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Technical Article

Performance evaluation of a solar-powered wastewater treatment plant (two-stage SBR) operated in tropical climate regions

Avaliação de desempenho de uma estação de tratamento de esgoto movida a energia solar (SBR de dois estágios) operada em regiões de clima tropical

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ABSTRACT

This article investigates the performance behaviour of a small decentralized wastewater treatment plant with a capacity of up to 50 population equivalents powered by solar energy. The two-stage sequencing batch reactor (SBR) consists of a photovoltaic (PV) system to deliver energy, a battery storage for night operation and two reactor tanks. In the experimental period of 157 days, the wastewater inflow was increased from 3 to 4.5 and 6 $m^3.d^{-1}$, with sludge ages of 32 ± 2 d in the beginning and 21 ± 2 d in the end. The results corresponding to the different phases indicated high efficiency and stability of the system with domestic wastewater, reaching efficiencies of the test periods of 93 ± 2%, 86 ± 4% and 93 ± 6% for removal of chemical oxygen demand, nitrogen and phosphorus, respectively. In the last 51 days, aeration in the night was interrupted for three hours to save energy and study the behaviour of extended non-aerated phases. A shortening of the aeration phases can help to extend the lifetime of batteries and reduce operational costs, while limiting values in the outlet are still met.

Keywords: two-stage SBR; activated sludge; solar energy; intermittent aeration; decentralized wastewater treatment.

RESUMO

Este artigo investiga o comportamento do desempenho de uma pequena estação de tratamento de águas residuais descentralizada, com capacidade de até 50 equivalentes de população alimentada por energia solar. O reator de bateladas sequenciais de dois estágios (SBR) consiste em um sistema fotovoltaico (PV) para fornecer energia, uma bateria de armazenamento para operação noturna e dois tanques de reação. No período experimental de 157 dias, a afluência de esgoto foi aumentada de 3 para 4,5 e 6 $m^3.d^{-1}$, com idades de lodo de 32 ± 2 d no início e 21 ± 2 d no fim. Os resultados correspondentes às diferentes fases indicaram alta eficiência e estabilidade do sistema com esgoto doméstico, que atingiu eficiências nos períodos de teste de 93 ± 2%, 86 ± 4% e 93 ± 6% para a remoção de demanda química de oxigênio (DQO), nitrogênio (N) e fósforo (P), respectivamente. Nos últimos 51 dias, a aeração noturna foi interrompida por três horas para economizar energia e estudar o comportamento das fases prolongadas sem aeração. A redução das fases de aeração pode ajudar a estender a vida útil das baterias e reduzir os custos operacionais, enquanto os valores limite na saída ainda são atendidos.

Palavras-chave: SBR de dois estágios; lodo ativado; energia solar; aeração intermitente; tratamento de esgoto descentralizado.

INTRODUCTION

According to the WHO (2017), more than two billion people are living without access to clean drinking water, which corresponds to 29% of the world's population. In addition, more than twice as many have a lack of sanitation facilities and appropriate wastewater drainage or treatment system. The resulting inadequate sanitation causes approximately 280,000 deaths worldwide annually due to contamination of drinking water (WHO, 2017). Especially in rural areas, many existing wastewater treatment facilities face the problem of unstable or not existing electrical power supply (USEPA, 2006). Nowadays the development of new energy sources opens alternative ways of providing power to

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wastewater treatment facilities other than public grids. Solar energy can easily be transformed to reasonable levels of power for running electrical equipment through photovoltaic systems (MCEVOY; MARKVART; CASTAÑER, 2011). In Brazil, solar radiation is above global average, especially in the Northeast region, with 5.7 to 6.1 kWh.m^{-2}, and shows the lowest inter-annual variability (PEREIRA *et al.*, 2006).

Sequencing batch reactor system

The activated sludge system is the most widely used technology in the biological treatment of domestic and industrial wastewater, providing high removal efficiencies of organic matter and nutrients as well as operational flexibility (KALAVROUZIOTIS, 2017). The sequencing batch reactor (SBR) system is quite popular in several existing variants, which can be subdivided in relation to continuous or batch inflow conditions. SBRs are mostly based on a single batch reactor concept, which incorporates all treatment steps of the activated sludge system in a single reactor. Sludge recirculation is not necessary, since the biomass remains inside the reactor until it is discharged as excess sludge (OBAJA *et al.*, 2003; HARTLEY, 2013). The SBR is operated in cycles, starting with its filling, followed by a reaction phase with (aerobic) and without (anoxic) aeration and settling of the sludge. Eventually, clear treated water can be pumped out from the upper part of the reactor chamber (ARTAN; ORHON, 2005).

Two-stage sequencing batch reactor system

In recent years, SBR system technologies have evolved continuously, leading to the development of a wide variety of systems for the optimization of biological processes like the phosphorus elimination, nitrification and denitrification (DUTTA; SARKAR, 2015). The system used in this study is a two-stage SBR with controlled operating conditions, so that aerobic, anoxic and anaerobic processes can take place at the same time in adjacent separate reactor chambers (ZENG; PENG; WANG, 2009). To promote high removals of both nitrogen and phosphorus, the batch system can act with intermittent aeration in each reactor chamber (UGGETTI *et al.*, 2016).

Solar system and battery storage

In general, the electric energy for aeration of activated sludge systems is the most cost-intensive part, representing between 25 and 45% of the total operational and maintenance expenses of most plants (SMITH; LIU, 2017). To reduce these expenses, the use of photovoltaic (PV) systems has a high potential (HAN *et al.*, 2013). On sunny days, the energy used for aeration during the daytime can be obtained directly from the solar panels. Potential surplus energy is stored in batteries and maintains the operation of the aeration during the night-time intervals. Climate conditions determine the size of the PV panels and the required battery capacity. Intermittent aeration is particularly advantageous when nocturnal aeration stages can be reduced, which leads to an increased life span of the battery storage (DHUNDHARA; VERMA; WILLIAMS, 2018). However, several studies associate long non-aerated stages with a reduction of the sedimentation capacity of activated sludge systems (GORONSZY, 1979; SINGH *et al.*, 2018).

Aim of the work

The main objective of this work was to evaluate the performance of a self-sufficient two-stage SBR system in an intermittent aeration powered by solar energy in a tropical region, as well as the removal of organic matter, nitrogen and phosphorus from domestic sewage. In addition, this research also seeks to evaluate the influence of aeration reduction during the night on the lifetime of the batteries and the activated sludge settleability.

MATERIAL AND METHODS

Specification of the two-stage sequencing batch reactor system

The experimental plant used in this work was installed next to the sewage treatment plant of the central campus of the Universidade Federal do Rio Grande do Norte (UFRN), in Natal, Brazil. The plant was fed with domestic sewage coming from a nearby student residence and a restaurant. The plant consists of an SBR system with a maximum capacity of 50 population equivalents (maximum daily inflow: 7,500 L.d^{-1}), composed of two chambers with mixed liquor recirculation between. The reactors work in a similar way to a biological nitrogen removal system with pre-denitrification. The first reactor (R1) is dedicated mainly to the denitrification process and the second reactor (R2) to the nitrification process and the removal of most organic material (see Figure 1). The aeration system configuration is as follows:

- aeration R1: 1 air blower (30 m³.h^{-1}; 1,330 W);
- aeration R2: 1 air blower (30 m³.h^{-1}; 1,330 W);
- air lifts 1–4: 1 air blower (12 m³.h^{-1}; 500 W).

It is designed not only to aerate the activated sludge but also to mix the reactors, and is therefore designed larger than necessary to meet the theoretical oxygen demand (TOD). The TOD for chemical oxygen demand (COD) and nitrification was 4.8 kW.h.d^{-1} (in both reactors), but the mean energy consumption with aeration was about 10 kW.h.d^{-1}.

Treatment cycle

A scheme of all process stages carried out in the investigated SBR system is shown in Figure 2. The first reactor chamber, R1, is the predominant anoxic/anaerobic reactor where the denitrification and the phosphate release occur. R1 receives the raw sewage, which includes biodegradable organic material as a co-substrate for the denitrification (and P release from cells). Nitrates are recirculated from R2 into R1. In R2, the nitrification of ammonia and ammonium occurs with high oxygen aeration, along with phosphorus uptake. Each batch cycle starts with controlled pumping of raw wastewater out of a storage tank into R1. By air lift pumps, water is exchanged between the reactor chambers. Raw sewage partly flows from R1 to R2 for nitrification. The recirculation pumps also deliver already nitrified volume fractions from R2 to R1. Subsequently, the aeration in R1 starts for a short time of about 10 minutes by membrane diffusers at the bottom of the reactor distributing fine bubbles with ambient air. Besides, oxygen supply aeration also leads to an intense agitation, which mixes water and activated sludge without an additional stirring device. In non-aerated stages, the sedimentation can take place to separate the water from the sludge phase. The short aeration time in R1, which changes the milieu from anaerobic to aerobic conditions during the time of aeration, is important for phosphorus elimination. Directly after the aeration stops, the dissolved oxygen concentration quickly falls down to 0 mg.L^{-1} and the milieu turns to anoxic and later to anaerobic conditions again, which takes around 30 minutes (GOLDBERG, 2016). In R2, a 20-minute aeration period starts right after the aeration in R1 finishes. The longer aeration time keeps oxygen in the reactor even after aeration is turned off again, which is beneficial for nitrification processes in R2. After the aeration phases in both reactors, a sedimentation interval follows. One batch consists of: in R1, two aerobic aeration phases followed by two anoxic sedimentation phases; in R2, three aerobic aeration phases and three sedimentation phases followed by the discharge of clear treated water, until the cycle starts again.

Specification of the photovoltaic system

The PV system, which is shown in Figure 3, consists of 18 solar panels, with a total installed power of 4,950 W, and eight lithium batteries for energy storage with a maximum storage capacity of 21.12 kWh. As the system is designed as a standalone solution (off-grid), the energy storing stops as soon as the capacity of the batteries is reached. The solar energy converted by the PV system in direct current (DC) can either be stored in the batteries (DC) or directly used for the air blowers after converting into alternating current (AC) by an inverter. The total energy demand of the system requires approximately 13.2 $kWh.d^{-1}$. The energy consumptions are 2.2 kWh (aeration R1), 7.8 kWh (aeration R2), 2.2 kWh (air lifts) and 1 kWh (control unit). The solar system was the only power supply of the pilot plant during all experimental phases, so electrical demands can be evaluated very accurately. Energy production ($kWh.d^{-1}$), solar radiation ($kW.m^{-2}$) and system interruptions overnight were the main observed parameters.

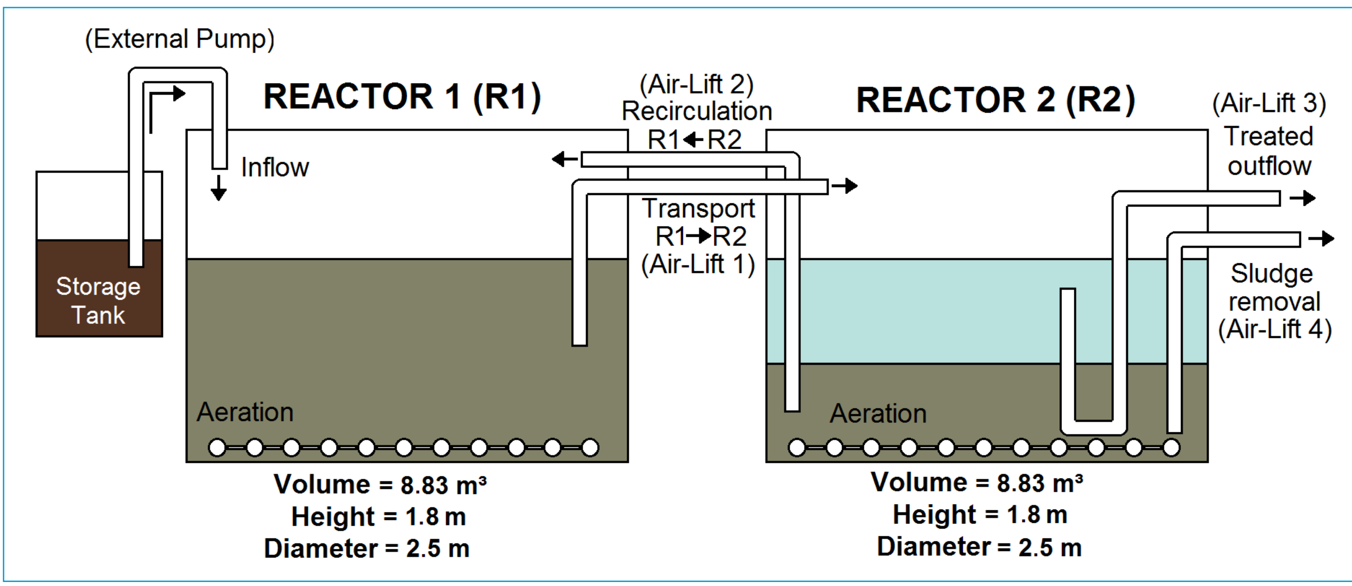


Figure 1 – Scheme of the reactor chambers and the aeration system.

R1 — Inflow (stage 1); Transfer to R2 (stage 7)

Process stage	1	2	3	4	5	6
Technical process	Aeration	No Aeration	No Aeration	Aeration	No Aeration	No Aeration
Environment	Aerobic	Anoxic	Anaerob	Aerobic	Anoxic	Anaerob
Time (duration)	10 min	30 min	140 min	10 min	30 min	140 min

R2 — Recirculation back to R1 (stage 1); Outflow

Process stage	7	8	9	10	11	12
Technical process	Aeration	No Aeration	Aeration	No Aeration	Aeration	No Aeration
Environment	Aerobic (partly anoxic)					
Time (duration)	20 min	100 min	20 min	100 min	20 min	100 min

Figure 2 – Wastewater path and treatment process stages in the investigated sequencing batch reactor system.

Experimental plan

The study consisted of five experimental phases. In the first three (P1, P2 and P3), the behaviour of four equal treatment cycles per day with increasing inflow was studied. R1 is able to receive raw sewage at any time of the treatment cycle because important stages of sedimentation for sludge and outflow removal only take place in R2. However, in this experiment, the feeding of the system was performed discontinuously, as shown in Figure 4. In experimental phase 4 (P4), the number of inflow batches was reduced from four to three while the daily

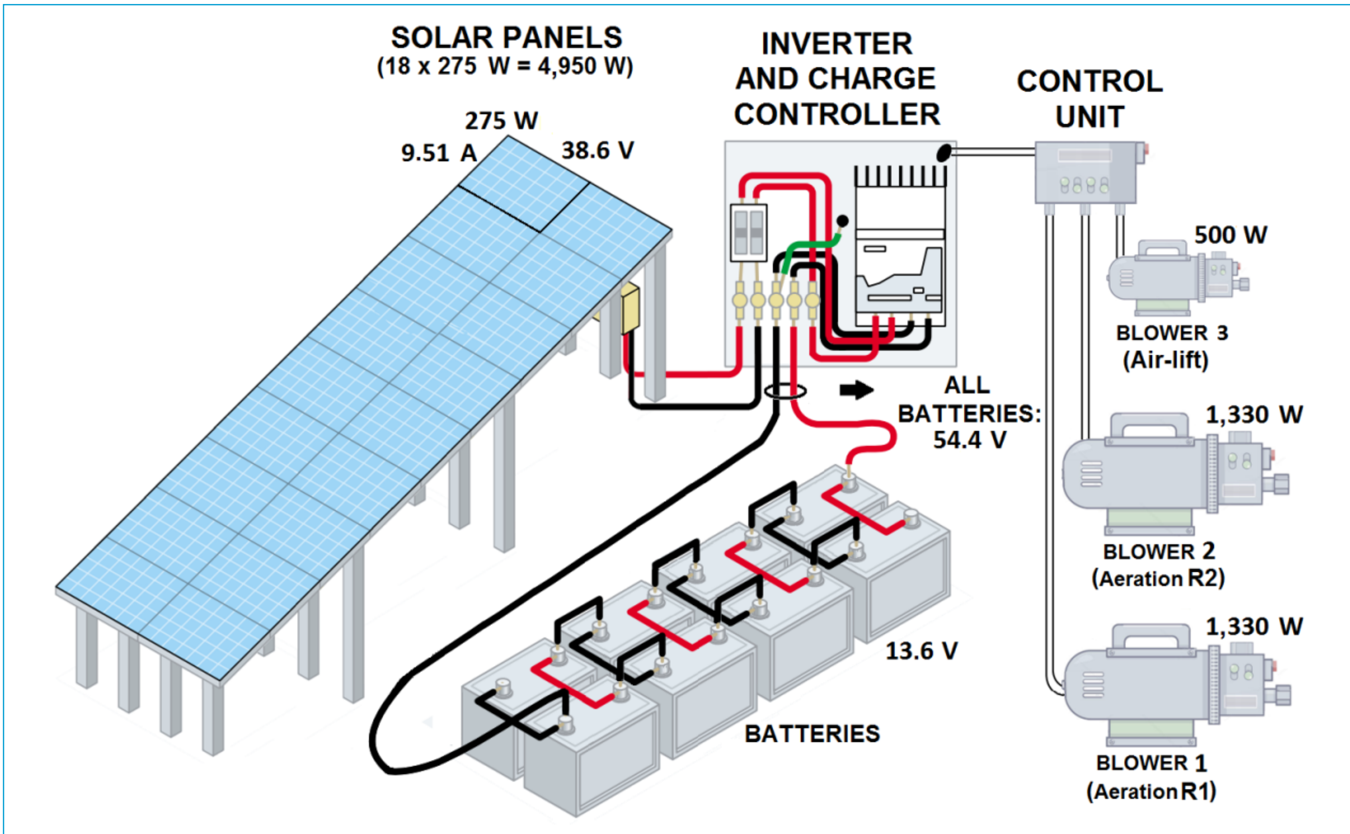


Figure 3 – Components of the photovoltaic system and the air blowers powered by this system.

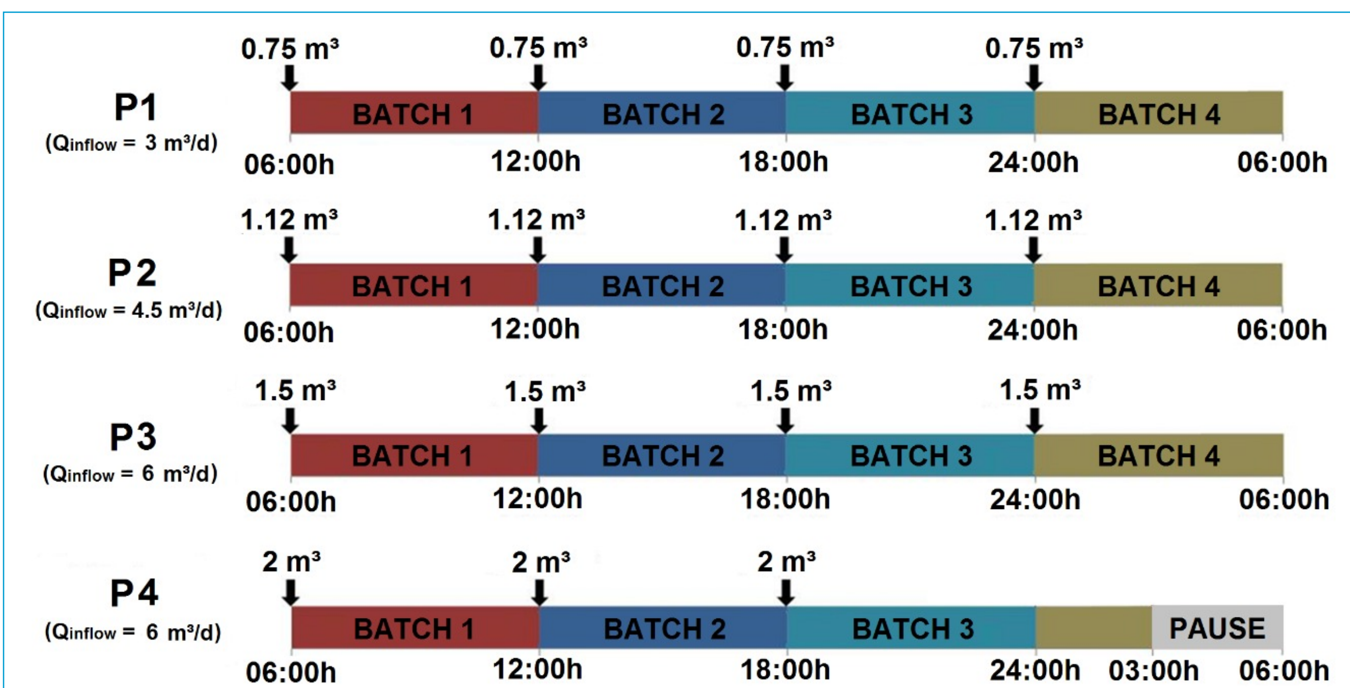


Figure 4 – Daily distribution of batches and inflow of the wastewater treatment plant during the experiments.

sewage volume was distributed equally to the remaining three batches. The volume of raw sewage per batch was increased from 1.5 to 2 m^3. In phase 5 (P5), the feeding process worked the same way than in P4 (see Table 1).

As in P4 there was no more sewage inflow at midnight, in the period between midnight and 3 a.m. the system worked only with short stages of aeration and recirculation. In the night, between 3 and 6 a.m., the operation was fully interrupted and the system was kept without aeration or movement of volume shares in the reactors. At 6 a.m., the system restarted with a new batch. This new configuration resulted in modifications of the total daily aeration time of the reactors, as summarized in Table 1.

In order to increase the evaluation period of the PV system, it operated in experimental P5 under the same conditions as in P4. However, during this last phase, no physical-chemical analyses were carried out and no biological parameters were monitored, but only the performance data of the photovoltaic system was recorded.

Analytical methods

The system was monitored through analysis of treated outflow and sludge samples weekly and the raw sewage analysis every two weeks in order to evaluate treatment efficiencies over time. Raw sewage was collected from the storage tank. Sludge samples were collected inside the reactors during the aeration phase. The treated outflow was sampled in a collection point outside the plant.

The applied methodologies follow the *Standard Methods for the Examination of Water and Wastewater* (APHA; AWWA; WEF, 2012). Some variables were measured in situ, such as pH, dissolved oxygen (DO), temperature and settleable solids (Standard Methods — Method 2540 F). As no analysis of volatile suspended solids (VSS) was performed, the values of sludge age and food-to-microorganism ratio (F/M) were estimated using the values of total suspended solids (TSS).

RESULTS AND DISCUSSION

Two-stage sequencing batch reactor system treatment performance

The raw sewage that fed the system had predominantly domestic sewage characteristics (HENZE *et al.*, 2008), as shown in Table 2. Only the phosphorus values are increased because of daily usage of cleaning detergent in a nearby restaurant. The system showed high efficiency in removing COD, total nitrogen and total phosphorus throughout the whole operation period. The changes of organic loads and sludge age did not impair the performance of the system in relation to the removal of COD, nitrogen and phosphorus (Table 3). In a study (OLIVEIRA; VON SPERLING, 2011) in which 166 different wastewater treatment plants throughout Brazil were investigated, the average efficiencies for the activated sludge systems were 81% (COD), 50% (N_{total}) and 46% (P_{total}), respectively. Compared to those common literature values, the experiments of this study show significantly better treatment results.

Table 1 – Experimental description.

Phase	Nº of days	Inflow Q_{daily} [$m^3.d^{-1}$]	Treatment cycles in 24 hours	Part of maximum capacity [%]	Sewage infill in the night	Total aeration time (R1+R2) [min]
P1	1-28 (28)	3	4	40	Yes	360 (280+80)
P2	28-56 (28)	4.5	4	60	Yes	360 (280+80)
P3	56-84 (28)	6	4	80	Yes	360 (280+80)
P4	84-106 (22)	6	3	80	No	300 (230+70)
P5	106-157 (51)	6	3	80	No	300 (230+70)

Table 2 – Mean concentration and standard deviation of chemical oxygen demand (COD), N-N_{total}, N-NH_4^+, N-NO_3^-, P_{total}, pH of the inflow throughout the experiment (two samples per phase).

Phase	COD [$mg.L^{-1}$]	N-N_{total}* [$mg.L^{-1}$]	N-NH_4^+ [$mg.L^{-1}$]	N-NO_3^- [$mg.L^{-1}$]	P-P_{total}** [$mg.L^{-1}$]	pH [-]
P1	647 ± 144	49 ± 6	48 ± 8	1.0 ± 0.7	29.3 ± 18	6.6 ± 0.5
P2	633 ± 45	57 ± 15	41 ± 2	1.2 ± 0.4	29.4 ± 6	7.2 ± 0.1
P3	645 ± 108	61 ± 3	46 ± 5	1.3 ± 0.6	35.7 ± 9	6.8 ± 0.8
P4	570 ± 24	65 ± 3	56 ± 1	1.5 ± 0.1	22.9 ± 4	7.0 ± 0.2

*N-N_{total} = NTK + Nitrate + Nitrite, as N; **P-P_{total} = $P_{organic}$ + $P_{inorganic}$, as P.

Table 3 – Mean concentration and standard deviation (sd) of chemical oxygen demand (COD), N-N_{total}, P_{total}, pH of the outflow throughout the experiment (four samples per phase).

Phase	Phase highlights	COD		N_{total}*		P_{total}**	
		Mean ± sd [$mg.L^{-1}$]	RE [%]	Mean ± sd [$mg.L^{-1}$]	RE [%]	Mean ± sd [$mg.L^{-1}$]	RE [%]
P1	(V_{batch} = 0.75 m^3) Sludge age = 31 d	36 ± 19	94 ± 1	6 ± 3	87 ± 7	1 ± 0.3	94 ± 4
P2	(V_{batch} = 1.12 m^3) Sludge age = 33 d	45 ± 16	93 ± 3	8 ± 3	87 ± 3	3 ± 3.7	90 ± 11
P3	(V_{batch} = 1.5 m^3) Sludge age = 22 d	52 ± 16	92 ± 2	10 ± 3	84 ± 4	2 ± 0.3	95 ± 2
P4	(V_{batch} = 2 m^3) Sludge age = 21 d	51 ± 9	91 ± 2	10 ± 1	85 ± 2	2 ± 0.3	92 ± 2

*N_{total} = NTK + Nitrate + Nitrite; **P_{total} = $P_{organic}$ + $P_{inorganic}$; RE: removal efficiency.

Figure 5 shows the values of TSS concentrations in each reactor and the average of both reactors during the first four experimental phases, as well as the respective modifications in the daily inflow and sludge age. After the second increase of the organic load, carried out between P2 and P3, both solids concentrations of R1 and R2 increased in relation to Phases 1 and 2, reaching values of 6.2 g.L^{-1} (R1) and 3.9 g.L^{-1} (R2). The concentration of sludge in an activated sludge system is mainly a function of the daily load of COD and the sludge age (HENZE *et al.*, 2008). Thus, by keeping the sludge age constant, increased daily organic loads tend to generate an increase of the sludge concentration. However, the increase in TSS concentrations observed in the beginning of P3 was accompanied by a poor sedimentation behaviour of the sludge, evidenced by an increase of the sludge volume index (SVI) observed at the beginning of P3 (Figure 5). One week after the beginning of P3, the sludge age was reduced by increasing sludge disposal from 11 to 18 kg/week. This change resulted in the reduction of TSS in both reactors and the sludge age from 32 to 21 d (Figure 5). Two weeks after reduction of the sludge age, the poor sedimentation properties of the sludge disappeared with the respective decrease in SVI (Figure 5).

Poor sedimentation behaviour of the sludge occurred (SVI > 150 mL.g^{-1} in both reactors) in the same period when the system was operated with the highest solids concentration (average of solids in both reactors). This shows that the system was pushed over the limit in relation to the biomass concentration, where sedimentation is impaired. In the experiments, this effect occurred when the average TSS concentration of the system (average of both reactor chambers) was higher than 4.2 g.L^{-1}.

This limit is linked to long non-aerated stages in intermittent aeration regimes, which commonly have negative effects on the sedimentation capacity of activated sludge systems (DOTRO *et al.*, 2011). According to Van Haandel and Van der Lubbe (2012), in activated sludge systems submitted to low dissolved oxygen concentration, the reduction of sludge age is a valid strategy aiming at the improvement of system sedimentation. Besides the observed effect in the reduction of solids concentration, the reduction of the sludge age can have a positive effect on sludge sedimentation by reducing endogenous oxygen demand (VAN HAANDEL; VAN DER LUBBE, 2012). However, the authors emphasize that this strategy may result in undesirable consequences that should be investigated, such as a potential decrease in nitrification efficiency.

The activated sludge remains most of the time without the presence of DO. The aeration stages of the reactors represent a small part of the total batch duration, especially during P4 and P5, where a nocturnal interruption was carried out. As can be seen in Table 4, during one day of system operation at P4 and P5, R1 remained non-aerated 84% of the time, and R2 more than 95% of the time.

One reason for the high ammonia removal in R2 is the low organic load transported from R1 to R2, which causes less substrate availability for heterotrophic bacteria. This creates a limitation of their growth in R2 and, as a consequence, a lower oxygen demand. Some studies applied to the nitrification

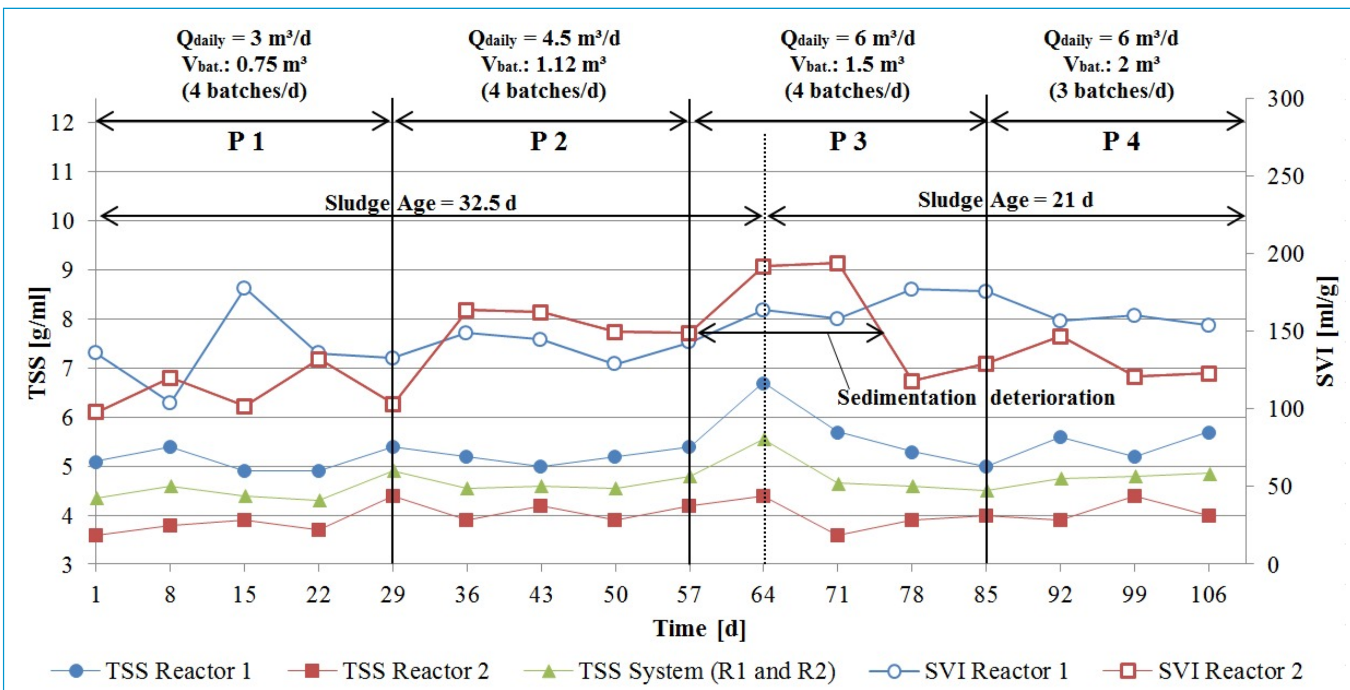


Figure 5 – Sludge volume index and total suspended solids values in each reactor and the average total suspended solids concentration of the system (R1 and R2) throughout the experimental phases.

Table 4 – Total daily aeration time of both reactors throughout the experiment.

Phase	R1		R2	
	Daily aeration time [min]	Part of aeration time to total time in 24 hours [%]	Daily aeration time [min]	Part of aeration time to total time in 24 hours [%]
P1, P2 and P3	280	19.4	80	5.6
P4 and P5	230	16	70	4.9

kinetics show that, when the organic loads to the nitrification reactor are low, the growth of autotrophic bacteria can exceed that of heterotrophic bacteria, which favours nitrification (HUANG *et al.*, 2007). The continuity of the high removal of ammonia nitrogen after the reduction of the sludge age (Table 5) shows that a sludge age of 21 days was sufficient for the development of nitrifying organisms due to the warm local temperature. The system operated over the entire time in tropical conditions, with an average temperature of 29.8 ± 0.4°C. There was no night setback measured because the samples were taken only in the daytime, but the room temperatures in the tropical Natal rarely undergo 22°C, so a strong temperature drop in the night is not expected.

The system also showed a positive performance with respect to denitrification, as shown by the average nitrate concentrations in the outflow (Table 5). The presence of nitrate coming from R2 by recirculation to R1, and organic matter provided by the raw sewage in R1, as well as the absence of oxygen, were most of the time given to reach good treatment results. Thus, the low concentrations of phosphorus (Table 3) and nitrate (Table 5) in the outflow indicate that the intermittent aeration regime was effective in creating an anoxic phase followed by an anaerobic phase, both presenting sufficient durations. In R1, the anoxic phase follows straight away after the aeration stops. In R2, it takes almost 20 minutes until the DO level drops to 0 $mg.L^{-1}$.

The pH values in both reactors were stable around the neutral point throughout the whole system operation period, with a minimum of pH 6.5 and a maximum of pH 7.5.

System performance related to solar energy

The PV system was the only energy source of the wastewater treatment plant. The daily energy generation of the solar panels was able to supply the consumption of the system in 152 of the 157 experimental days. There were only five days when the generation of energy was lower than the consumption of the system (Table 6). On these days, respectively in the following nights, the system operation was interrupted because the batteries were not charged enough to run the system all night. Comparing the daily radiation of these days and the average daily radiation of the whole period, these days are considered as days with low daily sunshine in Natal, with irradiation values of more than 30% below average. This resulted in reduced energy production by the solar panels and depleted the batteries for a short period (3 hours). However, during the experimental period P1–P4, none of the interruptions were observed in the efficiencies of treatment.

Figure 6 shows a comparison between the daily energy generated by the PV and the average daily radiation values in Natal for the end of phase 5 (days 135–157). The low daily energy produced by the PV system on day 151 (5.1 kWh) is related to the low global daily radiation (0.14 $kW.m^{-2}$) of this day in Natal. However, less intense variations in the global radiation values (days 135, 143, 146 and 157) or heavy precipitation (9 to 30 mm in days 142, 143, 144 and 152) were not sufficient to impair the system's energy production capacity, as the solar panels were able to capture a sufficient amount of solar radiation to operate the wastewater treatment system.

The estimated O_2 requirement for the system (50 people population equivalent) was 6.8 $kgO_2.day^{-1}$ (COD = 5,0 $kgO_2.day^{-1}$; nitrification = 1,8 $kgO_2.day^{-1}$), resulting in a required power for oxygenation at standard conditions of 3.4 $kW.h.day^{-1}$ (standard aeration efficiency of 2 kgO_2/kW.h), a required power for oxygenation in the field of 4.8 $kW.h.day^{-1}$ or 200 W (oxygenation efficiency in the field of around 70%), and a power density of ~12.5 $W.m^{-3}$ (volume of the two reactors = 16 m^3). This power density is quite low for ensuring complete mixing, justifying the adoption of a cycle with higher energy consumption of 10 $kW.h.day^{-1}$ to also promote enough mixing in the reactors with a mean power density of ~20 $W.m^{-3}$. Considering additional energy consumption for air lifts (2.2 $kWh.day^{-1}$) and control unit (1 $kWh.day^{-1}$) and losses (2.8 $kWh.day^{-1}$), the system generated around 16 $kWh.day^{-1}$ in the field. So the relation between the energy for oxygenation for COD and nitrification and the energy generated in the field is 30% (4.8 $kWh.day^{-1}$/16 $kWh.day^{-1}$) at most.

Night switch-off

In order to evaluate the impact of lower aeration (P4, P5) on the batteries, it was necessary to consider the electric charge status of the batteries. During phases 1, 2, and 3, the pilot plant worked, depending on the batteries, for approximately 16 hours a day, which represents a minimum energy demand of 8.8 kWh, while the total charge capacity of the batteries is 21.2 kW.h, so during night time the batteries discharged approximately 42% of the stored charge. In general, for all types of batteries used in PV systems, the factors that shorten their lifetime the most are deeper or more frequent discharges, and high operating temperatures (RYDH; SANDÉN, 2005). According to Figure 7, a battery discharge of 42% would allow the execution of approximately 500 load cycles, which results in a maximum lifetime of about one year and six months. As the system showed larger discharges on cloudy days, even with some full discharge cycles, the actual lifetime of the batteries might be shorter than estimated.

Table 5 – Mean concentration and standard deviation of $N\text{-}N_{total}$, $N\text{-}NH_4^+$, $N\text{-}NO_3^-$ of the outflow throughout the experiment (four samples per phase).

Phase	N_{total}* [$mg.L^{-1}$]	NH_4^+ [$mg.L^{-1}$]	NO_3^- [$mg.L^{-1}$]
P1	6.4 ± 2.9	4.9 ± 1.5	1.5 ± 0.7
P2	7.7 ± 2.9	3.3 ± 2.3	2.5 ± 1.0
P3	9.8 ± 2.6	6.2 ± 1.9	1.4 ± 0.7
P4	10.0 ± 1.4	5.3 ± 0.4	1.1 ± 0.6

*N_{total} = NTK + Nitrate + Nitrite.

Table 6 – Average daily irradiation and days on which the system suffered interruptions.

Phase	Daily average irradiation [$kW.m^{-2}$]	Days on which the system suffered interruptions	Daily irradiation in days with interruptions [$kW.m^{-2}$]	Reduction in relation to the average daily radiation of the phase [%]
P1	0.49 ± 0.50	11, 19, and 24	0.36, 0.36, and 0.32 respectively	31, 31 and, 39 respectively
P2	0.54 ± 0.07	45	0.37	30
P3	0.58 ± 0.04	None	-	-
P4	0.58 ± 0.04	None	-	-
P5	0.48 ± 0.10	151	0.14	74

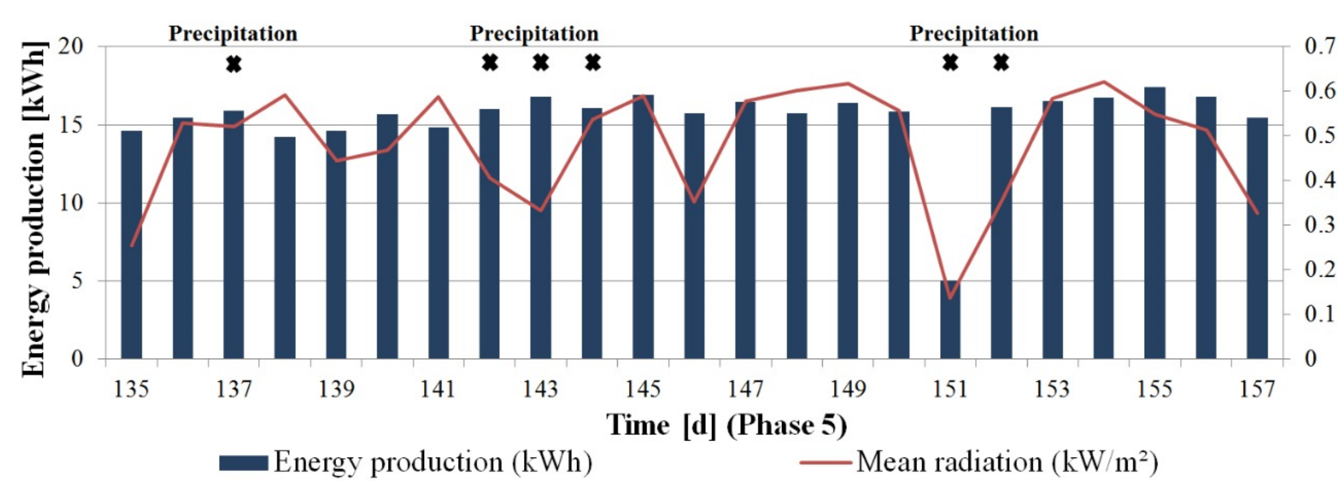
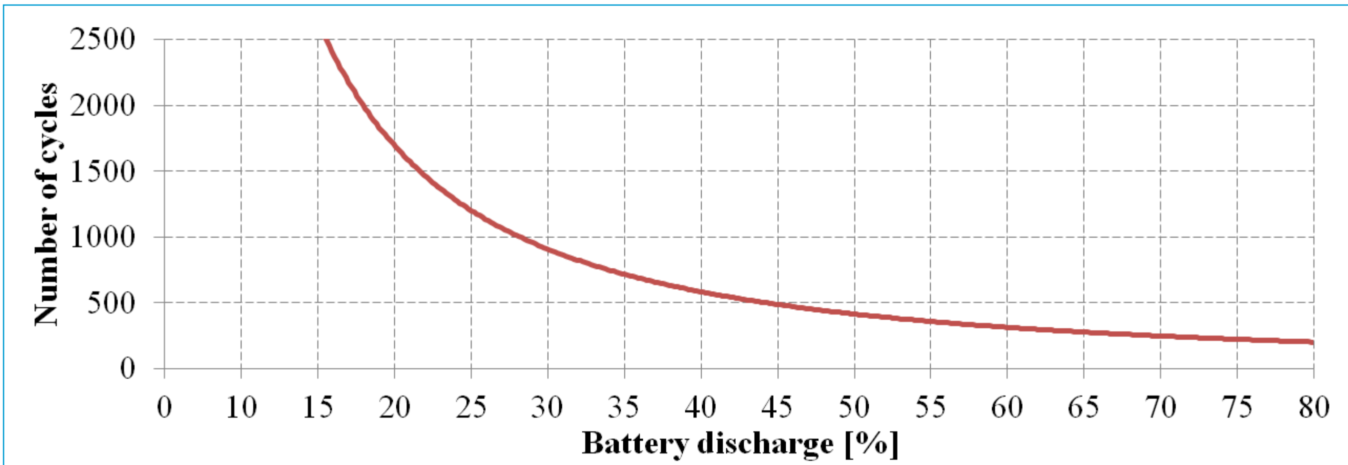


Figure 6 – Daily energy generation by the photovoltaic system and the average daily radiation in Natal, between days 135 (01/01/20) and 157 (01/23/20).



Source: Moura Acumuladores SA (2016).

Figure 7 – Discharge curve of the battery model used.

In experimental phases P4 and P5, the system was operated with the same daily inflow as P3 (6 $m^3.d^{-1}$), but with one night batch less (Figure 4). This shift leads to a 1/6 reduction of the daily aeration time from 360 to 300 minutes. As observed in the results of Table 3, the organic matter and nutrient removal efficiencies did not undergo significant changes in P4, which indicates that the reduction in aeration performed did not impair system performance.

During phases P4 and P5 the applied reduction of the aeration time reduced the energy demand from 8.8 to 7.15 kWh. In these conditions, the daily discharge status of the batteries went from 42 to 33.7%, which, according to Figure 7, increases the approximate number of cycles from approximately 500 to 750. This indicates an increase of 50% in the life expectancy of the battery set. This increase is very significant, especially when considering the consequences for the system. Battery replacement costs are high, and often this process presents technical and logistical difficulties (JUNG; ZHANG; ZHANG, 2015). In addition, the batteries that present the best cost-benefit currently for this use (lithium batteries) have a considerable risk of environmental pollution both in production and disposal, because of the toxic components and the difficulties to manage (RYDH; SANDÉN, 2005). Therefore, it is essential to use new strategies that increase the lifetime of the batteries, where the reduction of night aeration could be a promising strategy.

CONCLUSIONS

The investigated SBR system reached continuously high removals of organic matter, nitrogen and phosphorus, with efficiencies of 93 ± 2% of COD, 86 ± 4% of N_{total} and 93 ± 6% of P_{total}. The removal of organic matter and nutrients is widely stable, without causing a decrease in the efficiency in relation to the increasing inflow (3, 4.5 and 6 $m^3.d^{-1}$). High concentrations of microorganisms result in poor sedimentation behaviour of the sludge, which did not affect the quality of the outflow in this study. The limit in the TSS concentration of the system (R1 + R2) affecting the sedimentation was 4.2 $g.L^{-1}$. A reduction of the sludge age (from 32 ± 2 d to 21 ± 2 d) improved sedimentation properties of the activated sludge without reducing the nitrification capacity of the system. The two-stage SBR is robust in relation to the operation with long periods with low oxygen concentration. The operation with more than 80% of the cycle time non-aerated in both reactors did not compromise the development of autotrophic biomass and, consequently, the removal of ammoniacal nitrogen. It was also possible to shorten the durations of night aeration to save energy and prolong the lifetime of batteries.

The PV system failed to fully supply energy to run the treatment all night around 3% of the time (five out of 157 days), which happened in the days when solar irradiation was 30% below average. However, the interruptions had no influence in the treatment efficiencies. The relation between the energy for oxygenation in the field (COD and nitrification) and the energy generated in the system is 30% at most.

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AUTHORS' CONTRIBUTIONS

Dufner, L.: Conceptualization, Methodology, Data curation, Investigation, Writing — original draft. Selvam, T.S.S.: Methodology, Data curation, Investigation & Writing — original draft. Otto, N.: Formal Analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing — review & editing. Neuffer, D.: Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing — review & editing. Santos, H.R.: Supervision, Formal Analysis, Writing – review & editing.

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