Environmental assessment of an EBPR-SBR devoted to small populations

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Abstract

The European Water Directive 91/271/EEC introduced a series of measures for the purpose of protecting sensible areas against the emission of nutrients coming from Waste Water Treatment Plants (WWTP). However, there are environmental costs associated with attaining the required level of water quality such as greenhouse gases emissions from energy consumption. The goal of this study is to assess these environmental costs in an EBPR-SBR system for 45 population equivalent (p.e.). For that purpose three main environmental indicators have been estimated: the Global Warming Potential (GWP); the Eutrophication Potential (EP) and the Power Consumption (PC). Moreover, two different functional units (FU), one based on volume (m^3) and the other on eutrophication reduction (kg PO_4^{3-} removed) were used to further determine sustainability. In this case study, the EBPR-SBR-45p.e. showed a GWP of 150 kg CO_2/ kg $PO_4^{3-}{}_{removed}$, an EP of 13.6 equivalent gPO_4^{3-} /m^3 and a PC of 175 kWh/ kg $PO_4^{3-}{}_{removed}$. Those values are below the ones obtained for a conventional activated sludge system.

Keywords

Sequencing batch reactor (SBR), Global Warming Potential (GWP); Eutrophication Potential (EP)

INTRODUCTION

Aware of the problems associated with eutrophication of water bodies in Europe, the European Union is promoting, for more than two decades, policies to combat one of the main causes of this phenomenon, the discharge of urban waste water with high content of nutrients (Directive 91/271/EEC). For this reason, in recent years, a large number of wastewater treatment plants (WWTP) have incorporated in their flow-diagram specific units aiming at nutrients removal (nitrogen and phosphorus).

Nitrogen removal though biological reactions (nitrification-denitrification or ANNAMOX) are well-known processes and widely implemented in WWTPs. Meanwhile, phosphorous (P) has been removed through physicochemical processes traditionally. Nowadays, in most cases, physicochemical processes are being replaced by a biological process known as enhanced biological phosphorus removal (EBPR). EBPR involves cycling microbial biomass and influent wastewater through anaerobic and aerobic zones to achieve a selection of microorganisms with high capacity to accumulate polyphosphate intracellularly (Blackall et al., 2002). Those specific conditions are easily achievable in Sequencing Batch Reactors (SBR) which, actually, presents larger performances both in organic matter and nutrients removal than the conventional activated sludge system. The SBR has been widely applied for wastewater treatment because it is economical and its operating conditions are easily changed (Tsuneda et al., 2006). In fact, SBR systems are considered a suitable solution for wastewater treatment in small populations and decentralised areas (Puig et al., 2007; Aragon et al., 2011).

Conceptually, the WWTP help us to protect the environment, but in contrast to their main commissioned purpose, they can damage the environment through energy consumption, greenhouse gas emission, the utilization of chemicals, and some toxic material outcomes (Buyukkamaci, J., 2013). Given the need to achieve long-term sustainability, the objectives of urban water systems need to go beyond the protection of public health and receiving bodies. It is, therefore, necessary to reduce the impacts to natural resources, to optimize the use of energy and water, reduce waste generation and allow nutrients recycling in plants (Lundin M. *et al*., 2000).

In the last two decades a number of methodologies have been developed for evaluating the environmental sustainability of a product or process. Among them, Life Cycle Assessment (LCA) is a well-established procedure quantifying inputs and outputs as well as the potential environmental impacts associated with a product throughout its whole life cycle (Finnveden *et al*., 2009). LCA has been satisfactorily applied to water treatment systems (Larsen *et al*., 2007). The environmental impact of WWTPs is mainly related to three main issues: the emission of greenhouse gases, the release of nutrients (N and P) and the power consumption.

According to the U.S. EPA (1997), wastewater treatment plants (WWTPs) are one of the larger minor sources of GHGs emissions. These plants produce the three important GHGs namely carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) during the treatment processes, both directly and indirectly. Direct emissions occur during the treatment process through gaseous byproducts such as CO_2, CH_4, and N_2O, while indirect emissions occur during the use of energy and ancillary activities. Specifically, aerobic biological treatment plants emit a significant quantity of greenhouse gases because of using considerable amounts of power (Shaw et al., 2008).

The aim of this research paper is to environmentally assess the operation of an EBPR-SBR reactor devoted to small decentralised populations (45 p.e.) and compare it with a conventional activated sludge system.

MATERIAL AND METHODS

Experimental set-up

Assays were carried out in a Sequencing Batch Reactor (SBR) for 45 p.e., located in CENTA (Seville).

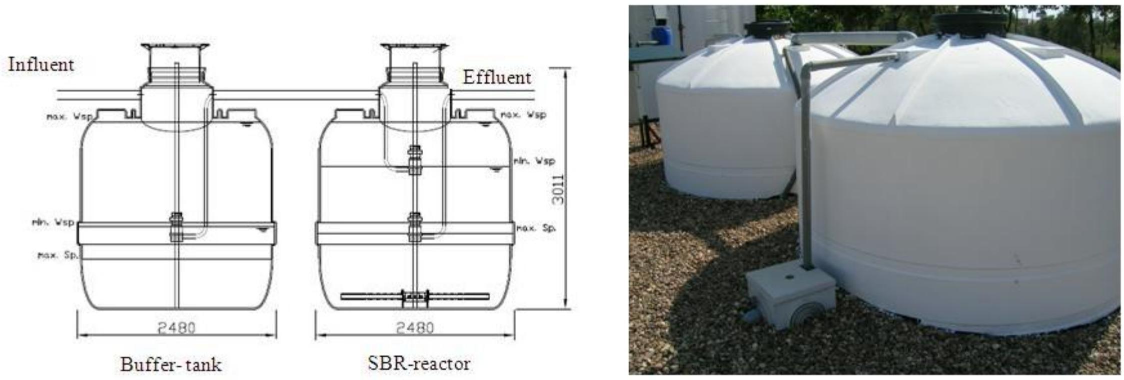

Figure 1. Draw and picture of the SBR-45 p.e. at CENTA (Seville)

The operational conditions of the system were set automatic employing for that purpose an automaton which allowed to define the number of cycles per day and to separate the different phases on each cycle temporarily. Three cycles (8 hours-lenght) per day were planed during the whole trial. Each cycle supposed in the reaction phase the sequence of a first aerobic phase (60 min) followed by an anaerobic/anoxic phase (250 min) and a final full aeration phase (90 min). This aeration pattern was designed with a double objective: firstly, to promote the presence of PAO (bacteria involved in the P uptake) and, secondly, to save energy. The flow rate was 9-10 m^3/day (in three cycles), the hydraulic retention time (HRT) was fixed in 0.66 days and the sludge age in 20 days.

In order to allow the comparison of the environmental behaviour of the SBR with a conventional activated sludge system (CAS), a 30 m^3/day reactor was run and monitored in parallel. This unit includes an anaerobic pond as primary treatment instead of a conventional primary settler. The biological reactor (17.8 m^3) is divided in two compartments: anoxic tank (1/3 approx.) and aeration tank (2/3 approx.) followed by a secondary settler. The reactor is designed for promoting the nitrification- denitrification reactions and, thus, the removal of nitrogen. During the assay, the HRT was 14 h and the sludge age was fixed in 15 days.

Figure 2. Picture of the activated sludge system-30 m^3/day at CENTA (Seville)

Weekly, samples from the influent/buffer and effluent of the SBR and the activated sludge system were taken and analysed (SS, COD, BOD_5, TN, NH_4^+, NO_3^-, TP and PO_4^{3-}) according to Standards Methods (APHA, 1998). The power consumption was recorded daily.

Environmental assessment of the SBR and CAS

Two different functional units (FU), one based on volume (m^3) and the other on eutrophication reduction (kg PO_4^{3-} $_{removed}$), were used to further determine sustainability of the EBPR- SBR- 45 p.e. and compare it with the CAS.

Global Warming Potential

The greenhouse effect was weighted by the Global Warming Potential (GWP) considering both the direct emissions (on site) of GHG from the organic matter removal (Kg BOD $_{removed}$) and the indirect (off site) ones related to energy consumption (Gupta D. & Singh S. K., 2012). The GWP of a greenhouse gas gives the ratio of time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas (IPCC 2001). Thus, the GWP is a relative measure used to compare the radiative effects of different gases. It also means that, the GWP of a GHG is the ratio of heat trapped by one unit mass of the gas compared to one unit mass of CO_2 over a certain time period, usually 100 years.

The N_2O and CH_4 gases are capable of absorbing more infrared radiation or heat per unit mass and this property translates into their greater global warming potential (EI-Fadel and Massoud, 2001). The relative GWP, radiative forcing, residence time, and atmospheric concentrations of the three major GHGs related to municipal WWTPs operations are shown in Table 1 (Wallington et al., 2004).

Table 1. The GWP, radiative forcing, residence time, and atmospheric concentrations of GHGs produced in the WWTPs (Wallington et al., 2004)

GHG	Radiative Forcing (W/m2)	GWP over 100-year period	Atmosphere residence time (years)	Atmospheric concentration (ppb)
CO_2	0.000018	1	5-200*	370000
CH_4	0.00037	23	12	1750
N_20	0.0032	296	114	314

*No single life time can be allotted to CO_2 because of different rates of uptake by different removal processes.

Table 2 shows the estimated productions of the three GHG in a CAS and a SBR according to different authors.

Table 2. GHGs emissions in SBR and CAS

	CO_2	CH_4	N_2O
CAS	168 g/m^3 (Monteith et al., 2005)	3.3 g/m^3 (Daelman et al., 2013)	1.6 g/m^3 (Daelman et al., 2013)
SBR	347.34 g/m^3 (Bao et al., 2014)	0.03 kg/kg $BOD_{5removed}$ (BreisingerInter, 2012)	3.2 g/inhab·year (BreisingerInter, 2012)

Those data have been employed in the calculation of the GWP of the pilots systems under study considering the monitoring results obtained on each one. CH_4 and N_2O emissions have been expressed in terms of CO_2 equivalent. Furthermore, the CO_2 emissions related to the energy consumption have been also considered in the calculation.

Eutrophication potential

Eutrophication potential (EP) due to the remaining nutrients in the effluent has been considered the most relevant environmental issue when performing environmental evaluation of WWTPs (Garrido-Baserba et al., 2014).The EP is expressed in equivalent mass units of phosphorous released. Table 3 shows the EP of the different substances that normally are discharged within the effluent of a WWTP. In the present study, the EP has been estimated through the concentration of nitrogen and phosphorus in the effluent along the test period.

Table 3. Equivalent EP factors (g eq. PO_4^{3-}) (TEAM, 1999)

Substance	**EP**
NH_3	0.35
NH_4^+	0.42
NO_2	0.13
COD	0.022
PO_4^{3-},HPO_4^{2-}, $H_2PO_4^-$, H_3PO_4	3.06
P	3.06
NO_3^-	0.095
NO_2^-	0.13

RESULTS AND DISCUSSION

Performance of the pilot units along the testing period

Table 4 summarises the performance of the SBR and CAS in terms of SS, COD, BOD_5 and nutrients removal.

Table 4. Effluent composition and removal rates for SBR and CAS along the study

Parameter	**SBR**		**CAS**	
	Effluent	**%**	**Effluent**	**%**
SS (mg/l)	9.3 ± 4.5	91	30.1 ± 10.4	84
COD (mg/l)	39.6 ± 13.5	90	75.2 ± 16.7	80
BOD_5 (mg/l)	6.9 ± 2.6	97	25.4 ± 8.3	90
TN (mg N/l)	15.8 ± 6.3	77	33.2 ± 14.4	32
$N\text{-}NH_4$ (mg N/l)	7 ± 7.4	91	18.3 ± 19.2	25
$N\text{-}NO_3$ (mg N/l)	5 ± 2.8	-	10.8 ± 12.5	-
TP (mg P/l)	0.5 ± 0.6	93	3.9 ± 2.6	45
$P\text{-}PO_4$ (mg P/l)	0.4 ± 0.6	94	2.1 ± 1.7	48

During the test period, the SBR-45 p.e. showed a great global performance as it can be observed in Table 4. Practically, all the removal rates exceeded 90%, except the TN. According to these results, the effluent of the EBPR-SBR met the requirements imposed by the 91/271/EEC Directive for sensitive areas. The energy consumption during the assay was 10 kWh/day.

On the contrary, the CAS presented good performances in terms of SS and organic matter removal but the nitrification-denitrification processes were limited. It is worth mentioning that the CAS system was designed for N removal (combination of anoxic/oxic conditions). However, some electromechanical failures on the operation of the system led to this low nitrification-denitrification rates. It is also remarkable that although the system is not specially devoted to the biological uptake of P, the removal rate reached 45%. The presence of PAO and the direct precipitation of phosphorous salts could explain this unexpected rates. The energy consumption reached 40 kWh/day.

GWP of the SBR-45 p.e. and CAS

In order to allow the comparison of results between the SBR and the CAS, the GWP was expressed in terms of kg CO_2/ kg PO_4^{3-} removed taking into account the flow-rate and P load on both systems. Figure 3 represents the values of GWP for each of the systems under study.

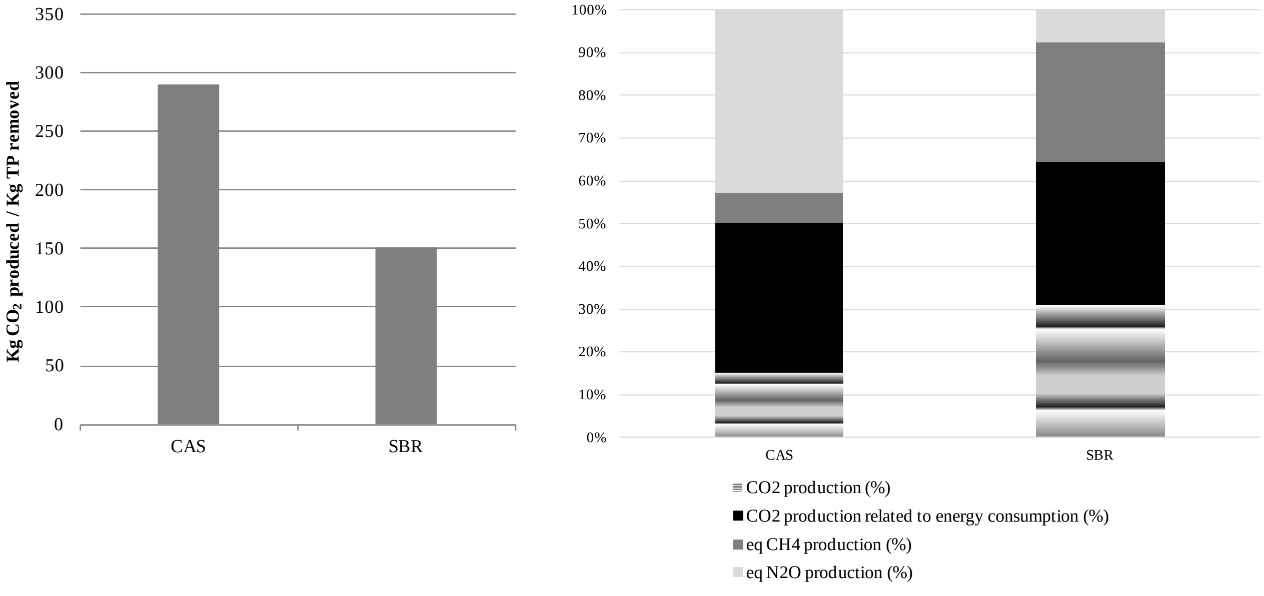

Figure 3. CO_2 generation and weighted sources of CO_2

As shown in Figure 3, the CO_2 production per kg of P removed in CAS practically doubled the one obtained for the SBR. Concretely, the GWP was estimated in 290 kg CO_2/ kg $PO_4^{3-}{}_{removed}$ and 150 kg CO_2/ kg $PO_4^{3-}{}_{removed}$ in the CAS and SBR, respectively. Those results are directly linked to the higher performance of the SBR in terms of P removal and, also, the lower energy consumption registered in that system.

Focusing on the weighted-sources of CO_2 (graph on the right, Figure 3) it is observed than in the SBR 1/3 of the CO_2 was related to the CO_2 produced during the oxidation of the organic matter (cellular respiration); another 1/3, to the energy production; and the remaining 1/3, represented the estimated CO_2 due to the emission of CH_4 and N_2O. In fact, those emissions are considered rather negligible in full aerated biological reactors (Johansson et al., 2004). On the contrary, the eq CO_2 due to N_2O emissions represented a large percentage in CAS. This large N_2O emission is explained through the incomplete nitrification and denitrification processes observed in CAS during the trial (Daelman et al., 2013). The second source of CO_2 in the CAS was the energy consumption.

EP of the SBR-45 p.e. and CAS

Figure 4 represents the EP associated to the CAS and the SBR-45 p.e.

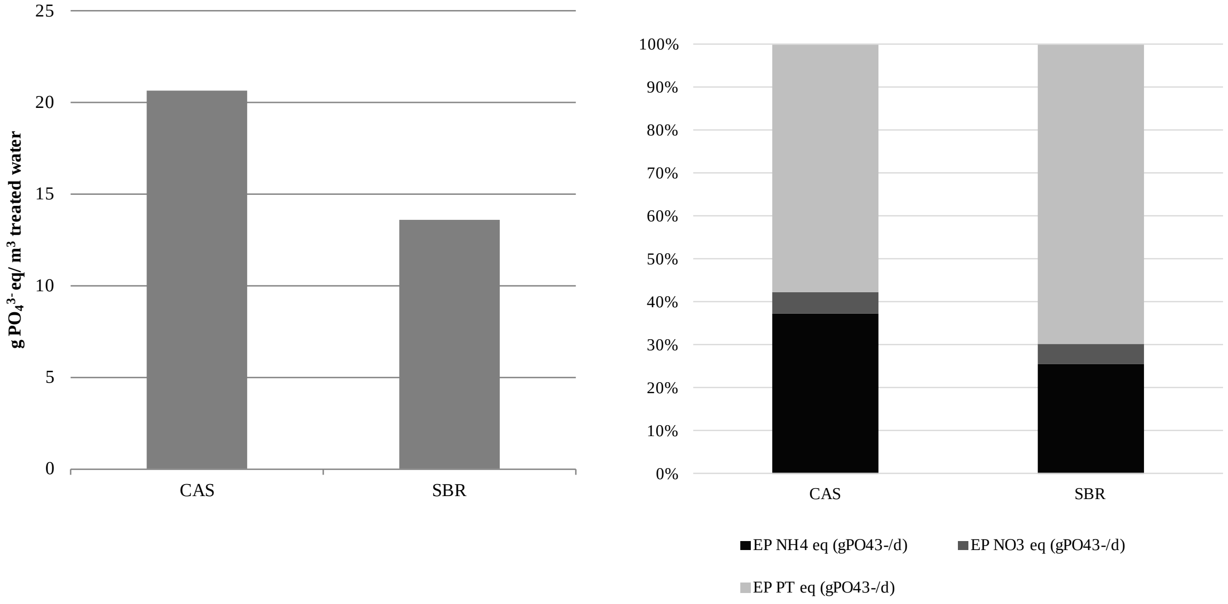

Figure 4. Eutrophication potential (EP) in CAS and SBR- 45 h.e.

Larger performances in terms of nutrients removal observed in SBR led to a lower EP in comparison with the CAS. Concretely, the EP reached 13.6 equivalent gPO_4^{3-} $/m^3$ and 20.6 equivalent gPO_4^{3-} $/m^3$ in the SBR and CAS, respectively. In both cases, the largest EP was related to the emission of PT in the effluent meanwhile the EP due to NH4 and NO3 emissions represented approximately 40% in the CAS and 30% in the SBR.

Power consumption (PW) related to P removal

The PC in SBR reached 175 kWh/ kg $PO_4^{3-}{}_{removed}$, meanwhile in the CAS it increased up to 350 kWh/ kg $PO_4^{3-}{}_{removed}$.

CONCLUSIONS

According to the results of this study, an optimised operation of an EBPR-SBR, involving a energy-saving aeration pattern, allows, on one hand, the fulfilment of the Directive 91/271/CEE and, on the other hand, the reduction of its environmental impact in terms of GWP, EP and PC if compared to a conventional activated sludge system.

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