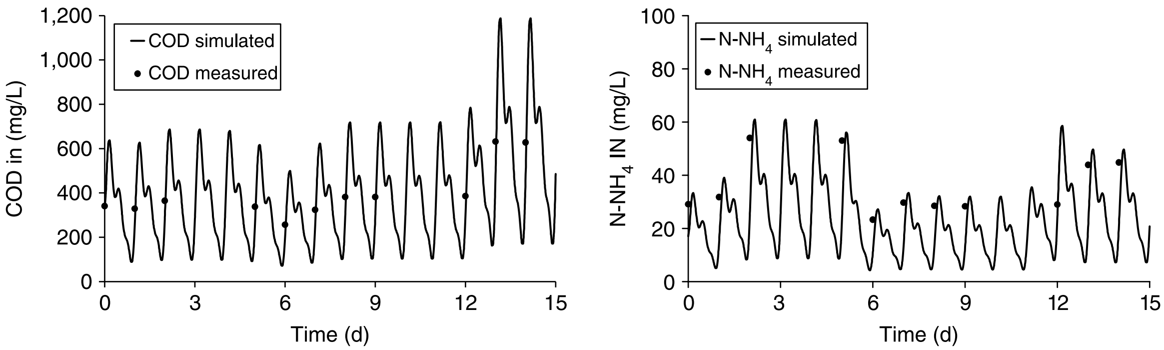

Figure 5 | Measured and simulated input series for the 15-days simulation of the HMBBR system in term of COD and N-NH_4.

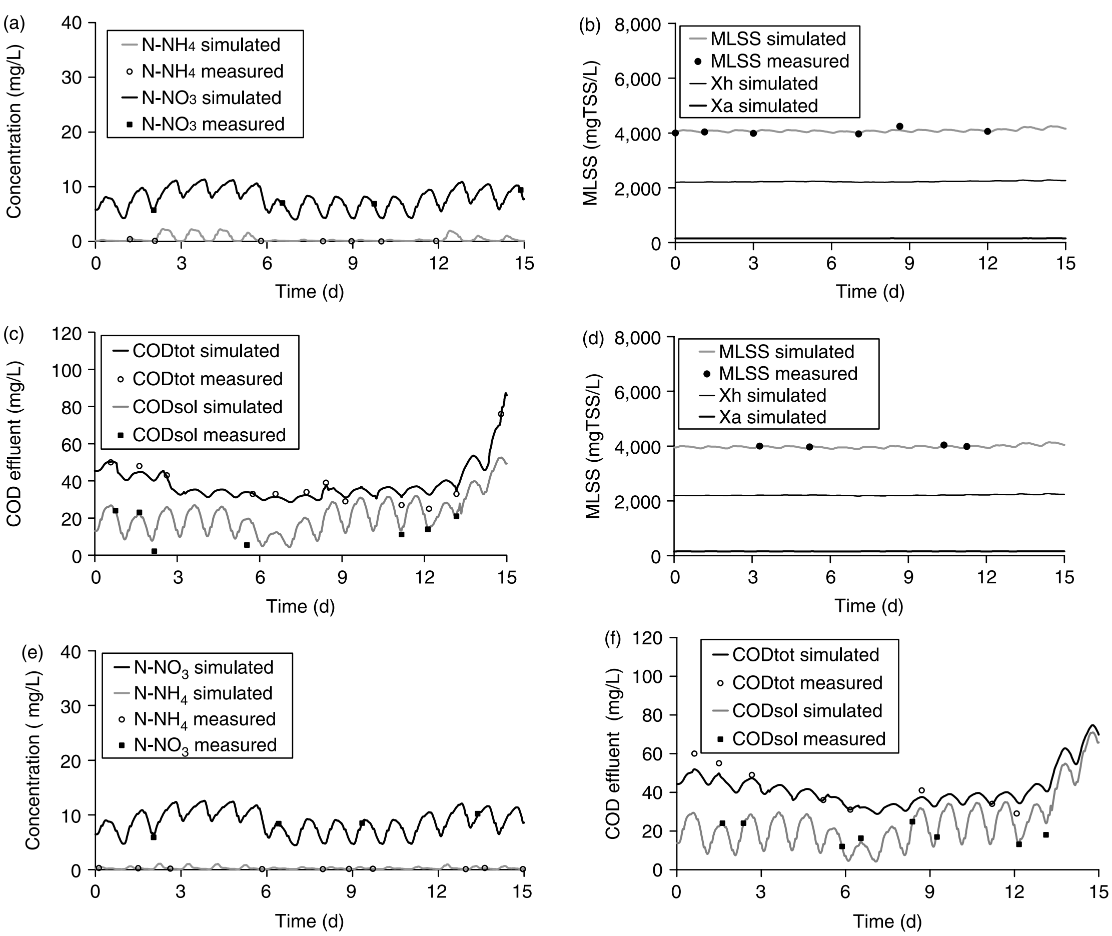

Figure 6 | Model results for the HMBBR pilot plant with different filling rates of 35% (a, b, and c) and 66% (d, e and f).

frame, here once evaluated the stoichiometric as well as kinetic parameters for the Acqua dei Corsari WWTP and for HMBBR system, the WWTP maximum capacity has been evaluated by means of GPS-X model considering dynamic conditions with reference both to the quantity and to the quality. The observed process variables were the following effluent concentrations: BOD, TSS and COD. In accordance with the legislation requirements the following effluent concentrations have to be met: TSS $\leq$ 35 mg/L, COD $\leq$ 125 mg/L and BOD $\leq$ 25 mg/L. As aforementioned, three configuration systems have been considered and for each of them the maximum WWTP capacity has been evaluated by means of dynamic simulations. More specifically, starting from the Fourier series determined for the WWTP inflow, the average influent flow (μ, Equation (1)) was changed in order to get an influent synthetic series correspondent to 80,000 and 1,100,000 PE, i.e an average inflow value variable from 25,000 to 400,000 m^3/day. From the dynamic simulation, for each scenario of PE, the average concentrations have been calculated. Figure 7 shows the model results of the dynamic simulations for the three simulates CSs. Analysing Figure 7 it can be seen that with reference with CS 1 the maximum WWTP is 480,000 PE while 570,000 PE for CS 2 (BOD is the first pollutant overcoming the legislation limits), while for CS 3 the maximum WWTP is 1,000,000 PE (TSS is the

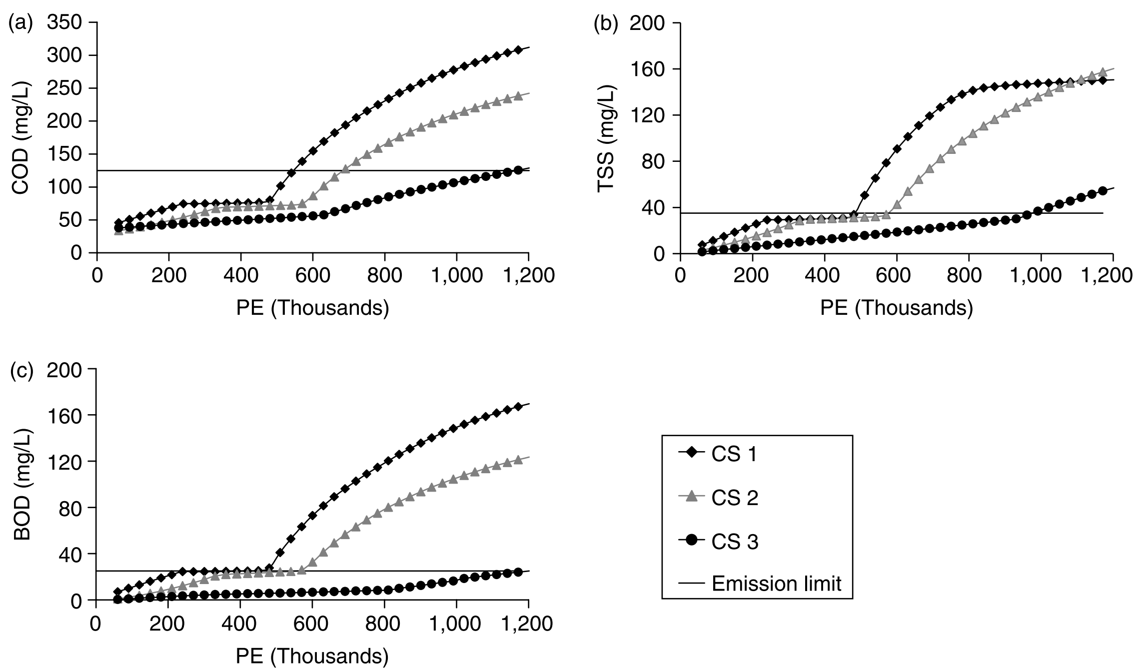

Figure 7 | CS comparisons, a, b, and c, respectively, for COD, TSS and BOD.

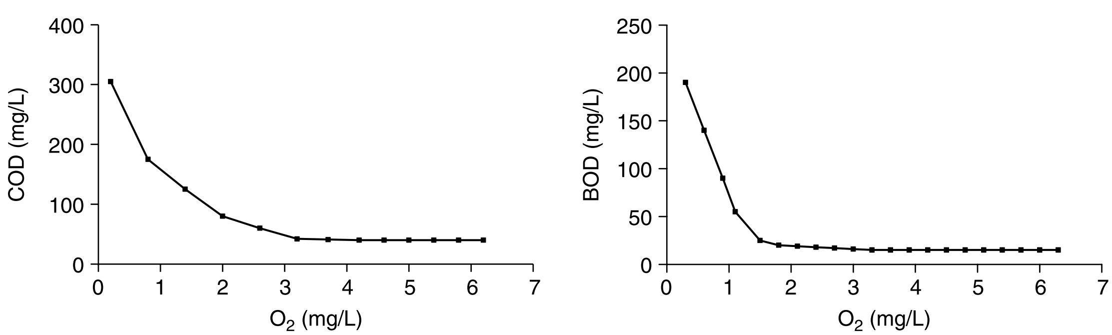

Figure 8 | Influence of the oxygen concentration on HMBBR performance.

first pollutant overcoming the legislation limits). The model simulation results showed a good capability to upgrade the Acqua dei Corsari WWTP by adopting HMBBR systems. However, such results have to be verified by cost/benefit analyses in order to weight and choose the best solution.

Indeed, since the HMBBR systems require a higher oxygen concentration for the carbon removal in the oxidation tanks, the operation maintenance costs will be higher compared with the traditional activated sludge processes (Hvala *et al.* 2002). More specifically, Figure 8 shows the oxygen concentration effect on HMBBR performance. In particular, the oxygen concentration in the aerobic reactors was gradually changed from 0 to 7 mg/L considering a constant influent in terms of both water quantity and quality (concentration). More specifically, imposing a constant influent on the plant, the operating variables were changed. The observed process variables were the following effluent concentrations: BOD and COD. As could had been expected, the HMBBR performance is not influenced by DO concentration whenever its value is above a certain threshold. However, a comparison between the performance of the HMBBR and the conventional activated sludge reveals that a much higher DO concentrations respect to the conventional activeated sludge is necessary for the HMBBR. This is because in the HMBBR the oxygen is transferred into the biomass by the diffusion process. Therefore, higher DO concentrations are needed in the bulk liquid for the oxygen to diffuse deep into the biofilm (Hvala *et al.* 2002). As a matter of fact, the oxygen concentration (O_2) in the HMBBR systems has been maintained 5 mg/L therefore 3 mg/L higher compared with the CS 1 and CS 2 (2 mg/L). It has to be stressed that for the case of CS 2 the oxygen concentration of 2 mg/L deserves to be verified by considering full-scale plant. Indeed, it could happen that such a oxygen concentration would draw to an insufficient driving force to move the carriers.

CONCLUSIONS

In the presented study, a survey where the decision about upgrading of a large WWTP based on mathematical model simulations and an extensive data base was worked out. For upgrading the WWTP the HMBBR systems were detected as a possible solution among the new technologies up to day available. The aim was focused on demonstrating the effectiveness of HMBBR systems for upgrading WWTPs rather than evaluating predictive capabilities of the employed model itself.

The mathematical models were implemented with the GPS-X simulation software. A HMBBR pilot plant was set up as well as modelled in order to evaluate the kinetic and stoichiometric parameters for modelling the upgraded WWTP.

Based on the results of the study conducted at the Acqua dei Corsari WWTP the following conclusions can be derived:

- During calibration the model default values were changed for three biological parameters for the Acqua dei Corsari WWTP and five parameters for the HMBBR system.
- The two HMBBR systems showed analogous efficiency regarding the COD removal addressing the choice of the filling ratio towards the 33%.
- The model results were encouraging towards the WWTP upgrading by means of HMBBR systems demonstrating their effectiveness towards overloaded WWTP issues.
- The model simulation results showed that the WWTP maximum capacity can be upgraded from 480,000 up to one million PE. However, it has to be stressed that cost/benefit analyses have to be carried out in order to choose the best WWTP upgrading solution.

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