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ORIGINAL PAPER

Structured-bed reactor with intermittent aeration and recirculation (SBRRIA) for treating UASB effluent combined with raw sewage

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Abstract

A long-term structured-bed reactor subjected to recirculation and intermittent aeration (SBRRIA) was operated to remove chemical oxygen demand (COD) and total nitrogen (TN) from sanitary sewage using different operational strategies. Upflow anaerobic sludge blanket (UASB) effluent has a low carbon to nitrogen (C/N) ratio, which is unfavorable for nitrogen removal. Consequently, to attempt to solve this problem, the SBRRIA was fed with raw sewage (S1) combined with UASB effluent (S2) in the following proportions (v/v): 100:0; 75:25; 50:50; 25:75 and 0:100. The effects of hydraulic retention times (HRT), of 12 and 8 h; internal recirculation of 300, 200 and 100%; and aeration periods of 180, 90 and 60 min in 180-min cycles, were also evaluated. The influent COD in the SBRRIA ranged from 83 ± 10 to 200 ± 74 mg L^{-1}, and the total Kjeldahl nitrogen (TKN) content ranged from 35 ± 7 to 60 ± 18 mg L^{-1}. In Phase 2, with 8 h HRT and internal recirculation of 200%, the efficiencies in COD and TN removal were up to 91 and 78%, respectively. This study demonstrates the viability of a SBRRIA to remove COD and TN from influent composed of raw sewage and/or UASB effluent, enabling an increase in capacity of existing wastewater treatment plants (WWTP) or an adaption of the characteristics of effluent from anaerobic reactors to the release standards required by Brazilian legislation.

Keywords Denitrification · Long-term operation · Low C/N · Nitrification · Polyurethane foam · Simultaneous nitrification and denitrification

Introduction

Because of problems caused by excessive amounts of nutrients discharged into water bodies, wastewater treatment plants (WWTPs) have been remodeled to remove nitrogen from effluent. The majority of Brazilian WWTPs were designed to remove COD but not nutrients, and Brazilian WWTPs that only have anaerobic processes are an example of this. Chernicharo et al. (2018) carried out a survey of the most used technologies for sewage treatment in the south, southeast and central-west regions of Brazil. They found that UASB reactors were used in approximately 40% of the studied WWTPs. In the southern Brazilian state of Paraná, UASB reactors are operated in 89% of WWTPs (258 units), which can be considered the largest UASB reactors park in Brazil and probably the world (Chernicharo et al. 2018).

In conventional WWTPs that involve TN and COD removal, the nitrification and denitrification phases take place in separate units, which makes system implementation and monitoring more expensive (Seifi and Fazaelipoor 2012; Li et al. 2015; Iannacone et al. 2021; Souza et al. 2021).

Simultaneous nitrification and denitrification (SND) systems can simplify operations because they combine nitrification and denitrification in a single reactor (Liu et al. 2010; Guo et al. 2013; Moura et al. 2018b). Other advantages of SND include: a low carbon and alkalinizing requirement; reduced costs for the treatment and final disposal of sludge due to a decrease in the generation of solids; and less energy

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consumption for aeration because part of the oxygen used to stabilize organic matter is in the form of nitrite and nitrate (Yoo et al. 1999; Chiu et al. 2007; Canto et al. 2008; He et al. 2009; Iannacone et al. 2019).

Studies of SBRRIA show that this technology is capable of promoting the removal of COD and TN in a single unit (Moura et al. 2012, 2018a, 2018b; Barana et al. 2013; Wosiack et al. 2015; Santos et al. 2016; Leick et al. 2017; Silva et al. 2018). SND occurs in this type of reactor due to the oxygen concentration gradient in the support medium, which is made of foam. This favors the formation of aerobic communities on the outer layers, where the oxygen concentration is high, and facultative communities in the inner layers, with the absence of oxygen. Aerobic autotrophic bacteria, which oxidize ammonium nitrogen, predominate on the biofilm surface, and denitrifying heterotrophic facultative bacteria, which use NO_3^- or NO_2^- as final electron acceptors and convert them into N_2, predominate in the deeper layers (Munch et al. 1996; Zeng et al. 2003; Seifi and Fazaelipoor 2012).

Some researchers have studied the use of SBRRIA for sewage treatment. Silva et al. (2018) evaluated COD and TN removal from UASB effluent, and Moura et al. (2018b) studied the effect of aeration time and HRT on COD and TN removal from raw sewage. Jenzura et al. (2018) evaluated COD and TN removal from an influent composed of a mixture of UASB effluent and raw sewage in the same proportion.

As far as we are aware, there are no literature reports that discuss the use of SBRRIA for treating a mixture of different proportions of real untreated sewage and real UASB effluent. Also, there are no literature reports that studied long-term operation SBRRIA. The benefits of this combination are (a) the availability of electron donors for denitrification from raw sewage; and (b) the possibility of taking advantage of the anaerobic process such as the reduction of energy consumption and of sludge generation.

Considering the adaptation of existing WWTPs, which use UASB as one of the treatment steps and the methane generated as an energy source, this 453-day study aimed to evaluate the effect of aeration, HRT, recirculation and different proportions of UASB effluent and untreated sewage on the efficiency of COD and TN removal. The data obtained will be useful for WWTP managers to design strategies to improve systems, aiming to remove nutrients and polishing of effluent to comply with legislation.

Materials and methods

Influent

The SBRRIA was fed with a mixture of different proportions of two substrates: raw sewage and UASB effluent. Both of these were collected from a WWTP located in the state of Paraná in southern Brazil that serves about 100,000 inhabitants and has an average flow of 100L s^{-1} on dry days and 200L s^{-1} in the rainy season. The HRT of the WWTP UASB is 8 h.

The raw sewage was collected after preliminary treatment, bar screen and grift chamber and the UASB effluent was collected at the exit of the reactor.

Prior to feeding, the alkalinity of the influent was corrected with sodium bicarbonate in the proportion of 7.14 mg $CaCO_3$ to 1 mg TKN, to offer the necessary alkalinity for nitrification to occur.

Start-up and bacteria adaptation

Before this experiment, the reactor had been successfully operated without interruption for more than 300 days with an HRT of 12 h, and intermittent aeration cycle to treat raw sewage by the SND process by Leick et al. (2017), that inoculated the reactor following the methodology described by Zaiat et al (1994), immersing the support material in a 1:1 mixture of aerobic sludge from an activated sludge reactor rich in nitrifying bacteria, and anaerobic sludge from a UASB; both of the reactors treated domestic sewage. To adapt the existing bacteria to the new condition, the reactor was operated with 12 h HRT, continuous aeration, and a substrate composed of a mixture of 50% raw sewage and 50% UASB effluent. After 28 days in this condition, SND occurred, with NH_4^+ consumption, and NO_3^- generation and consumption.

Experimental setup and operation

This study used a cylindrical, acrylic SBRRIA reactor that was 80.0 cm high, with an internal diameter of 14.5 cm and a useful volume of 8.4 L. The reactor was filled with 13 cylinders made of polyurethane (PU) foam, 2.0 cm in diameter and 70.0 cm high, which were used as support for adherence and biomass growth. The support material was arranged vertically and fixed inside the reactor (Fig. 1).

This experiment was performed in two phases, which differed in relation to operational conditions (Table 1). In Phase 1, operated for 256 days, the operational variables of aeration periods and recirculation rates were studied, maintaining the HRT fixed at 12 hours, a 1:1 ratio of raw sewage (S1), and UASB effluent (S2) for the influent. In Phase 2, operated for 183 days, less aeration time was used, aiming to save energy; the HRT was reduced to 8 h and recirculation was fixed at 200%. Different proportions of S1 and S2 were also used to evaluate the different quantities of electron donors in the denitrification process. The operational conditions of each experimental phase were defined using the

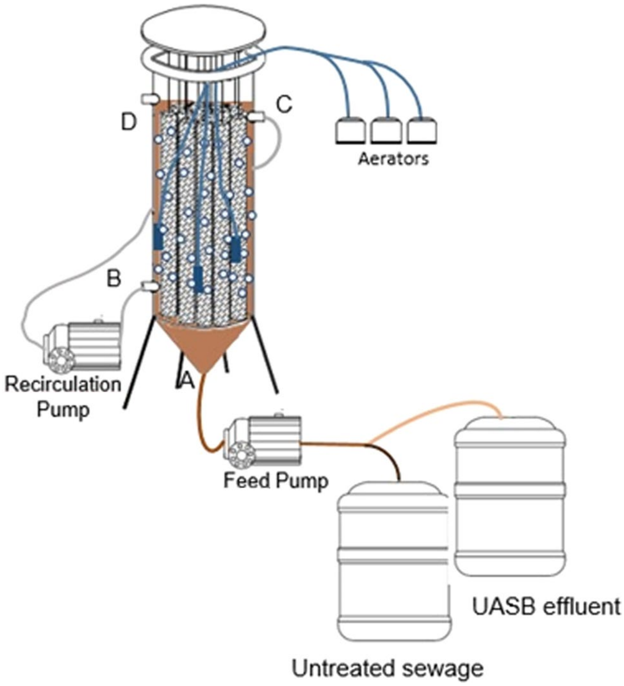

Fig. 1 Schematic diagram of the SBRRIA (A: Inlet; B: Inlet recirculation; C: Recirculation exit; D: Effluent discharge)

Table 1 Operational conditions and influent composition

Test	Infl. composition (%)		Internal recirculation (%)	Aeration (ON/OFF) (min)	Time (day)
	E1	E2			
Phase 1–HRT = 12 h					
1	50	50	300	180/0	0–21
2	50	50	300	90/90	21–46
3	50	50	300	60/120	46–97
4	50	50	200	180/0	97–125
5	50	50	200	90/90	125–160
6	50	50	200	60/120	160–182
7	50	50	100	180/0	182–202
8	50	50	100	90/90	202–225
9	50	50	100	60/120	225–256
Phase 2–HRT = 8 h					
10	0	100	200	60/120	256–287
11	25	75	200	60/120	287–332
12	50	50	200	60/120	332–350
13	75	25	200	60/120	350–394
14	100	0	200	60/120	394–439

E1: untreated sewage; E2: UASB effluent

results from Moura et al. (2012), Leick et al. (2017), Moura et al. (2018a), Moura et al. (2018b) and Silva et al. (2018).

The aeration system was formed of 3 aquarium air compressors (AcquaFlux), with a flow rate of 35 L h^{-1}, connected to a timer that allowed intermittent aeration. Porous stones were connected to the ends of the aeration hoses to allow air to diffuse into the liquid in the form of small bubbles. During aerobic periods, the concentration of dissolved oxygen in the reactor was maintained between 2.9 and 3.5 mg L^{-1}, and close to 0 when the aerators were turned off. The reactor was fed continuously, and the system was maintained at 30±1 °C.

The influent was pumped into the reactor from the bottom (A) using a peristaltic pump (Ismatec brand, Ecoline model). The recirculation was performed using a Prominent Dosiertechnik, GmbH model, membrane pump. The effluent left at the top of the reactor (C) and its recirculation entered at the bottom (B), favoring the mixing and dilution of the influent with the effluent. The recirculation input (B) was 5 cm above the inflow (A) to allow the sedimentation of solids. The output of the treated effluent was located at the top of the reactor (Fig. 1).

Table 1 shows the conditions of the tests that were performed. E1 was defined as the concentration of raw sewage (after preliminary treatment) and E2 was defined as the effluent from the UASB.

Physicochemical analysis

In order to analyze the reactor efficiency, the pH, alkalinity, TKN, ammoniacal nitrogen (NH_4^+-N), nitrite (NO_2^--N), nitrate (NO_3^--N) and COD parameters were monitored according to the methods described in the APHA (2017). Alkalinity was determined according to the method proposed by Ripley et al. (1986).

All the analyses were performed in duplicate. In order to analyze the efficiency of each test, samples were taken in a steady state period. The reactor was considered to be in steady state when the results of removing nitrite and nitrate effluent did not differ by 10% from the average.

Balance of total alkalinity and nitrogen

Considering the conventional SND process as the main pathway of each test, the balance of the theoretical and measured alkalinity of the effluent was calculated based on the balance of the influent and effluent nitrogen concentrations. Knowing that for nitrification, 1 mg of NH_4-N consumes 7.14 mg of $CaCO_3$, and for denitrification, 3.57 mg of $CaCO_3$ is generated for 1 mg of NO_3-N, the theoretical alkalinity was calculated using the results presented in Table 4 and the equations shown below Table 4.

Results and discussion

The concentrations of all the parameters were expressed as averages for all the tests. The presented results refer to the continuous operation of the reactor over 439 days.

Long-term performance of the SBRRIA

The influent COD concentration varied from 83 ± 10 to 237 ± 123 mg L $^{-1}$, depending on the variation of the characteristics of the sewage influent to the WWTP and the E1/E2 proportions. The TKN influent concentration did not vary much because there was no removal of TN during anaerobic treatment (Table 2).

In Phase 1, operated with 12-h HRT and influent composed of a S1:S2 mixture of 1:1, independently of the recirculation and aeration conditions it was possible to meet the COD and NH_4-N discharge standards in all of the conditions. The effluent COD values ranged from 27 ± 30 to 68 ± 22 mg L $^{-1}$, and the local regulation is 150 mg L $^{-1}$ (Grant Ordinance 488/2018-Paraná Water and Soil Institute). The NH_4^+-N concentration reached a maximum value of 7.1 ± 3 mg L $^{-1}$, which is less than the value permitted by Brazilian federal legislation, i.e., 20 mg NH_4^+-N L $^{-1}$ (Brasil 2011). Effluent NO_2-N concentrations were also found in low concentrations in Phase 1, up to 3.2 ± 0.7 in all the tests. Nitrification efficiency varied from 68 ± 13 to 98 ± 3% (Table 3), which explains the low effluent nitrite concentrations. The lowest effluent NO_3-N concentrations were observed in tests 4, 5 and 6, with 200% internal recirculation, and they varied from 4.9 ± 2.6 to 13.3 ± 0.4 (Table 2). In addition, these tests presented the highest denitrification rates, from 62 ± 3 to 87 ± 1%, in Phase 1 (Table 3).

After studying the aeration and internal recirculation parameters, the lowest aeration time and 200% of internal recirculation were chosen for Phase 2, where different influent proportions of S1 and S2 were evaluated (Tests 10 to 14).

It can be observed that the nitrification efficiency in Phase 2 decreased from 85 ± 11 to 69 ± 13%, tests 10 to 14, when the influent concentration COD increased from 83 ± 10 to 200 ± 74 mg L $^{-1}$ (Tables 2 and 3). The highest TN removal (78%) took place in test 10, while the lowest (50%) occurred in test 14, whose removal of influent COD was the highest. The same behavior was observed by Fu et al. (2009), Santos et al. (2016) and Moura et al. (2018b). In the presence of oxygen and the availability of excess organic matter, aerobic heterotrophic bacteria compete with aerobic autotrophic nitrifiers for the electron acceptor, O_2. As aerobic heterotrophic bacteria are more energy efficient than nitrifying autotrophic bacteria, they prevail, occupying space and consuming oxygen (Schmidt et al. 2003; Kulikowska et al. 2010; Ding et al. 2012; Wu et al. 2012; Santos et al. 2016; He et al. 2018; Iannacone et al. 2019; Iannacone et al. 2020). Although the COD/TKN ratios in most of the tests evaluated in Phase 2 were below 4.0, a value considered as the minimum adequate for the occurrence of heterotrophic denitrification, the denitrification efficiency ranged from 74 ± 18 to 86 ± 14% (Table 3), resulting in low levels of nitrite and nitrate in the reactor effluent (Table 2).

Table 2 Average characterization of the influent and effluent of each test of the two evaluated phases

Test	Influent (mg L $^{-1}$)				Effluent (mg L $^{-1}$)				
	TKN	NH_4-N	COD	COD/TKN	TKN	NH_4^+-N	NO_2^--N	NO_3^--N	COD
Phase 1–HRT = 12 h									
1	52 ± 4	46 ± 4	134 ± 21	2.6	0.9 ± 0.8	0.7 ± 1	1.0 ± 0.8	14.0 ± 0.8	34 ± 19
2	47 ± 5	47 ± 3	203 ± 128	4.3	1.8 ± 1.1	1.5 ± 2	3.2 ± 0.7	16.7 ± 3.2	43 ± 35
3	47 ± 3	47 ± 3	237 ± 123	5.0	1.7 ± 1.4	1.1 ± 1	0.7 ± 0.6	13.5 ± 2.7	27 ± 30
4	46 ± 4	30 ± 10	148 ± 26	3.2	4.6 ± 2.6	7.1 ± 3	0.3 ± 0.4	4.9 ± 2.6	39 ± 10
5	47 ± 4	39 ± 5	143 ± 26	3.0	8.9 ± 9.6	4.1 ± 10	0.9 ± 0.2	9.5 ± 4.3	40 ± 18
6	40 ± 0	32 ± 4	147 ± 20	3.7	3.4 ± 0.3	2.8 ± 0.4	0.8 ± 0.3	13.3 ± 0.4	41 ± 16
7	45 ± 3	28 ± 7	155 ± 30	3.4	5.3 ± 2.5	4.6 ± 5	2.5 ± 0.8	15.3 ± 1.1	33 ± 20
8	45 ± 11	26 ± 7	148 ± 29	3.3	4.5 ± 1.6	4.2 ± 2	2.4 ± 0.5	13.8 ± 1.5	60 ± 15
9	42 ± 5	27 ± 5	175 ± 45	4.2	5.0 ± 1.1	4.6 ± 1	2.6 ± 1.6	13.5 ± 1.4	68 ± 22
Phase 2–HRT = 8 h									
10	37 ± 8	32 ± 5	83 ± 10	2.3	6 ± 6	3 ± 1	3 ± 1	2 ± 0.12	14 ± 5
11	35 ± 7	27 ± 4	147 ± 17	4.2	8 ± 6	6 ± 4	5 ± 3	2 ± 0.10	36 ± 27
12	36 ± 2	32 ± 3	134 ± 52	3.7	12 ± 1	10 ± 2	4 ± 1	2 ± 0.04	18 ± 9
13	41 ± 11	27 ± 8	168 ± 12	4.2	13 ± 2	4 ± 4	2 ± 1	2 ± 0.06	16 ± 8
14	60 ± 18	46 ± 8	200 ± 74	3.3	19 ± 9	22 ± 2	5 ± 2	2 ± 0.13	25 ± 13

E1: untreated sewage; E2: UASB effluent

Values represent the mean ± standard deviation

Table 3 Efficiencies in COD removal, nitrification, denitrification and TN removal, TN loading rate (NLR)

Test	E1/E2	COD	Nitrif. (%)	Denitrif	TNrem	NLR (kg N m^{-3} d^{-1})
Phase 1 HRT = 12 h						
1	50/50	74	98 ± 3	71 ± 11	70 ± 4	0.103
2	50/50	78	96 ± 2	56 ± 9	54 ± 3	0.090
3	50/50	88	95 ± 10	54 ± 6	52 ± 10	0.090
4	50/50	73	89 ± 11	87 ± 1	78 ± 3	0.091
5	50/50	71	81 ± 8	73 ± 2	59 ± 8	0.090
6	50/50	70	91 ± 10	62 ± 3	56 ± 11	0.080
7	50/50	78	89 ± 12	56 ± 12	50 ± 10	0.090
8	50/50	59	90 ± 6	60 ± 3	54 ± 9	0.090
9	50/50	60	88 ± 6	56 ± 8	50 ± 7	0.083
Phase 2–HRT = 8 h						
10	0/100	83	85 ± 11	86 ± 5	78 ± 11	0.097
11	25/75	76	79 ± 11	74 ± 18	63 ± 16	0.082
12	50/50	86	68 ± 3	76 ± 4	56 ± 4	0.095
13	75/25	91	70 ± 17	86 ± 14	64 ± 18	0.081
14	100/0	84	68 ± 13	83 ± 11	50 ± 15	0.139

Values represent the mean ± standard deviation. E1: raw sewage; E2: UASB effluent

Table 4 Balance of total alkalinity consumed and generated in each test

Test	Oxidized nitrogen [A]	Ammonified nitrogen [B]	Denitrated nitrogen [C]	Alkalinity influent measured [D]	Theoretical alkalinity consumed [E]	Total theoretical alkalinity generated [F]	Theoretical effluent alkalinity [G]	Measured effluent alkalinity
	($mgN.L^{-1}$)			($mgCaCO_3 L^{-1}$)				
10	31	2	29	264 ± 57	221	110	153	86 ± 39
11	27	6	25	249 ± 49	192	110	188	109 ± 53
12	24	2	22	257 ± 14	171	85	171	168 ± 82
13	28	5	26	292 ± 78	199	110	203	84 ± 59
14	37	13	35	428 ± 129	264	171	335	221 ± 114

Values represent the mean ± standard deviation

$A = TKN_{influent}\text{-}TKN_{effluent}$

$B = (TKN_{influent}\text{-}NH_4\text{-}N_{influent})\text{-}(TKN_{effluent}\text{-}NH_4\text{-}N_{effluent})$

$C = (TKN_{influent}\text{-}TKN_{effluent})\text{-}NO_3\text{-}N_{effluent}\text{-}NO_2\text{-}N_{effluent}$

$E = A \times 7.14\ mgCaCO_3\ L^{-1}$

$F = C \times 3.57\ mgCaCO_3\ L^{-1} + B \times 3.57\ mgCaCO_3\ L^{-1}$

$G = D + F\text{-}E$

Systems with immobilized biomass can produce increased efficiency in terms of nitrogen removal. This is because they ensure the retention of nitrifying bacteria, whose growth is slow due to low energy usage, so that the cell retention time does not depend on the HRT, increasing the stability and performance of the system (Wijffels and Tramper 1995; Rostron et al. 2001; Almeida et al. 2018; Chen et al. 2018). Iannacone et al. (2019) operated a moving-bed biofilm reactor (MBBR) with micro-aeration; after a long operation period (227 days) they evaluated the nitrification and denitrification activities on the biofilm. The nitrifying and denitrifying activities for the C/N ratio of 5.6 were 81 and 66 mg N g VSS^{-1} d^{-1}, respectively, while for a C/N ratio of 2.7 these activities were, respectively, 3.9 and 2.3 times larger. In the present study, it can be assumed that in test 10, with a lower concentration of influent COD, the development of heterotrophic aerobic bacteria was lower, which resulted in a better balance of oxygen and space for the growth of nitrifying autotrophs, justifying the higher nitrification rate. It is noteworthy that the influent of test 10 consisted only of the UASB effluent, since it had already undergone a treatment process.

The remaining organic matter was difficult to degrade, which probably reduced the speed of its use by aerobic heterotrophic bacteria, making it available for denitrifying organisms.

The fact that this reactor had been operated for a long time, more than 400 days, promoted the stability of the system due to the adaptation of the bacteria to the operational conditions. Iannacone et al. (2019) operated a MBBR for more than 200 days and observed that changes in operational conditions produced both short- and long-term effects. They concluded that the longer the operation, the more efficient the nitrification and denitrification process at C/N ratio 4.2

In the present study, the rate of TN removal was also explained by the high retention of solids in the reactor. This was due to the characteristics of the foam used as support, which allowed the retention of solids. In this experiment, the average retention of total solids was 59% (data not shown). The retained solids may have been used as a source of organic matter for denitrifying heterotrophic bacteria. Almeida et al. (2018) and Silva et al. (2018) have highlighted the fact that when there is little COD availability part of the biomass can also be used as a source of endogenous carbon for heterotrophic denitrification. After having studied SND in a reactor with a long cell retention time to treat sewage with a C/N ratio between 2.5 and 4.0, Gong et al. (2012) observed high efficiency in TN removal, which they attributed to endogenous denitrification. After analyzing SND with a low DO concentration and a C/N ratio below 3.5, Wang et al. (2015) achieved good rates for TN removal, which was also attributed to endogenous denitrification. After operating the same type of reactor used in the present study (SBRRIA) to treat different effluents with a C/N ratio below 3, Barana et al. (2013), Santos et al. (2016) and Almeida et al. (2018) observed the occurrence of the anammox process in all the experiments. The anammox process takes place in this type of reactor because the biomass immobilizes in the foam due to the oxygen gradient. This allows the development of communities in aerobic, anoxic and anaerobic conditions, enabling the removal of various forms of nitrogen by different metabolic pathways.

To confirm the occurrence of the SND process (nitrification from ammonium to nitrate, and heterotrophic denitrification) in Phase 2, the mass balance of the measured influent alkalinity and theoretical and measured effluent alkalinity was performed (Table 4). Lower values for measured effluent alkalinity when compared with theoretical values, Test 10, 11, 13 and 14, suggest the presence of anammox bacteria that consume alkalinity (Moura et al., 2018a), but more investigations must be doing to confirm this occurrence. Moura et al. (2018a) evaluated raw sewage treatment in a SBRRIA and also found real effluent alkalinity value lower than the theoretical one, but they did not find bacterial genus related to anammox.

Conclusion

The operation of the SBRRIA for a long period of time (more than 400 days) showed it was efficient regarding COD and TN removal without the need for an external carbon source. The SBRRIA was operated with 8 h HRT, 60 aerated minutes followed by 120 min of no aeration (180-min cycles) and was fed with a mixture of raw sewage and UASB effluent (proportions of 0:100, 25:75, 50:50, 75:25 and 100:0). It reached effluent concentrations of COD in a range from 14 ± 5 to 68 ± 22 mg L $^{-1}$; of NH_4-N from 3 ± 1 to 12 ± 2 mg L $^{-1}$; and maximum concentrations of NO_2-N and NO_3-N of 5 ± 3 mg L $^{-1}$ and 2 ± 0.13 mg L $^{-1}$, respectively.

Thus, it can be concluded that using a SBRRIA represents an alternative for the treatment of raw sewage, and for the polishing of UASB effluent or of a mixture of this effluent with raw sewage, which will also allow WWTPs to increase levels of treated flow. In addition, the use of a SBRRIA should ensure that effluent reaches legal requirements for effluent discharge standards.

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Declarations

Conflict of interest The authors declare that they have no competing financial interests.

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