Efficiency of wastewater treatment in SBR and IFAS-MBSBBR systems in specified technological conditions
K. Sytek-Szmeichel, J. Podedworna and M. Zubrowska-Sudol

ABSTRACT

The objective of this study is to compare wastewater treatment effectiveness in sequencing batch reactor (SBR) and integrated fixed-film activated sludge–moving-bed sequencing batch biofilm reactor (IFAS-MBSBBR) systems in specific technological conditions. The comparison of these two technologies was based on the following assumptions, shared by both series, I and II: the reactor’s active volume was 28 L; 8-hour cycle of reactor’s work, with the same sequence and duration of its consecutive phases; and the dissolved oxygen concentration in the aerobic phases was maintained at a level of 3.0 mg O₂/L. For both experimental series (I and II), comparable effectiveness of organic compound (chemical oxygen demand (COD)) removal, nitrification and biological phosphorus removal has been obtained at levels of 95.1%, 97% and 99%, respectively. The presence of the carrier improved the efficiency of total nitrogen removal from 86.3% to 91.7%. On the basis of monitoring tests, it has been found that the ratio of simultaneous denitrification in phases with aeration to the total efficiency of denitrification in the cycle was 1.5 times higher for IFAS-MBSBBR.

Key words | activated sludge, biofilm, IFAS-MBSBBR, nutrient removal, SBR

INTRODUCTION

Analysis of the literature shows many directions of research on nutrient removal from municipal wastewater, both in batch and continuous flow systems. One advantage of sequencing batch reactors (SBR) compared to continuous flow systems is their ability to remove carbon, nitrogen and phosphorus in one tank without the need for a secondary settling tank and without recirculation of wastewater and sludge. Additional gains include a much smaller need for land area, diminished sensitivity to changes in the quantity and quality of the reactor influent in comparison to continuous flow systems, easier control of the treatment process and smaller energy consumption (Pan et al. 2013; Wang et al. 2015).

The enhancement of conventional SBR technology, using biomass in the form of activated sludge in one tank with biofilm growing on moving carriers (integrated fixed-film activated sludge–moving-bed sequencing batch biofilm reactor (IFAS-MBSBBR)), additionally allows for elimination of the problem of sludge bulking, the independence of biomass retention time from wastewater hydraulic retention time and the possibility of receiving a relatively larger contamination load (without changing the reactor volume and without deterioration of treatment effectiveness) or reducing the volume of designed bioreactors (compared to that used for SBR) (Ødegaard 2009; McQuarrie & Boltz 2011). Moreover, some unexpected effects of the immobilization of biomass were demonstrated, entailing the fundamental difference between the physiological characteristics of cells suspended in wastewater and those attached to the carriers. It was proved that immobilized microorganisms may exhibit several times greater metabolic activity than suspended cells (Grady et al. 1999).

In activated sludge floc, as well as in the biofilm stratification of oxygen (aerobic/anoxic conditions), it is possible to achieve that which enables the simultaneous run of specific processes (nitrification, denitrification, P-PO₄ uptake) despite the presence of dissolved oxygen in the treated wastewater (Jamal Khan et al. 2011; Han et al. 2012). This stratification in the case of activated sludge is limited only by the size of the flocs, the concentration of oxygen in the wastewater and the availability of sufficient organic carbon substrate. However, in the biofilm, an additional factor

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limiting the depth of the oxygen layer is the more difficult oxygen diffusion into the interior of the biofilm (Rahman et al. 2009; Ning et al. 2014). This is reflected by the required level of oxygen concentration, higher than in the case of activated sludge technology (Zinatizadeh & Ghaytooli 2015). To ensure highly effective nitrification in pure moving bed technology, a concentration of at least 5 mg O₂/L is required (Rother & Cornel 2004; Pal et al. 2012), which is a major drawback of the MBSBBR technology.

Based on previous results of studies, it has been hypothesized that the differences in the rate and depth of diffusion of oxygen and substrates and/or products of biochemical changes in activated sludge and biofilm may influence the paths of nutrient removal in biological reactors depending on the biotope formed by growing biomass. To prove this hypothesis, it is necessary to conduct testing in two reactors operating under the same working parameters (such as active volume, characteristics and the amount of influent, reactor cycle regime and oxygen concentration in the aerobic phases) and differing only in the form in which the biomass develops.

Studies conducted on wastewater treatment in SBR or MBSBBR are usually independent and do not exhaust the issue of the performance of various processes (removal of carbon compounds, nitrification, denitrification, release and uptake of orthophosphate), especially in terms of comparing technology in which biomass develops in suspended form and/or biofilm growing on a moving bed.

The objective of this study is to compare the effectiveness of wastewater treatment and to identify possible differences in nutrient removal performance in SBR and IFAS-MBSBBR systems under specific technological conditions. The choice of SBR and IFAS-MBSBBR (not MBSBBR!) has been dictated by the ability to perform this experiment with a balanced concentration of oxygen for both reactors. In the case of using MBSBBR in the study, the required level of oxygen concentration for pure moving bed technology would be far too high for activated sludge in SBR.

**METHODS**

The study consisted of two series. The effectiveness of wastewater treatment was tested in series I in SBR with activated sludge and in series II in IFAS-MBSBBR in which biomass developed as activated sludge and biofilm formed on the surface of moving carriers.

The comparison of these two technologies was based on the following identical assumptions for series I and II: the same working volume of the reactors, an 8-hour cycle in reactors with the same sequence and duration of successive phases, maintenance of the same level of dissolved oxygen in both reactors in aerobic phases of the cycle, characteristic of the reactor influent is constant and the same for both series.

Each of the 2-month long series was carried out in a laboratory SBR with a working volume of 28 L (Figure 1). The SBR (series I) was inoculated with activated sludge from a full biological nutrient removal wastewater treatment plant (WWTP), which guaranteed the presence of nitrifiers, denitrifiers and PAOs (phosphorus accumulating organisms) in the biomass. The sludge originating from SBR (series I) became in turn an inoculation for IFAS-MBSBBR. Series I was preceded by a 30-day period of acclimation, whereas in the case of series II the acclimation period lasted 6 months due to the need for biofilm development on a moving bed.

The cycle of both reactors was 8 hours (three cycles per day). Each full reactor cycle consisted of the following phases: I unaerated (I Unaer.) – 90 min., I aerated (I Aer.) – 160 min., II unaerated (II Unaer.) – 40 min., II aerated (II Aer.) – 120 min., sedimentation (Sed.) – 60 min., decanting (Dec.) – 10 min. The reactors were thoroughly mixed in both aerated and unaerated phases (Figure 1).

In each cycle, the reactor was fed with 10 L (two-thirds of the volume in phase I Unaer. and the remaining one-third in phase II Unaer.) of synthetic raw wastewater prepared once a day on the basis of peptone (219 mg/L), starch (75 mg/L), glucose (75 mg/L), glycerol (80.5 mg/L), ammonium acetate (240 mg/L), Na₂HPO₄.12H₂O (25.2 mg/L) and KH₂PO₄/L (7.5 mg/L). The composition of raw wastewater was the same in both series (chemical oxygen demand (COD): 668 ± 32.5 mg O₂/L, total nitrogen: 3.03 mg N/L, N-NH₄: 0.42 mg P-PO₄/L, total phosphorus: 40.8 ± 2.24 mg N-NH₄/L; P-PO₄: 7.98 ± 0.42 mg P-PO₄/L, pH: 7.7 ± 0.3).

The concentration of oxygen in aerobic phases of the cycle was maintained at 3.0 mg O₂/L by an automatic control system with an optical oxygen probe Oxymax COS61D with a Liquiline CM442 (Endress-Hauser) controller. The operations of the mixers, the dosing pump and the solenoid valve used for the decanting of treated wastewater (decanting factor of 0.4) were controlled using DreamSpark Premium software based on the SCADA system. The reactors were operated in an air-conditioned room while the temperature was maintained at 18 °C.

As a carrier of biofilm in IFAS-MBSBBR (series II) a EvU-Perl moving bed was used (an active surface of 600 m²/m³ and density of 1.1 kg/L) occupying 25% of the working volume of the reactor, i.e. approximately 7 L (Figure 1).
In both reactors, the sludge age (SRT) was maintained at 10 days and the concentration of activated sludge averaged $3.05 \pm 0.23\text{ g/L}$ and $2.75 \pm 0.37\text{ g/L}$ for series I and II, respectively.

**Chemical analysis**

The scope of analytical testing included the following:

1. Changes in the characteristics of the influent and effluent (COD, total Kjeldahl nitrogen (TKN), N-NH$_4^+$, N-NO$_2^-$, N-NO$_3^-$, total phosphorus (TP), P-PO$_4^{3-}$, pH, alkalinity).

2. Monitoring tests of the treatment cycle involving multiple analytical tests of changes in contaminant indicators in the treated wastewater (range as in the characteristics of the influent and effluent without TP). Sampling took place at the beginning and at the end of each phase and/or after the intermediate stages of the phase. Each sample, before being analyzed, was filtered through a filter with a pore diameter of 0.45 $\mu$m immediately after collecting.

All chemical analyses were performed in duplicates and in accordance with *Standard Methods* (APHA, AWWA & WEF 1998).

**RESULTS AND DISCUSSION**

**Treatment effectiveness**

As shown in Table 1, both in SBR (Series I) and IFAS-MBSBBR (Series II) during the whole study a high effectiveness of organic contaminants removal was achieved (95.1%). The value of COD in the final effluent did not exceed 50 mg O$_2$/L.

In both types of reactors, a high and steady effectiveness of biological phosphorus removal was also observed which, expressed as a decrease in orthophosphate concentration in relation to raw wastewater, stood at 98.9% and 99.3% for SBR and IFAS-MBSBBR, respectively. These values corresponded with the decrease in P-PO$_4^-$ concentrations in effluent from the average level of influent to the reactor equal to 7.98 mg P-PO$_4^-$/L to the level of effluent in the each of them below 0.2 mg P-PO$_4^-$/L.

Despite the very high effectiveness of biological orthophosphate uptake, the remaining total phosphorus concentration in the effluent from SBR ($1.29 \pm 0.63\text{ mg P/L}$) was higher than in the treated wastewater in IFAS-MBSBBR ($0.69 \pm 0.46\text{ mg P/L}$). The most likely reason for this was the possible presence of dissolved and/or colloidal...
organic phosphorus fractions in the SBR effluent, resulting from the processes of suspended biomass decomposition, running intensively at an applied level of oxygen concentration of 3.0 mg O₂/L.

The data summarized in Table 1 also demonstrate that both series were characterized by a highly effective process of ammonia nitrogen oxidation (99.5%), which allowed for obtaining N-NH₄ concentrations in the effluent from the reactors of approximately 0.2 mg/L. However, a difference in total nitrogen removal effectiveness was observed. A higher reduction of total nitrogen load was achieved in IFAS-MBSBBR where the biomass grew not only in suspended form but also in the form of biofilm.

Table 1 | Characteristics of the reactor effluent in series I (SBR) and II (IFAS-MBSBBR)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Series I (SBR)</th>
<th>Series II (IFAS-MBSBBR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD [mg O₂/L]</td>
<td>32.8 ± 6.74</td>
<td>32.4 ± 9.71</td>
</tr>
<tr>
<td>η [%]</td>
<td>95.1 ± 1.05</td>
<td>95.1 ± 1.39</td>
</tr>
<tr>
<td>TP [mg P/L]</td>
<td>1.29 ± 0.63</td>
<td>0.69 ± 0.46</td>
</tr>
<tr>
<td>η [%]</td>
<td>88.3 ± 5.24</td>
<td>93.4 ± 4.48</td>
</tr>
<tr>
<td>PO₄³⁻ [mg P-PO₄³⁻/L]</td>
<td>0.09 ± 0.04</td>
<td>0.06 ± 0.02</td>
</tr>
<tr>
<td>η [%]</td>
<td>98.9 ± 0.50</td>
<td>99.3 ± 0.25</td>
</tr>
<tr>
<td>TN [mg N/L]</td>
<td>9.67 ± 1.51</td>
<td>5.68 ± 1.33</td>
</tr>
<tr>
<td>η [%]</td>
<td>86.3 ± 2.13</td>
<td>91.7 ± 2.08</td>
</tr>
<tr>
<td>TKN [mg N/L]</td>
<td>2.52 ± 1.09</td>
<td>1.68 ± 0.81</td>
</tr>
<tr>
<td>η [%]</td>
<td>96.4 ± 1.55</td>
<td>97.5 ± 1.23</td>
</tr>
<tr>
<td>N-NH₄⁺ [mg N-NH₄⁺/L]</td>
<td>0.20 ± 0.08</td>
<td>0.19 ± 0.10</td>
</tr>
<tr>
<td>η [%]</td>
<td>99.5 ± 0.19</td>
<td>99.5 ± 0.24</td>
</tr>
<tr>
<td>N-NOₓ⁻ [mg N-NOₓ⁻/L]</td>
<td>7.15 ± 0.83</td>
<td>4.01 ± 0.96</td>
</tr>
</tbody>
</table>

The remaining N-NOₓ⁻ concentration in the treated wastewater in IFAS-MBSBBR ranged from 2.81 to 5.41 (4.01 on average) mg N-NOₓ⁻/L, whereas in the effluent from SBR it fluctuated in the range of 5.79–8.39 with a mean value of 7.15 mg N-NOₓ⁻/L. The average effectiveness of the denitrification process was 86.3% and 91.7% in series I and II, respectively.

Results of monitoring tests

Monitoring tests of selected treatment cycles involving changes in the quality of wastewater characteristics control in consecutive phases of the cycle enabled a comparison of the removal of contaminants in two types of batch reactors – a SBR with activated sludge and a hybrid batch reactor in which biomass developed both in the form of activated sludge and biofilm.

Figures 2–4 illustrate average phase efficiencies of the following processes: the removal of organic compounds (E COD), nitrification (E nit) and denitrification (E den), which, related to the phase load (L) with a compound being a substrate in the process, has enabled determination of percentage phase effectiveness (η) of the processes listed above. Figure 4 shows the average phase efficiency of orthophosphates release (E UP) and uptake (E UP) in successive phases of the treatment cycle.

The values of phase efficiency for each of the analyzed processes and the values of the phase contamination load were determined based on the volume of the reactor filling in order to compare them with the results obtained in the
hybrid MBSBBR. In the case of IFAS-MBSBBR, the dry weight of biofilm was not determined, firstly due to the limited number of carriers in the moving bed reactor, secondly due to the fact that the reuse of these carriers from which biofilm would be removed (to determine its dry weight) would be impossible. The difference in the loads of chemical compounds specific for each biochemical process was calculated according to Podedworna & Zubrowska-Sudol (2012).

According to the data shown in Figure 2, in both series the organic compounds (COD) were removed from the wastewater mainly in unaerated phases. The percentage of organic compounds removed in unaerated phases in relation to the total efficiency of removal of organic contaminants in the cycle averaged 84.8% (SBR) and 87.8% (IFAS-MBSBBR).

The maximum efficiency of organic compounds removal occurred in all the analyzed cycles in I Unaer. phase due to the availability of the highest load of organic compounds in this phase. The low efficiency of organic compounds removal under aerobic conditions indicates that dissolved organic compounds remaining after the unaerated phases belonged...
to a hardly biodegradable fraction. In both types of reactors, nitrification took place with a similar total efficiency in the cycle of 22.5 mg/L and 21.6 mg/L for SBR and IFAS-MBSBBR, respectively (Figure 3). A slightly higher phase efficiency of nitrification in I Aer. phase for SBR than for IFAS-MBSBBR resulted from a higher reactor load of TKN remaining in the reactor after the previous cycle, which can also be seen by analyzing TKN in the effluent (Table 1).

The values of N-NO₃ phase load and the efficiency and effectiveness of the denitrification process in successive phases of the cycle for SBR and IFAS-MBSBBR are shown in Figure 4. In both series, the process of denitrification occurred in unaerated phases and aerobic phases, simultaneously with nitrification. The highest denitrification effectiveness (over 80%) was always observed in unaerated phase I when the lowest N-NO₃ load occurred accompanied by the highest COD load.

In the aerobic phases, under comparable values of N-NO₃ in both reactors, far larger and more significant effectiveness of simultaneous denitrification was achieved in IFAS-MBSBBR (58–60%) than in SBR (26–30%), which is probably associated with the presence of biomass in the form of biofilm, where, with the same value of dissolved oxygen concentration (3.0 mg O₂/L), a relatively larger anoxic zone can be obtained due to hindered oxygen diffusion into its inner layers. The presence of zones in the biofilm to which oxygen does not diffuse (despite its presence in the treated wastewater) was documented using a dissolved oxygen (DO) microelectrode (Ning et al. 2014), showing at the same time that aerobic oxidation mainly occurred above the middle of the biofilm during the aeration stage. This means that in series II (IFAS-MBSBBR) nitrates (a product of nitrification running in the outer layers of the biofilm) could diffuse into its depth where, with the use of intracellularly accumulated organic carbon, they were reduced to nitrogen gas. A similar hypothesis was formulated by Lim et al. (2011). Also, Jin et al. (2012) obtained simultaneous nitrification and denitrification (SND) in the biofilm. It should be emphasized that the reactors in the cited studies worked under a high concentration of oxygen of 6–8 mg/L and still achieved a very high efficiency of SND (81.7–95.2%), which offers additional evidence of the ability to create anoxic zones in the biofilm. Moreover, Lo et al. (2010) compared the efficiency of SND in batch tests in a hybrid system and independently in a system with activated sludge only and biofilm only found that simultaneous denitrification is most favored by a hybrid system in which the sludge uses a large amount of oxygen, resulting in low concentrations of dissolved oxygen and, consequently, highly effective denitrification in the biofilm. SND was 75.9% for the hybrid system and 41.0% and 16.7% for the biofilm and suspended sludge system, respectively. SND effectiveness in aerobic phases at a level close to 30% (obtained in series I – SBR with activated sludge at the analyzed oxygen concentration level of 3 mg O₂/L) remains in some conflict with the results of Tain et al. (2011) which showed that, in conventional SBR systems, SND was inhibited when DO concentration was over 1.5 mg O₂/L. However, other studies have shown that the efficiency of SND in activated sludge floc depends not only on the oxygen concentration in wastewater but also on the floc size and the availability of sufficient organic carbon substrate (Pochana & Keller 1999; Zhu et al. 2008). Third et al. (2005), in a study on SND using stored substrate (polyhydroxybutyrate (PHB)) as the electron donor in SBR, stated that the nitrogen removal performance at full aeration (DO concentration >5mg/L) resulted only in a small percentage of SND (31%). It thus appears that the SND efficiency obtained for activated sludge in series I (the aerobic phases after the unaerated phases in which organic matter was accumulated intracellularly) can be considered comparable to the results of Third et al. (2005).

Analyzing the data shown in Figure 5, it can be seen that the typical biological phosphorus removal process occurred only in I Unaer. phase and I Aer. phase. The high efficiency of P-PO₄ release in I Unaer. phase (approximately 32.6 and 28.6 mg P-PO₄/L in series I and II, respectively) was caused by the high value of the organic compounds load (Figure 2) and the low load of N-NO₃ (Figure 4) during this phase.

Considering the fact that more than 80% of organic compounds expressed as COD were removed from wastewater in unaerated phases (Figure 2) with the concurrent release of orthophosphates (Figure 5), simultaneous denitrification occurring under aerobic conditions had to take place with the use of carbon compounds accumulated intracellularly, with PAOs the process of biological phosphorus removal. The presence of simultaneous denitrification in aerobic phases and the observed low efficiency of organic compounds removal in these phases suggests that the uptake of orthophosphates occurred using both oxygen and N-NO₃ as electron acceptors. It was found much earlier that when nitrate and PHA-rich sludge are present simultaneously (i.e. when the anoxic zone follows the anaerobic phase), simultaneous denitrification and P removal can be achieved. Denitrifying phosphorus removal occurs due to the capacity of at least a fraction of PAOs to use nitrate and/or nitrite as an electron acceptor for P removal instead of oxygen (Kerr-Jespersen & Henze 1995; Kuba et al. 1995). A higher efficiency of denitrifying phosphorus removal in IFAS-MBSBBR in comparison to SBR led to a reduction in organic carbon demand for nutrient removal. This is possible because, in this process, both a reduction in N-NO₃ and
the accumulation of orthophosphates occur at the same time and are carried out by a single group of heterotrophic microorganisms, DPAO (denitrifying phosphorus accumulating organisms) (Kuba et al. 1996).

In the hybrid IFAS-MBSBBR (in series II), the percentage share of simultaneous denitrification related to the total efficiency of the denitrification process in the cycle averaged 77.0%, while in the SBR it was significantly lower (44.2% – Figure 3). The increase in SND percentage in series II resulted from combining two biotopes in IFAS-MBSBBR – activated sludge and biofilm formed on a moving carrier. This phenomenon was also observed by Rodríguez-Hernández et al. (2014). The presence of larger anoxic zones in deeper layers of the biofilm determine the occurrence of processes of simultaneous denitrification and denitrifying phosphorus removal.

CONCLUSIONS

1. In SBR and IFAS-MBSBBR working under the same process conditions (8-hour cycle of reactor’s work, with the same sequence and duration of its consecutive phases, oxygen concentration in the aerated cycle of 3.0 mg O2/L, sludge age of 10 days), a comparable effectiveness of organic compounds (COD) removal, nitrification and biological phosphorus removal at levels of 95.1%, 97%, and 99%, respectively, have been obtained.

2. Despite the very high effectiveness of biological orthophosphates uptake, the remaining total phosphorus concentration in the effluent from SBR (1.29 mg P/L on average) was higher than in the treated wastewater in IFAS-MBSBBR (0.69 mg P/L), which may have been caused by decomposition of the suspended biomass intensively running at the applied level of oxygen concentration of 3.0 mg O2/L.

3. In IFAS-MBSBBR, a slightly higher average total nitrogen removal effectiveness was observed (91.7%; average N-NOx concentration equal to 4.01 mg N-NOx/L in the effluent) in relation to SBR (86.5%; 7.15 mg of N-NOx/L) with a significant difference in performance of the denitrification process. The presence of biomass in the form of biofilm created favorable conditions to conduct SND. The percentage of SND in the total efficiency of denitrification in the cycle was 66.0–86.7% for IFAS-MBSBBR and 39.9–52.7% for SBR.

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