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Comparison between hybrid moving bed biofilm reactor and activated sludge system: a pilot plant experiment

Daniele Di Trapani, Giorgio Mannina, Michele Torregrossa and Gaspare Viviani

ABSTRACT

The paper presents the comparison between the traditional activated sludge system (AS) and a hybrid moving bed biofilm reactor (HMBBR). In particular, an experimental campaign has been carried out at the WWTP in Palermo (Italy), on a pilot plant consisting of two pre-anoxic schemes. The aerated tank of the HMBBR line was filled with suspended carriers (AnoxKaldnes™ K1), with a 30% filling ratio. The hydraulic load of the HMBBR line was increased up to two times the AS one. Further, in order to distinguish the additional contribution of the attached biomass for the HMBBR system, in the two lines the Mixed Liquor Suspended Solids (MLSS) was maintained as equal as possible. The monitoring period lasted three months during which several parameters were monitored. The obtained results showed a good treatment ability of the HMBBR system, referring to the organic matter removal as well as to the ammonium removal. In particular, in spite of the increase of the hydraulic load for the HMBBR line, the two systems showed a similar performance in terms of both organic and nitrogen removal. The results demonstrate the higher treatment capacity of the HMBBR addressing such system as an effective technology for the upgrading of overloaded wastewater treatment plants.

Key words | biological treatment, HMBBR, hybrid biofilm reactors, municipal wastewater, nitrification, organic and nitrogen load

Daniele Di Trapani
Giorgio Mannina (corresponding author)
Michele Torregrossa
Gaspare Viviani
Dipartimento di Ingegneria Idraulica ed Applicazioni Ambientali,
Università di Palermo,
Viale delle Scienze,
90128 Palermo,
Italy
E-mail: *mannina@idra.unipa.it*

INTRODUCTION

Recently there has been an increase of the urbanization together with the even more strict effluent limits imposed at the outlet of municipal Wastewater Treatment Plant (WWTP) by the Water Framework Directive (Chave 2001). In addition, there has been also an increasingly limited area for the construction of new plants; these factors have often led to the necessity of upgrading of existing WWTP. The secondary treatment of the WWTP is usually accomplished by biological processes that can be classified as being either suspended or attached growth. The conventional and mostly used suspended growth system is represented by the classical and well known activated sludge process (AS). Indeed, this process can present some shortcomings when exposed to increased hydraulic and organic loads. To increase the performances of an existing AS system it would be necessary to increase the amount of biomass inside the aerobic reactor; however, in such a case, the major WWTP limitation is represented by the following unit i.e. the settling tank.

In the last years, the idea to combine the 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

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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 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). 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*; Mannina & Viviani 2009) or HYBAS (AnoxKaldnes 2009).

Up to now, many suspended carriers have been used in the HMBBR process (Christensson & Welander 2004; Germain *et al.* 2007), and the results supported the idea that adding suspended carriers is a good solution to improve nitrification or carbonaceous removal at high loading rate in existing treatment plants. In the present study the AnoxKaldnes™ K1 carrier was used. However, the hybrid reactors are of quite recent acquisition, and there are still some uncertainties regarding their design and behaviour.

Bearing in mind such considerations, the main aim of the study was to gain insight about the performances of the HMBBR process and, in particular, to evaluate the system behaviour when exposed to increased hydraulic and organic loads. To achieve such a goal, the traditional AS process has been compared to the HMBBR process. In particular, the first results from a gathering experimental campaign on a pilot-scale system are presented and discussed.

MATERIALS AND METHODS

The pilot plant was built at Palermo (IT) municipal WWTP (Acqua dei Corsari). The pilot plant consisted of two parallel lines, each in a pre-anoxic scheme, in one of which the suspended carriers were added to the aerobic reactor with a 30% filling ratio. Each line consisted of a 6-litres anoxic reactor, a 12-litres aerobic one and a 3.5-litres final clarifier. In Figure 1 the pilot plant layout with the sampling sections is reported.

Mixing in the aerobic reactors was due to the medium-coarse bubble aeration systems installed at the bottom of each tank, while in the anoxic tanks mixing has been realized by mechanical stirrers. Special sieve arrangements were adopted to retain the carriers inside the aerobic reactors. The support carrier material used was the well known AnoxKaldnes™ K1, with a 30% filling ratio, corresponding to an actual specific surface in the reactor of 150 m^2/m^3. The experimental campaign lasted for a period of approximately three months. However, in order to allow microbical communities in the wastewater to adapt to the configuration used as well as to enhance the biofilm

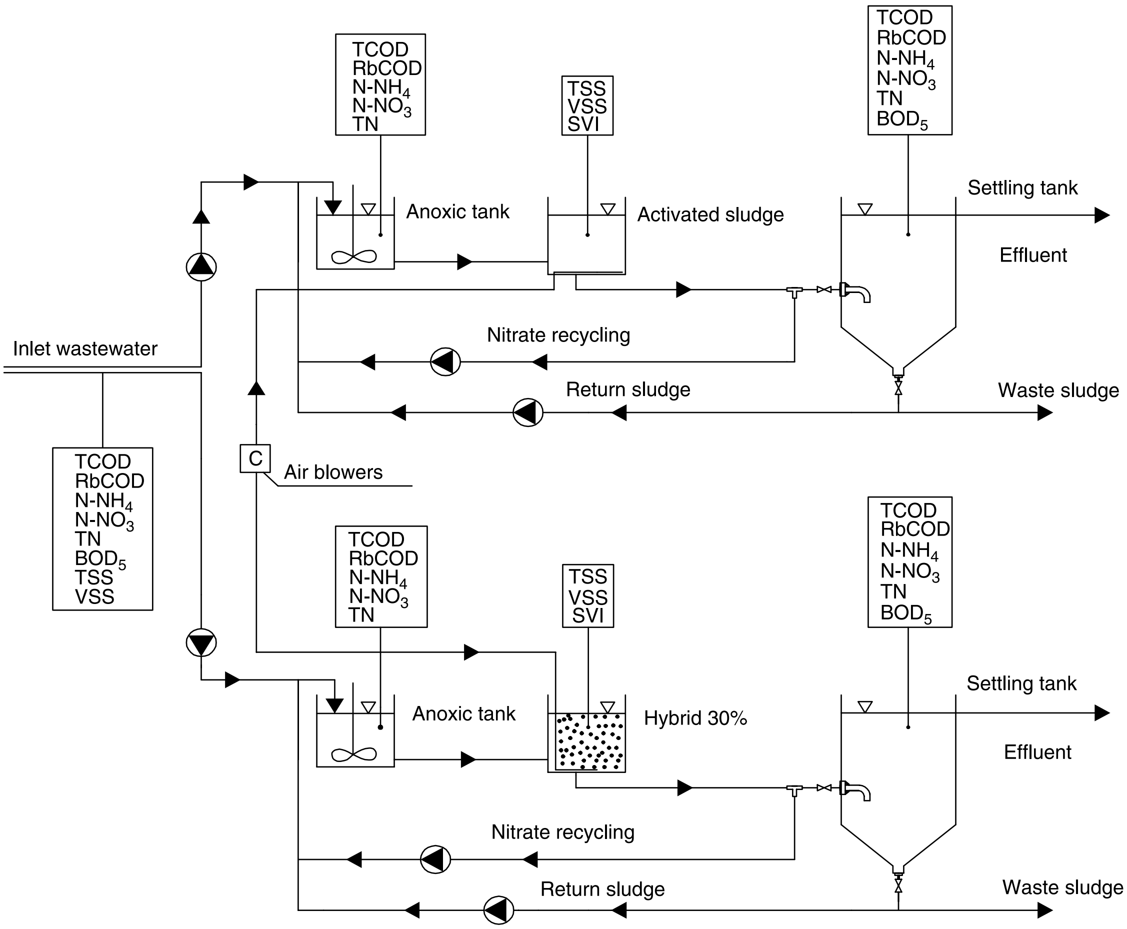

Figure 1 | Pilot plant layout.

growth on the carriers, the pilot plant lines were kept under the same conditions in terms of influent load during approximately 40 days before starting the field campaign. The pilot plant was continuously fed with municipal wastewater taken immediately downstream of the fine screen of the WWTP.

The experimental campaign was divided into three different phases. At the beginning of the experimental period, the influent flow was the same for both lines, with a constant value of 1.5 L/h, a hydraulic retention time (HRT) in the biological reactors of almost 12 h and a nitrate recycle of 6 L/h (first phase); a second phase during which the flow rate of the HMBBR line was increased up to 3 L/h, corresponding to a 6 h HRT, and a nitrate recycle of 12 L/h, in order to better highlight the difference with respect to the AS system. In order to better single out the attached biomass contribution of the HMBBR system, the MLSS concentrations of the two systems were kept as similar as possible. In this phase of the study it was decided to keep the AS line under the same operative conditions of the previous one in order to investigate only the performance of the HMBBR process under the new operative conditions. It has to be stressed that in order to increase the influent organic load to the plant it should also have been possible to add synthetic substrates. Such choice was discarded due to the fact that the idea was to study a pilot plant fed with real wastewater. Indeed, this latter choice is more representative of a real WWTP characterised by the increase of the influent organic load. Finally, in the third experimental phase, the influent flow to the HMBBR

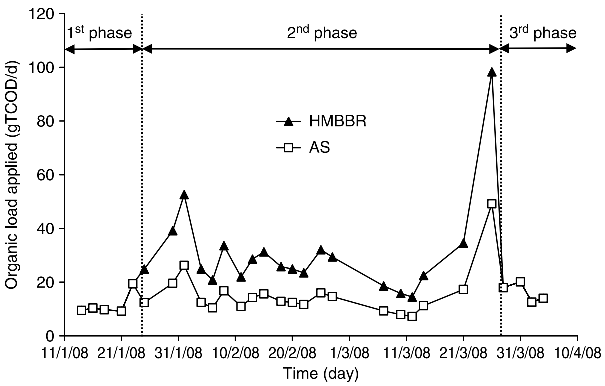

Figure 2 | HMBBR and AS influent organic load for the three sub-periods.

line was reduced to the original value; therefore, in the last experimental days, the two lines have worked still under the same operative conditions. In Figure 2, the influent organic loads, in terms of TCOD, during the three phases are reported. In particular, the average influent organic load in the first and latter phase is approximately 14 gTCOD/d and it rises up to 30 gTCOD/d in the second phase for the HMBBR due to the increase of the flow rate. The influent organic load generally shows a sensibly variability assuming a maximum peak of 50 and 100 gTCOD/d, respectively, for the AS and HMBBR system.

During the whole experimental period, samples were taken from the influent and the effluent for chemical analysis three times a week, while periodical samples have been taken from the anoxic tank to check if there was some anomaly. TSS and VSS, TCOD, NH_4-N, NO_3-N, TN, were analysed according to the Standard Methods (APHA 1995), while the readily biodegradable COD (rbCOD) was determined according to Mamaïs *et al.* (1993). Periodical sludge volume index (SVI) tests have been also carried out in order to evaluate the sludge settleability properties for the two lines. Test on carrier samples were carried out, in order to establish the amount of biomass attached on the carriers. The assessment of attached biomass was carried out considering the TSS on the support carriers. To evaluate the latter, a sample of carrier elements was taken from the aerobic reactor, dried at 105°C for 24 h and weighted. Then, this value was compared with an average "zero" weight determined at the beginning of the experimental period, thus obtaining the biomass weight in a single carrier element. So, as the number of carrier was known for each reactors, it was calculated the total attached biomass in the reactor and consequently, through the filling ratio, the grams of TSS per litre of reactor volume.

In Table 1 the operative conditions in the whole experimental period, as well as average TSS and VSS values in the influent wastewater, are summarised.

RESULTS AND DISCUSSION

Organic carbon removal

As above mentioned, in the 2nd experimental phase, it was decided to increase the hydraulic load in the hybrid line only, remanding to further experimental analysis the study of the two lines under the same operative conditions.

Table 1 | Operative conditions during the whole experimental period

		HMBBR			AS		
Parameters	**Unit**	**Average**	**Min**	**Max**	**Average**	**Min**	**Max**
Influent flow	(L/h)	2.65	1.5	3	1.5	1.5	1.5
Nitrate recycling	(L/h)	10.61	6	12	6	6	6
Influent TSS	(mg/L)	223.82	124.6	452.6	223.82	124.6	452.6
Influent VSS	(mg/L)	140.79	78.4	285	140.79	78.4	285
T	(°C)	16	14	18	16	14	18
pH	–	8	7.3	8.2	8	7.3	8.2
DO	(mg/L)	8	4	8.2	4	2	4.5
HRT	(h)	7.4	12	6	12	12	12
SRT	(d)	8.32	1	23.0	9.85	4.81	15

Table 2 | Influent and effluent COD (total and readily biodegradable) and BOD_5 concentrations in the overall experimental period

	Inlet			Outlet					
				HMBBR			AS		
	TCOD (mg/L)	rbCOD (mg/L)	BOD_5 (mg/L)	TCOD (mg/L)	rbCOD (mg/L)	BOD_5 (mg/L)	TCOD (mg/L)	rbCOD (mg/L)	BOD_5 (mg/L)
Min	201	61	130	10	7	1	10	9	2
Max	1,365	368	250	103	64	14	96	60	20
Average	409	128	167	63.1	29.2	9.2	58.8	29.8	9.7

In Table 2 the minimum, maximum and average values, for the overall experimental period and for TCOD, rbCOD and BOD_5 are reported.

In Figure 3a the inlet and outlet TCOD concentrations for the two systems are shown. In spite of the sensible variability of the inlet TCOD, characterized by a maximum peak concentration of 1,350 mg TCOD/L, the effluent TCOD concentrations are almost constant assuming an average value of approximately 80 mg/L for both systems. It is important to highlight that the TCOD concentrations at the outlet are always under the Italian Standard limit equal to 125 mg TCOD/L. The good behaviour of the two systems is also shown in terms of removal efficiency (Figure 3b). In particular, both systems showed good removal efficiencies in each experimental phase, except in the period ranging from the 27th of February to the 12th of March, probably related to a sharp decrease in the inlet COD concentration. The average TCOD removal efficiencies for the HMBBR and the AS are very similar with average values of 82.7 and 83.3% respectively in the overall experimental period. In Figure 3c and 3d, respectively, the inflow and outflow rbCOD as well as the correspondent removal efficiencies are shown. More specifically, the average rbCOD removal efficiencies are 74.5 and 73.6%, respectively, for the

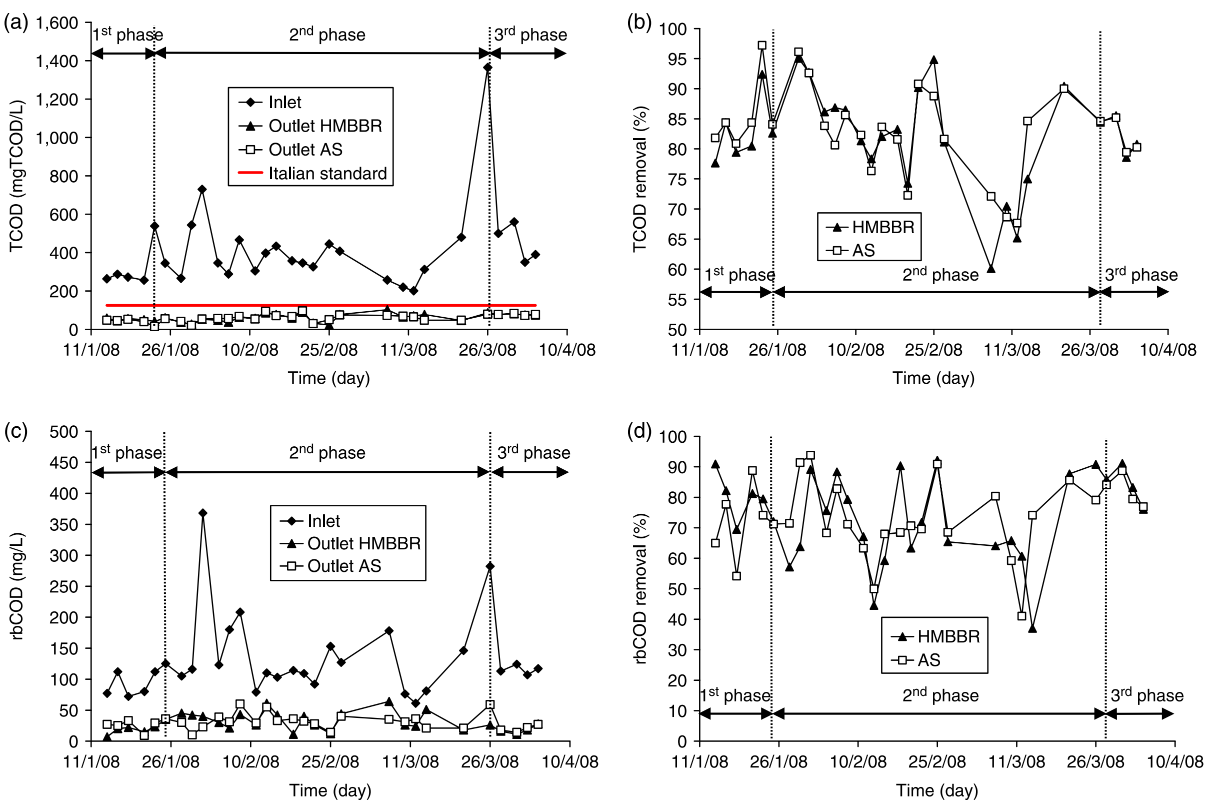

Figure 3 | Inlet and outlet TCOD concentrations (a) and removal efficiencies; (b) inlet and outlet rbCOD concentrations; (c) and removal efficiencies; (d) for the two lines.

HMBBR and for the AS system. In particular, in the first and in the third phase, both lines showed the same removal efficiency in terms of TCOD, with an average value of 82.6%; such result shows that the attached biomass basically does not provide an extra effective contribution to the TCOD removal; indeed, although the total biomass in the HMBBR system is higher respect to the AS one, due to the contribution of the attached biomass, the efficiencies are comparable. As will be better discussed in the following, the suspended biomass concentration has been kept almost equal in the two lines and therefore the HMBBR biomass concentration is always higher than the AS one due to the attached biomass contribution.

Referring to the rbCOD, the HMBBR system showed a better performance than AS line in the first and latter phase, with average removal efficiencies of 82.16 and 76.8% respectively. In this case, the attached biomass gave a sensible contribution, suggesting that the rbCOD is removed on the basis of the total biomass amount in the reactor.

Further, the higher removal capacity of the rbCOD operated by the HMBBR system respect to the AS and on the other hand the equal TCOD removal, lead to conclude that the particulate COD is less removed by the HMBBR system. This result suggests that a reduction of the hydrolysis and bioflocculation capacity that is generally operated by the suspended biomass (Andreottola *et al.* 2000) takes place. This reduction is likely due to the presence of the carrier that reduces the floc dimensions, as addressed by other authors (Christensson & Welander 2004). Although such result is reasonable it deserves to be confirmed in the future by rheological analysis of the floc structure.

During the second experimental phase, the two systems showed almost equal removal performances; in terms of TCOD, the average removal efficiency was almost 82% for both lines, while for the rbCOD the removal efficiency was 70 and 72% for HMBBR and AS respectively. It has to be stressed that the HMBBR system in this phase is characterized by an influent organic load that is approximately two times higher, and by a half hydraulic retention time, respect to the AS one. These results suggest that the effectiveness of the HMBBR system is in the case of high organic loads corresponding to overloading conditions for the traditional AS.

Concerning the BOD_5, the average effluent concentration were lower than 10 mg BOD_5/L for the two lines (well within the Italian Standard limits), with average removal efficiencies in the overall period higher than 94% for both systems; more specifically, in the first and third experimental phase, the percentage removal was almost 93% for both lines, while in the second phase it was as high as 95% for the two lines; this result is a confirmation of the fact that the behaviour of the HMBBR system was really good, even after the influent hydraulic load, and consequently the organic one, was increased. In Figure 4, the inlet and outlet BOD_5 concentrations (Figure 4a) and the BOD_5 removal performances (Figure 4b) for the two lines are reported; it can be noticed from Figure 4a that the effluent BOD_5 concentrations were almost constant in the overall experimental period, despite the sensible variability of the influent concentration. Further, the BOD_5 concentrations at the outlet of both lines were always lower than the imposed Italian Standard limit of 25 mg BOD_5/L.

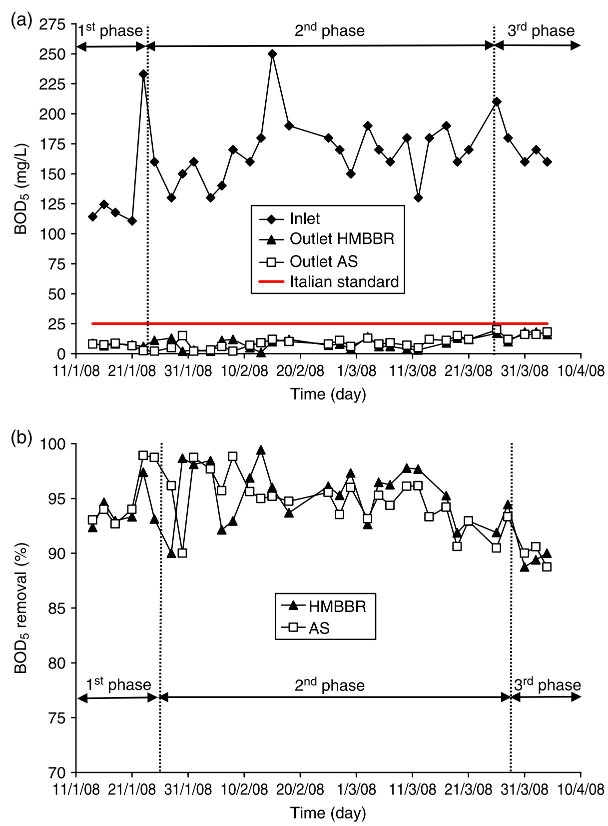

Figure 4 | BOD_5 concentrations at the inlet and outlet of the two systems (a) and removal efficiencies; (b) for the two lines.

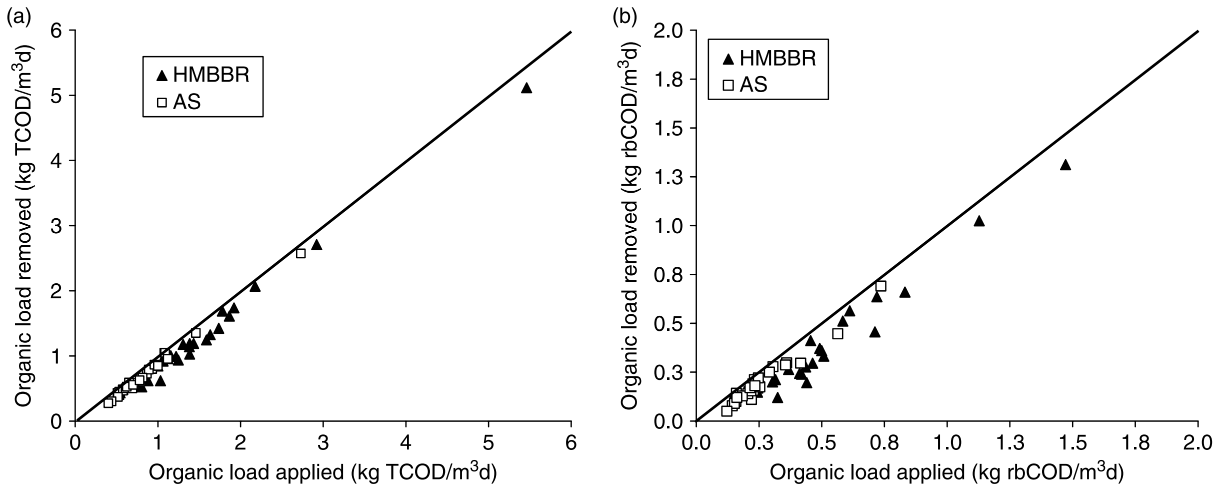

Figure 5 | TCOD and rbCOD, respectively, (a) and (b), organic loads applied and removed.

In Figure 5 the organic loads applied and removed have been reported both in terms of TCOD (Figure 5a) and in terms of rbCOD (Figure 5b). The experimental points of the both systems are really close to the bisector line, which indicates a 100% removal efficiency. Due to the fact that the HMBBR organic load was increased in the second phase, it is evident the high treatment ability of this kind of process, able to maintain very good removal efficiencies, even working with a hydraulic and organic load that is double. Indeed, even with inlet organic loads as high as 5.5 kg TCOD/m^3 d (Figure 5a) the hybrid line showed very good removal efficiency values, higher than 80%, while referring to the rbCOD, the system showed a good behaviour also with load as high as 1.5 kg rbCOD/m^3 d (Figure 5b). The maximum organic loads applied to the activated sludge control line were 2.8 kg TCOD/m^3 d and 0.8 kg rbCOD/m^3 d in terms of, respectively, TCOD and rbCOD.

This results are in good accordance with previous studies (Jianlong *et al.* 2000), suggesting that it can be advantageous to load hybrid systems at high rates, since the removal efficiency does not decrease significantly and there probably is a more efficient utilization of the substrate.

Referring to the biomass concentration, as previously explained, the TSS concentration was maintained as equal as possible in the two lines, in order to better understand the contribution of the attached biomass in the removal process. In Figure 6a the TSS concentrations for the two lines along with the attached biomass concentration is shown. The biofilm concentration in the first phase of the study was almost equal to the TSS concentration; in the period from the 30th of January to the 6th of February,

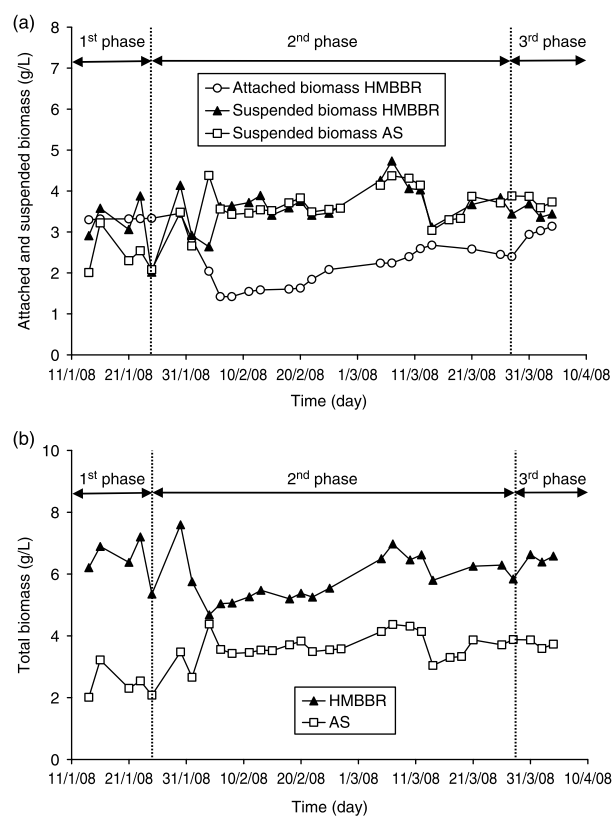

Figure 6 | Attached and suspended biomass in hybrid reactor (a) and total biomass in the two lines (b).

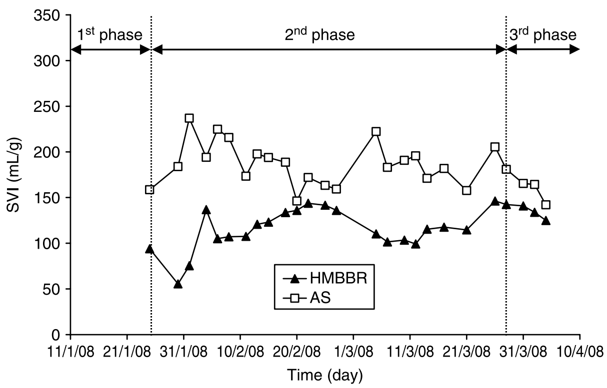

Figure 7 | Sludge Volume Index values in the two lines.

a sharp decrease in the attached biomass concentration was recorded, reaching a concentration of 1.4 g/L. Such a result was maybe related to a detachment process occurring inside the biofilm; in the following days, the attached biomass concentration slowly increased again reaching a final value of 3.14 g/L, almost equal to the suspended biomass one. In Figure 6b, the total biomass concentration for the HMBBR and the AS line is reported. It can be easily noticed that the total biomass in the HMBBR line is higher compared to that in the AS line. In particular, the HMBBR and AS systems are characterized by an average total biomass values, respectively, the former of almost 6 and the latter 3.4 g TSS/L thus allowing a very high treatment ability for the HMBBR process, but without significantly increase the solids load to the final clarifier.

Concerning the sludge settleability properties of the two systems, in Figure 7 the SVI values for the entire experimental period as well as for the two systems have been reported. The SVI values of the HMBBR are always lower respect to the AS ones highlighting a better sludge settleability despite the fact that the HMBBR was fed with a higher organic load. 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.

Ammonia and total nitrogen removal

In Table 3, the minimum, maximum and average concentrations, for ammonium and nitrate, are reported. In Figure 8a the inlet and outlet ammonium concentrations for the two lines are shown; on the other hand, in Figure 8b the corresponding removal efficiencies are reported. The experimental results showed that both the two lines behaves a good removal performances, in the overall experimental period, referring to the ammonium nitrogen oxidation; the average removal efficiency for the AS line was almost 90%, with an average effluent concentration of 3 mg NH_4-N/L, while the removal efficiency in the HMBBR system was as high as 95%, with average effluent concentration lower than 2 mg NH_4-N/L. Only in the period ranging from the 11th of February to 10th of March three sensible decreases in the removal efficiency were recorded for both the lines. However, this result is related to the fact that the air flow was intentionally decreased to enhance denitrification in the anoxic tank. In the last days of March (Figure 8a) there was a noticeable increase in the inlet ammonium concentration, resulting in an immediate increase in the activated sludge system effluent ammonium concentration, while the ammonium effluent concentration was not influenced in the HMBBR line; this results is a confirmation of the robustness of the HMBBR systems, which are well able to resist shock-loading. Focusing on the different phases, the HMBBR line showed better nitrification performances in all the three phases, even in the second one, characterised by higher organic and

Table 3 | Influent and effluent NH_4-N, NO_3-N and TN concentrations in the overall experimental period

	Inlet			Outlet					
				HMBBR			AS		
	NH_4-N (mg/L)	NO_3-N (mg/L)	TN (mg/L)	NH_4-N (mg/L)	NO_3-N (mg/L)	TN (mg/L)	NH_4-N (mg/L)	NO_3-N (mg/L)	TN (mg/L)
Min	10	0.01	22	0.01	3.8	3.8	0.01	2	2.6
Max	60	1.1	121	10.65	21	24.6	22.4	11.4	27.4
Average	26	0.46	40.1	1.91	11.6	14.9	2.79	7.33	11.6

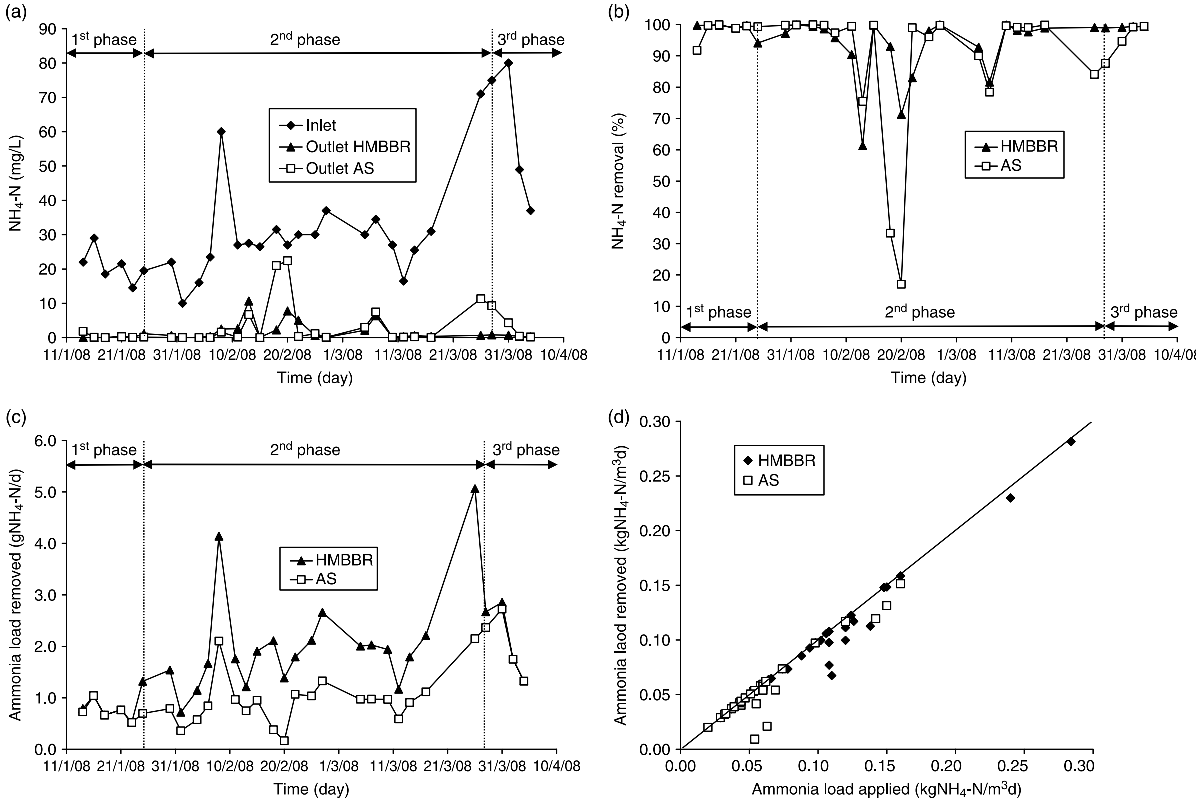

Figure 8 | Inlet and outlet ammonium concentration (a) removal efficiencies; (b) ammonium loads removed; (c) and ammonium loads applied and removed; (d) in the two lines.

ammonium loads. More specifically, in the first and in the third phase, the average removal efficiencies were 99.4 and 96.7% for the HMBBR and the AS, respectively. Despite the higher loads, a sensible contribution from the attached biomass was recorded in the second phase, when the average removal efficiencies were 93 and 88% for HMBBR and AS, respectively. In particular, it can be noticed that, in the second phase, when the HRT in HMBBR reactor was only 6 h, and 12 h in the AS line, the HMBBR line was able to oxidize a much higher ammonium load than the AS system, with average ammonium loads removed equal to 1.8 and 1.04 g NH_4-N/d in the HMBBR and AS line respectively (Figure 8c). This result is probably related to the fact that the biofilm attached on the carriers enhanced the increase of the overall sludge age, leading to a sharp growth in the number of nitrifying bacteria in the reactor, thus allowing better nitrification performances, even if it was expected that the higher organic load should actually lead to a strong competition between autotrophic and heterotrophic bacteria for the dissolved oxygen, thereby inhibiting nitrification activity. With regards to the influence of ammonium load in the removal process (Figure 8d), even with an influent load up to 0.28 kg NH_4-N/m^3 d, the HMBBR system showed a removal efficiency close to the 100% (the bisector line), while the maximum influent ammonium load in control system was equal to 0.16 kg NH_4-N/m^3 d. Such result demonstrates the very high nitrifying capacity of a HMBBR system confirming the results obtained in previous studies reported in the technical literature (Münch *et al.* 2000). Referring to the TN removal, the average removal efficiency was better in the AS system. Indeed, while in the first and third phase the TN removal percentage was similar in the two lines, it has to be noticed that during the second phase, due to the increase of the inflow rate and therefore a corresponding nitrate recycle in the HMBBR line, the nitrate mass transferred to the anoxic tank was much higher; as consequence, the anoxic tank resulted overloaded and thus unable to guarantee the same removal efficiencies showed in the first phase. Furthermore, the better AS denitrification activity than the HMBBR one was probably emphasized by the scarce anoxic conditions of the HMBBR denitrification tank. Indeed, due to the fact that the oxygen concentration in the HMBBR system has to be kept higher than the AS one due to the presence of the biofilm (possible diffusion issue), the oxygen mass transferred by nitrate recycle is higher respect to the AS one. In particular, the oxygen concentration was, respectively, 8 and 4 mg/L for the HMBBR and AS system; therefore the HMBBR oxygen mass transferred by the nitrate recycle is two times higher than the AS one. Such oxygen mass contributes negatively to the establishment of the anoxic conditions in the denitrification tank. Such aspect is emphasized during the second phase during which the influent flow is increased and therefore the recycled oxygen mass become four times the AS one. The effluent TN concentrations, as average values during the whole experimental period, were 14.9 and 11.6 mg TN/L for the HMBBR and the AS line respectively, while, on the other hand, the Italian Standards are 15 mg TN/L for plant capacity in the range 10,000–100,000 PE and 10 mg TN/L for plant capacity higher than 100,000 PE. In this last situation, both lines would not be able to meet the limits at the outlet.

In the Figure 9a the TN removal efficiency is reported, while in Figure 9b the effluent nitrate concentrations for the two lines are shown. It can be noticed from Figure 9a that the TN removal efficiency was almost the same for the two lines in the first and in the third phase, while in the second one, it was significantly higher in the AS line. This result is confirmed in Figure 9b, where it can be noticed that the nitrate effluent concentration in the HMBBR line was higher than in the AS line.

The higher HMBBR nitrate concentration respect to the AS system is likely not only due to the scarce anoxic conditions discussed above, but also to the higher nitrification capacity of the HMBBR system. Indeed, looking at the first and third phase, the higher nitrate concentration of the HMBBR system respect to the AS one can be only justified by a higher nitrification capacity of the HMBBR. Indeed, the two systems have the same denitrification capacity. During the second phase such results is further emphasized due to the increasing of the flow.

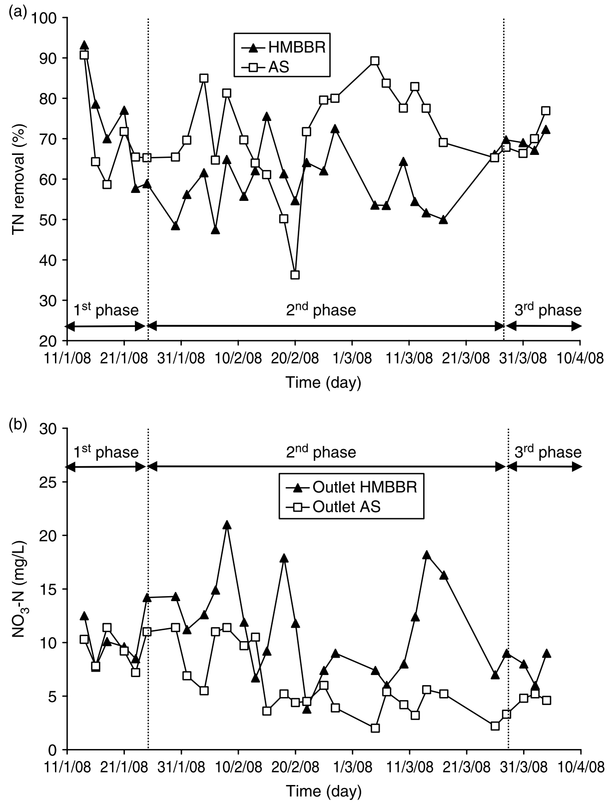

Figure 9 | Total nitrogen removal efficiencies (a) and NO_3-N concentrations; (b) at the outlet for the two lines.

However, it has to be stressed that, despite this negative aspects, the HMBBR line showed a good behaviour in terms of TN removal also in the second phase, with average removal efficiency equal to 60%.

CONCLUSIONS

An experimental gathering campaign on a pilot-scale HMBBR reactor was carried out. The main aim of the study was to gain insight about the performances of the HMBBR process; to achieve this goal, the traditional AS process has been compared to the HMBBR process. The experimental results enable us to address the following considerations.

- In the first and latter phase, the performances of the two systems were almost comparable, in terms of TCOD, suggesting that the attached biomass did not give an extra contribution to the removal process. On the other hand, in the second phase, the HMBBR showed a better performance respect to the AS one suggesting an employment of such systems for the case of high load WWTP.

- In terms of rbCOD, the HMBBR system showed a better performance than AS line in the first and latter phase, with average removal efficiencies of 82.2 and 76.8% respectively. The lower particulate COD removal operated by HMBBR, suggests that a reduction of the hydrolysis and bioflocculation capacity occurred in the HMBBR system; this reduction is probably related to the presence of the carriers in the reactor that can obstacle the formation of flocs.
- Referring to the sludge settleability properties of the two systems, the SVI values of the HMBBR were always lower respect to the AS ones highlighting a better sludge settleability; the suggestion is that the number of filaments was probably moderate, thus inhibiting the creation of networks typical of bulking sludge.
- In terms of ammonium removal, the experimental results showed that HMBBR line had a really good removal performances, better than the AS one, in all the three phases, even in the second one, characterised by higher organic and ammonia load values. This result is probably related to the fact that the biofilm attached on the carriers enhanced the increase in the overall sludge age, thus allowing better nitrification performances, and the suggestion is that this kind of process is really suitable for the upgrading of existing AS plants that cannot sustain a stable nitrification process all year-round. Nevertheless, in terms of TN, the removal performances were similar in the first and third phase, while in the second phase the AS line showed better performances; this result is probably related to the higher nitrification ability of HMBBR line, the higher nitrate mass transferred to the anoxic tank and to the fact that the higher oxygen mass recycled in the HMBBR denitrification tank contributes negatively to the establishment of the anoxic conditions in such reactor.

The obtained results deserve to be confirmed also taking into account that for the second phase the HMBBR was likely overloaded with respect to the anoxic unit. Indeed, the up-grading of both aerobic tank and the anoxic one should be detected in order to gaining insight on possible enhancement of the TN removal.

Finally, it has to be stressed that the hydraulic load should also be increased in the AS line during the second experimental phase, in order to better outline the differences between the two systems also in these operative conditions. Indeed, although it is possible to suppose a weak treatment ability for a classical activated sludge system in presence of high hydraulic and organic load (2nd phase), it deserves to be better addressed by experimental analysis. This latter is still in progress and will regard a future development of the research.

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