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EFEITO DA TAXA DE AERAÇÃO NO DESEMPENHO DE ALAGADOS CONSTRUÍDOS AERADOS INTERMITENTEMENTE

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1 RESUMO

O presente trabalho foi conduzido com o objetivo de avaliar o efeito de diferentes taxas de aeração na remoção de nitrogênio total (NT) e demanda química de oxigênio (DQO) em alagados construídos de fluxo subsuperficial horizontal (ACFH) aerados intermitentemente. Para isso, foram avaliados quatro ACFH em escala piloto utilizando diferentes taxas de aeração (0; 2; 5 e 10 L min^{-1}) com intervalo de aeração intermitente fixo de 3 h d^{-1} (1h com aeração/7 horas sem aeração). Os sistemas receberam 8,6 L d^{-1} de efluente sintético, resultando em tempo de detenção hidráulica de 3 dias. Os resultados mostram que os ACFH aerados intermitentemente apresentaram elevada eficiência na remoção de DQO (>97%), NT (>80%) e NH_4^+ (>97%), enquanto o ACFH sem aeração apresentou menor eficiência na remoção de DQO (93,9%), NT (48,8%) e NH_4^+ (57,7%). Adicionalmente, os resultados também mostram que os três ACFH aerados intermitentemente obtiveram desempenho similar na remoção de DQO, NT e NH_4^+. Finalmente, os resultados permitem concluir que a aeração intermitente permite a ocorrência simultânea da nitrificação e da desnitrificação, aprimorando, assim, o desempenho dos ACFH na remoção de NT. Entretanto, o uso de diferentes taxas de aeração não altera a eficiência de remoção de NT e DQO.

Palavras-chave: aeração artificial, remoção de DQO, remoção de nitrogênio.

QUELUZ, J. G. T.; YABUKI, L. N. M.; GARCIA, M. L.
EFFECT OF AERATION RATE ON THE PERFORMANCE OF INTERMITTENTLY AERATED CONSTRUCTED WETLAND

2 ABSTRACT

The aim of the present work was to evaluate the effect of different aeration rates on the removal of total nitrogen (TN) and chemical oxygen demand (COD) in intermittently aerated horizontal subsurface flow constructed wetlands (HFCW). Four pilot-scale HFCWs were evaluated using different aeration rates (0, 2, 5, and 10 L min^{-1}) with a fixed intermittent aeration interval of 3 h d^{-1} (1 h with aeration / 7 h without aeration). The HFCWs received 8.6 L d^{-1} of synthetic effluent, resulting in a hydraulic retention time of 3 days. The results show that intermittently aerated HFCWs were highly efficient in removing COD (>97%), TN (>80%) and $NH4^+$ (>97%), while the HFCW without aeration showed lower efficiencies in the removal of COD (93.9%), TN (48.8%), and $NH4^+$ (57.7%). In addition, the results also show that the three intermittently aerated HFCW achieved similar performance in the removal of COD, TN, and

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NH4+. Finally, the results indicate that intermittent aeration allows the simultaneous occurrence of nitrification and denitrification, thus improving the performance of HFCW in removing TN. However, the use of different aeration rates does not alter COD and TN removal efficiencies.

Keywords: artificial aeration, COD removal, the nitrogen removal.

1 INTRODUCTION

Subsurface flow constructed wetlands are easy-to-operate, simple, and inexpensive wastewater treatment systems with high organic matter, solid, and pathogen removal efficiency, making them ideal for isolated, low-income rural communities. However, owing to the limited supply of dissolved oxygen (DO), the total nitrogen (TN) removal efficiency in subsurface flow constructed wetlands is limited (SAEED; SUN, 2012; WU et al., 2014). Nitrification is the primary limiting process for TN removal, since nitrifying bacteria depend on the availability of DO (FAN et al., 2013).

Thus, to allow effective nitrification, continuous artificial aeration was implemented in constructed wetlands as an alternative to supplemental oxygen (BUTTERWORTH et al., 2013). Although continuous artificial aeration allows nitrification, the high DO concentrations supplied to the system can change the medium conditions from anoxic/anaerobic to aerobic, inhibiting the denitrification process, which consequently limits TN removal (MALTAIS-LANDRY et al., 2009; NIVALA et al., 2007).

On the other hand, recent studies have shown that the use of intermittent artificial aeration is preferable since it alternates the environmental conditions between aerobic and anoxic conditions, allowing nitrification and denitrification processes to occur simultaneously and increasing the efficiency of NT removal .

(UGGETTI et al., 2016; WU et al., 2016a; LIU et al., 2019).

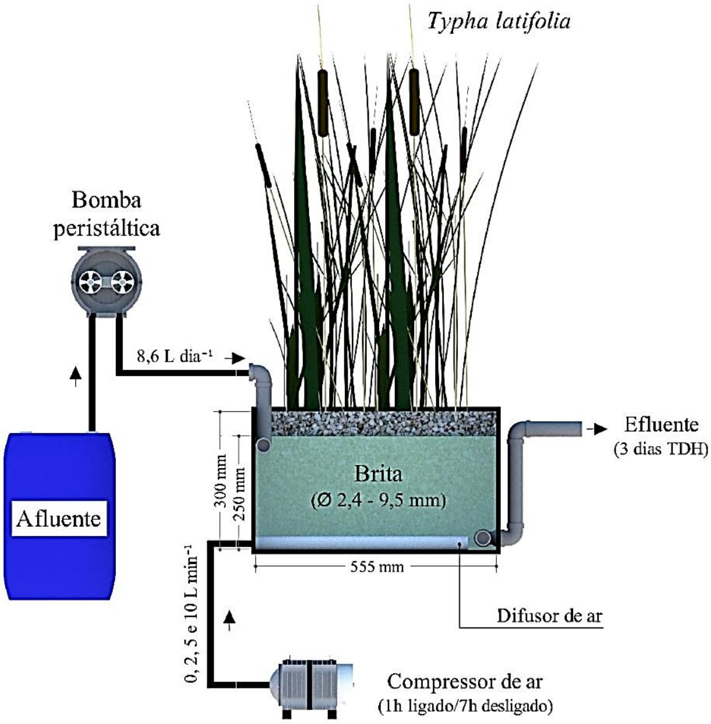
However, most studies have evaluated the effects of intermittent aeration in vertical subsurface flow (VSF)-constructed wetlands with fixed aeration rates. Therefore, the objective of this study was to evaluate the effects of different aeration rates on the removal of TN and COD in intermittently aerated horizontal subsurface flow (HSF) constructed wetlands.

2 MATERIAL AND METHODS

4.1 Characteristics of the treatment system

The experiment was carried out in a protected environment (agricultural greenhouse) at the Center for Environmental Studies (CEA) - UNESP, Rio Claro-SP, Brazil. The treatment system consisted of four pilot-scale ACFHs. Each of the ACFHs consisted of a rectangular polypropylene water tank with an approximate capacity of 61 liters (31.0 × 35.5 × 55.5 cm), and as a support medium, gravel #0 (Ø = 2.4–9.5 mm) with 53% porosity was used. The water tanks were filled with support material to a height of 30 cm, and the effluent level was maintained at 25 cm, resulting in an approximate saturated volume of 26 liters. The systems were cultivated with *Typha latifolia*. Figure 1 shows a schematic diagram of ACFHs.

Figure 1. Schematic diagram of constructed wetlands



4.2 Aeration rates

The ACFHs were aerated intermittently for 3 h day^{-1} (1 h aerating/7 h without aeration), and different aeration rates were used in each system: AC1: without aeration (0 L min^{-1}); AC2: 2 L min^{-1}; AC3: 5 L min^{-1}; and AC4: 10 L min^{-1}. Different aeration rates were obtained via the use of commercially available air compressors. Air was applied to the systems via a tubular diffuser (porous hose for fish farming) installed at the bottom and along the longitudinal section of the polypropylene boxes.

4.3 System operation, influent origin and retention time

The systems were operated for 250 consecutive days from April 2, 2018, to December 7, 2018. The synthetic effluent was prepared via the addition of 387 mg/L sucrose, 188 mg/L (NH_4), $2SO_4$, 18 mg/L KH_2PO_4, 10 mg/L $MgSO_4$, 10 mg/L $FeSO_4$, and 10 mg$_{/L\ CaCl2}$, as described in the works of Fan et al. (2016), Wu et al. (2015a) and Wu et al. (2016a). Using peristaltic pumps, 8.6 L/day of synthetic effluent was applied to the ACFHs, resulting in 3 days of hydraulic retention time (HRT). Along the ACFHs, sample collection points were located at distances of 0, 18.5, 37 and 55.5 cm from the influent inlet zone. The TDH of each collection point was assumed to be proportional to its relative distance to the beginning of the ACFH; therefore, the TDHs adopted for each collection point were 0, 1, 2 and 3 days.

4.4 Sample analysis

At each collection point, five samples were taken to determine the concentrations of COD, NH^{4+}, NO_3^-, NO_2^-, and pH. TN concentrations were estimated by the sum of the other nitrogen forms. The DO levels inside the ACFH were determined *in situ via a portable* Akso DO meter (model: DO Eco 1.00). All samples were collected, stored and analyzed according to the methodologies described by the American Public Health Association (2012) from 11/01/2018 to 12/07/2018, with the exception of DO determinations, which were performed from 09/17/2018 to 09/21/2018.

4.5 Statistical analysis

The COD and NT data obtained from the ACFHs were compared via analysis of variance (ANOVA), and the discrimination between the means was performed via the Tukey test. The analyses were performed via the statistical program Statgraphics (version 16.2.04), and for both tests (ANOVA and Tukey), a significance level of 5% ($P < 0.05$) was adopted.

3 RESULTS AND DISCUSSION

5.1 Overall performance of treatment systems

Table 1 shows the characteristics of the influent and effluent of the four ACFHs and their respective removal efficiencies. The systems with intermittent aeration (AC2--4) presented high removal efficiencies. Notably, the COD, TN and NH_4^+ removal rates of these systems were similar but higher than those of the system without aeration (AC1).

Table 1. Influent and effluent characteristics of the four ACFHs and their respective removal efficiencies (mean ± SD, n = 5)

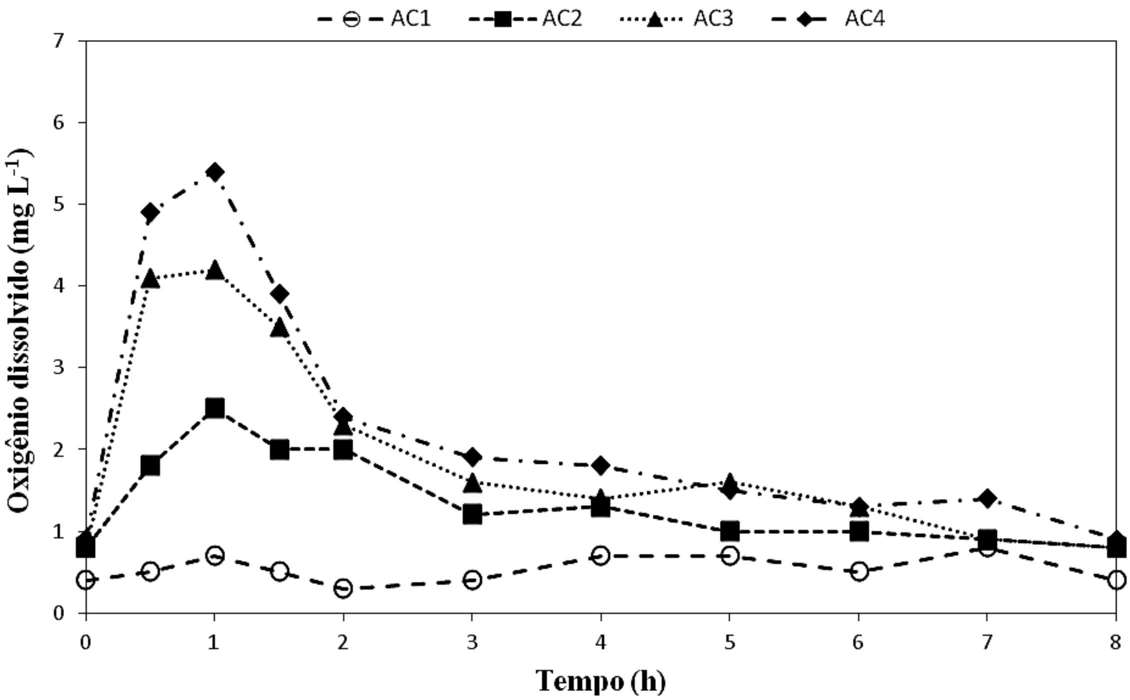
Parameter	Affluent	ACFH effluent			
		AC1	AC2	AC3	AC4
COD (mg L^{-1})	388.8 ± 19.7	23.8 ± 6.6	9.6 ± 5.1	8.2 ± 3.7	9.4 ± 4.3
(%)	-	93.9 ± 1.6	97.5 ± 1.4	97.9 ± 1.0	97.6 ± 1.1
NT (mg L^{-1})	40.5 ± 2.3	20.8 ± 2.0	8.0 ± 2.6	7.9 ± 1.5	7.6 ± 1.5
(%)	-	48.8 ± 6.3	80.3 ± 7.1	80.5 ± 3.8	81.2 ± 4.4
NH_4^+ (mg L^{-1})	39.2 ± 2.3	16.5 ± 1.0	0.8 ± 0.8	0.6 ± 0.6	0.5 ± 0.5
(%)	-	57.7 ± 4.5	97.8 ± 2.2	98.4 ± 1.6	98.6 ± 1.4
NO_3^- (mg L^{-1})	1.4 ± 0.3	4.3 ± 1.6	7.0 ± 3.0	7.2 ± 1.3	7.0 ± 1.3
NO_2^- (mg L^{-1})	0.004 ± 0.002	0.02 ± 0.01	0.09 ± 0.18	0.10 ± 0.14	0.05 ± 0.07
DO (mg L^{-1})	-	0.5 ± 0.2	1.4 ± 0.6	2.0 ± 1.3	2.4 ± 1.6
pH	7.0 ± 0.3	7.1 ± 0.4	6.7 ± 0.5	6.5 ± 0.6	6.3 ± 0.6

5.2 DO concentrations

As expected and in agreement with the literature data (FAN et al., 2013; FAN et al., 2016; UGGETTI et al., 2016), AC1 presented anaerobic conditions with an average concentration of 0.5 mg L^{-1} (range: 0.3--0.8). In contrast, the systems with intermittent aeration presented higher average DO concentrations: AC2 = 1.4 mg L^{-1} (range: 0.8--2.5), AC3 = 2.0 mg L^{-1} (range: 0.8--4.2), and AC4 = 2.4 mg L^{-1} (range: 0.9--5.4). Furthermore, in AC2-4, the increase in aeration rates (2.5 to 10 L min^{-1}) increased the average concentrations and the maximum DO values in the systems.

The average DO concentrations of the four systems over an aeration cycle are shown in Figure 2. During aeration, the DO concentration increased in system AC2-4, with maximum concentrations obtained at the end of the aeration phase, with values positively correlated with the aeration rates; that is, the higher the aeration rate was, the higher the DO concentration. After aeration, during the 7-h rest period, the DO concentration decreased until it reached the minimum value observed. Similar DO profiles of intermittently aerated constructed wetlands were also described by Fan et al. (2013) and Wu et al. (2016b). Therefore, the changes in DO concentrations provided by intermittent aeration create alternating aerobic and anaerobic conditions, which consequently facilitate the simultaneous occurrence of nitrification and denitrification (FAN et al., 2012).

Figure 2. Average dissolved oxygen concentrations in the four constructed wetlands over an aeration cycle



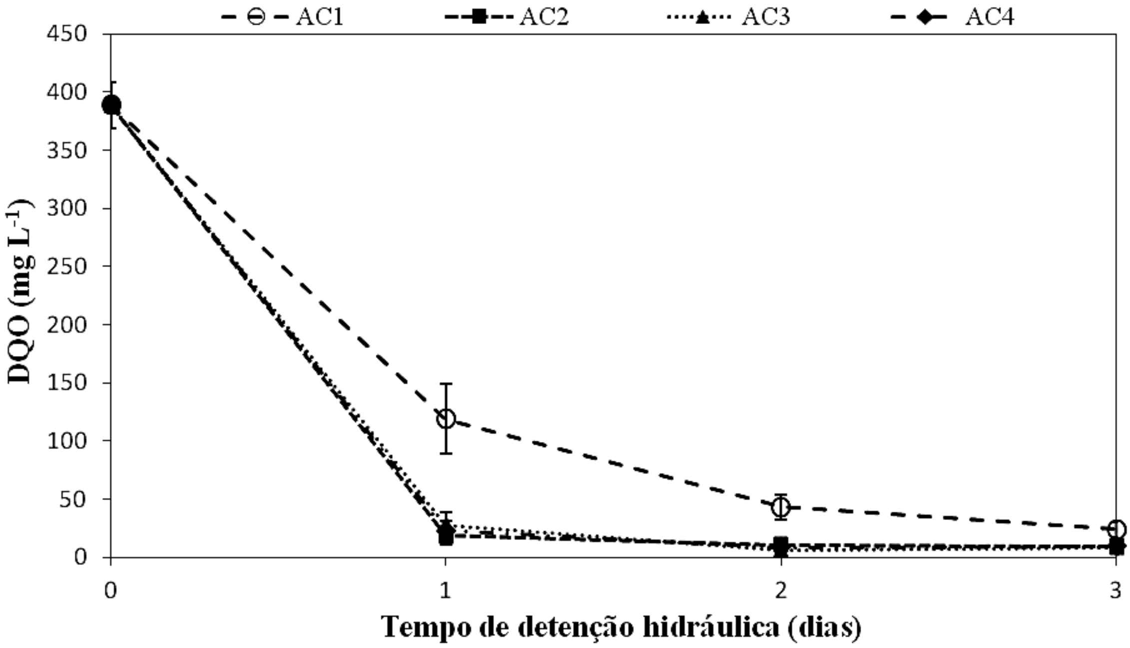
Notably, the DO levels were determined at a depth of 10 cm in the center of the systems, that is, above the air diffusers; therefore, the concentrations obtained may not adequately represent the general distribution of DO in the ACFHs under study.

5.3 COD removal

In terms of COD removal, the efficiency was greater than 90% in all systems, including AC1. However, the systems with intermittent aeration performed better. AC2, AC3, and AC4 presented COD removal rates of 97.5%, 97.9%, and 97.6%, respectively, while the COD removal rate of AC1 was 93.9%. Notably, the high organic matter removal efficiencies obtained in this study may be associated with the high biodegradability of sucrose.

The COD concentrations in the effluent of AC2, AC3, and AC4 were 9.6, 8.2, and 9.4 mg L^{-1}, respectively. The highest removal efficiency was obtained for AC 3 (97.9%), as shown in Figure 3, which also reveals that the increase in the aeration rate did not cause significant changes in the respective efficiencies of the systems; that is, the efficiencies of AC2--4 were similar (only 0.4% difference in removal efficiency). The results also revealed that the difference in COD removal between the nonaerated and aerated systems was small; the average COD concentration in the effluent of AC1 was 23.8 mg L^{-1}, and the COD concentration in ACF2-4 ranged from 9.6 to 8.2 mg L^{-1}, that is, a difference of only 3.6--4.3%. It is known that nonaerated ACFHs can present high performance in COD removal, as described by Abou-Elela et al. (2013), Caselles -Osorio et al. (2017) and Liu et al. (2018), who obtained efficiencies of 91.5%, 80--91%, and >85%, respectively. Thus, depending on the operating conditions, for example, the TDH and effluent characteristics, the efficiency of organic matter removal in nonaerated ACFHs can be similar to that in aerated systems. Butterworth et al. (2013) did not identify significant differences in organic matter (BOD) removal between nonaerated and continuously aerated systems, and Uggett et al. (2016) reported a difference of only 1% in COD removal efficiency between nonaerated and intermittently aerated systems.

Figure 3. Average COD concentrations in the four constructed wetlands in relation to hydraulic retention time



Although the final COD concentrations were similar across the four systems, there was a clear difference in the COD removal efficiency across the systems. After one day of TDH, the average COD concentration in AC2-4 decreased to 18--27 mg/L, and in AC1, it decreased to 119 mg/L, corresponding to 93--95% and 69% removal efficiency, respectively. These data are similar to those reported in the work of Wu et al. (2016a), in which the authors evaluated ACFVs and, in just 12 hours, obtained COD removal efficiencies of >88% (<50 mg L^{-1}) and 76–82% (75–100 mg L^{-1}), respectively, in intermittently aerated systems. These results indicate, therefore, that the use of intermittent aeration in constructed wetlands increases the rate of organic matter removal. The increase in the COD removal rate in the intermittently aerated ACFH may be associated with the stimulation of direct biological removal pathways (respiration/fermentation) and the removal of organic carbon during denitrification.

In constructed wetlands, organic matter can be biologically oxidized by aerobic and anaerobic processes (SAEED; SUN, 2012) and can also be removed by physical processes, such as sedimentation and filtration (ONG et al., 2010; FAN et al., 2013). A study by Ong et al. (2010) revealed that the artificial addition of oxygen facilitated the growth of aerobic microorganisms and intensified COD biodegradation. Additionally, the authors concluded that the combination of aerobic and anaerobic conditions improved the performance of constructed wetlands in removing organic matter.

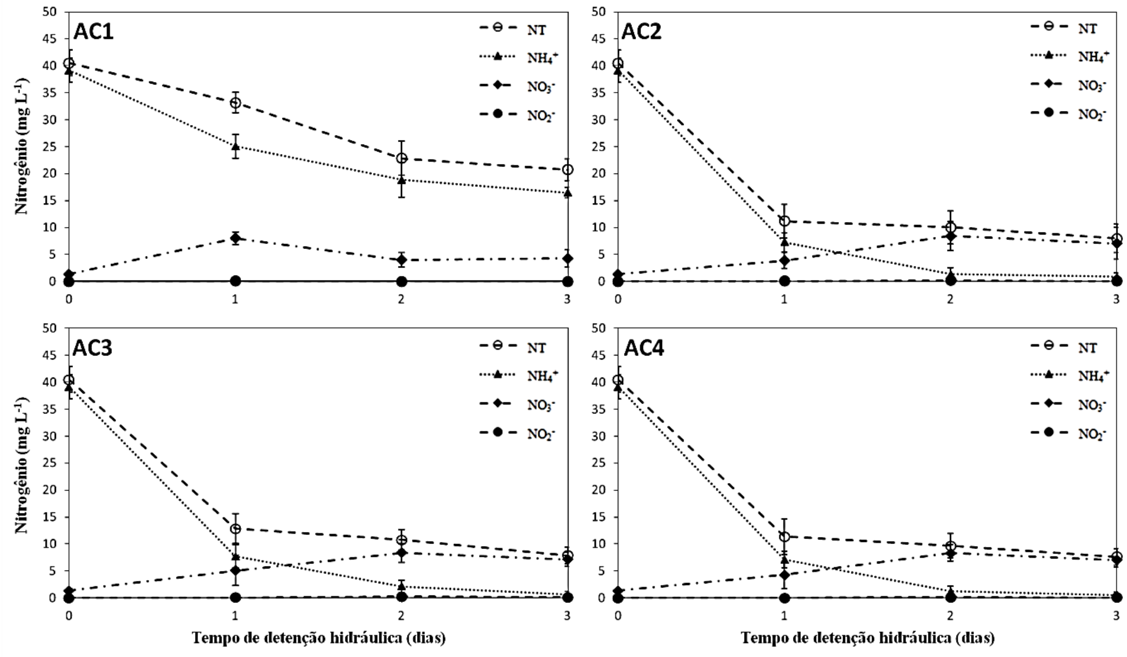
5.4 Nitrogen removal

According to Saeed and Sun (2012), nitrogen transformation and removal in subsurface flow constructed wetlands occur both through classical pathways (ammonification, nitrification/denitrification, plant uptake, biomass assimilation, and ammonia volatilization) and through recently discovered pathways (partial nitrification/denitrification, ANAMMOX, and the Canon process). Maltais-Landry et al. (2009) reported that TN removal is associated mainly with four processes: 1) plant uptake; 2) sediment storage; 3) partial nitrification/denitrification; and 4) complete nitrification/denitrification. However, complete nitrification/denitrification is considered the main mechanism of TN removal, accounting for 47 to 96% of nitrogen removal (L IN et al., 2002; MALTAIS-LANDRY et al., 2009; CHEN et al., 2014).

With respect to plants, some studies suggest that macrophytes are responsible for up to 34.3% of TN removal (MALTAIS-LANDRY et al., 2009; WU et al., 2013; CHEN et al., 2014; LIU et al., 2019). The results obtained by Maltais-Landry et al. (2009) revealed that in continuously aerated subsurface flow constructed wetlands, the species *Typha angustifolia* was responsible for the removal of approximately 135 mg N m^{-2} d^{-1}, a value that represents 7.6% of the nitrogen application rate in the present work (1768 mg N m^{-2} d^{-1}). Other authors (WU et al., 2013) estimated removal rates of 40 mg N m^{-2} d^{-1} for *Typha orientalis,* representing only 2.3% of the nitrogen applied in our study. Therefore, when analyzing the results obtained in the present study, we considered that complete nitrification/denitrification was the main route of NT removal.

The average removals of NH^{4+} and TN in AC1 were 57.7% and 48.8%, respectively, confirming that conventional ACFHs (without aeration) have limitations in terms of nitrogen removal (WU et al., 2015a). For example, Hua et al. (2017) reported NH^{4+} and TN removal rates ranging from 20.7--66.9% and 38.1--51.6%, respectively, and Wu et al. (2015b) reported values ranging from 32--61% for NH^{4+} removal and 13--44% for TN removal. On the other hand, the AC2-4 systems showed satisfactory efficiencies in the removal of NH_4^+ (97.8--98.6%) and TN (80.3--81.2%), indicating that intermittent aeration alternates between aerobic and anoxic media, which allows the simultaneous occurrence of nitrification and denitrification. These findings are similar to the results obtained by Fan et al. (2016) and Wu et al. (2016 a). Figure 4 shows the dynamics of nitrogen transformation in the five constructed wetlands.

Figure 4. Nitrogen transformation dynamics in the four constructed wetlands in relation to hydraulic retention time



Notably, the NH4+ concentration decreased rapidly in the aerated system (AC2--4), reaching values less than or equal to 7.7, 2.1, and 1 mg/L at 1, 2, and 3 days of TDH, respectively. On the other hand, AC1 had a lower NH4+ removal efficiency, with an average final concentration of 16.5 mg/L. These results were expected, since this system presented anaerobic conditions (DO = 0.3--0.8 mg L^{-1}) that consequently limited nitrification. NH4+ removal in aerated systems was greater than 97%, corroborating the findings of Li et al. (2014), who also reported almost total NH4+ removal in aerated subsurface flow constructed wetlands. Additionally, NH4+ removal in AC2-4 was ~40% greater than that observed in AC1 (57.7% vs 97.8--98.6%). Similarly, increases in the NH4+ removal efficiency between intermittently aerated and nonaerated systems of 46, 65, and 45--88% were reported in the literature by Uggeti et al. (2016), Fan et al. (2016), and Liu et al. (2019), respectively. Finally, these results show that artificial aeration creates suitable conditions for the effective occurrence of nitrification in constructed wetlands.

Figure 4 also shows that the removal pattern of NT was similar to that of the NH4+ removal pattern; that is, the NT concentrations decreased faster in the aerated systems (AC2--4). The systems with intermittent aeration had lower final concentrations (7.6-8.0 mg L^{-1}) than did the nonaerated system (20.8 mg L^{-1}), and the average NT removal efficiencies were 48.8% for AC1, 80.3% for AC2, 80.5% for AC3, and 81.2% for AC4. Therefore, these data show that the intermittently aerated systems were 31.5–32.4% more efficient at removing NT than the nonaerated systems were. These results are higher than those obtained by Uggetti et al. (2016) (23% improvement) and lower than those obtained by Liu et al. (2019) (37% to 81% improvements). These findings suggest that the use of intermittent aeration allowed simultaneous nitrification and denitrification in the constructed wetlands, thus increasing the NT removal efficiency.

Figure 5 shows the TN concentrations in the influent and effluent in relation to the aeration rates and their respective removal efficiencies. As previously mentioned, the figure shows that the intermittently aerated systems presented greater TN removal efficiency than did the nonaerated system. Furthermore, increasing the aeration rate from 2 to 10 L min^{-1} gradually increased the system efficiency. However, similar to the COD data, the increase in the aeration rate did not cause significant changes in the respective TN removal efficiencies of the systems; an improvement of only 0.9% was observed between AC2 and AC4. Unlike our results, the work of Wu et al. (2016b) indicates that increases in the aeration rate can reduce the TN removal efficiency. The difference between the results obtained may be related to the efficiency of oxygen transfer to the effluent; for example, Wu et al. (2016b), who used an aeration rate of 2 L min^{-1} (air application rate of 308 L m^{-3} min^{-1}), obtained DO concentrations greater than 8 mg L^{-1} in vertical flow constructed wetlands (VCFW), whereas in the present work, the aeration rate of 10 L min $^{-1}$ (air application rate of 385 L m^{-3} min^{-1}) generated a maximum concentration of 5.4 mg DO L^{-1}. This discrepancy may be associated with several factors, such as 1) the spatial arrangement of the air diffusers; 2) the size of the bubbles released by the diffuser; 3) the type of feed (continuous flow or batch); and 4) the reactor configuration (VCFW vs VCFW). Furthermore, Wu et al. (2016b) used an intermittent aeration pattern (4 h day^{-1}) different from that used in the present work (3 h day^{-1}).

Figure 5. Influent and effluent TN concentrations in relation to aeration rates and their respective removal efficiencies

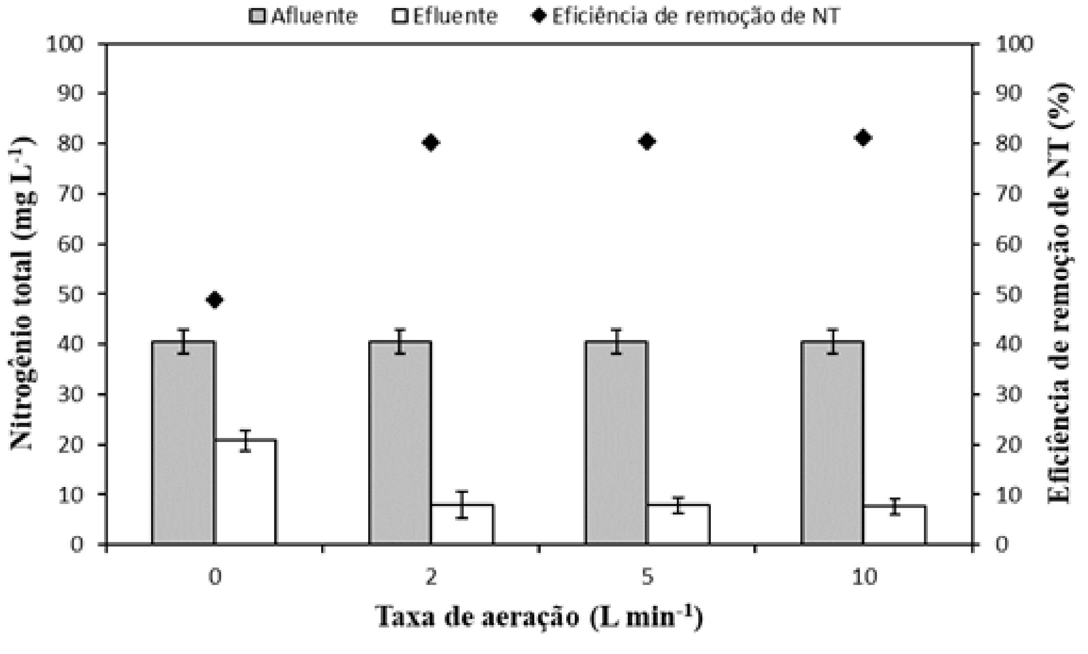
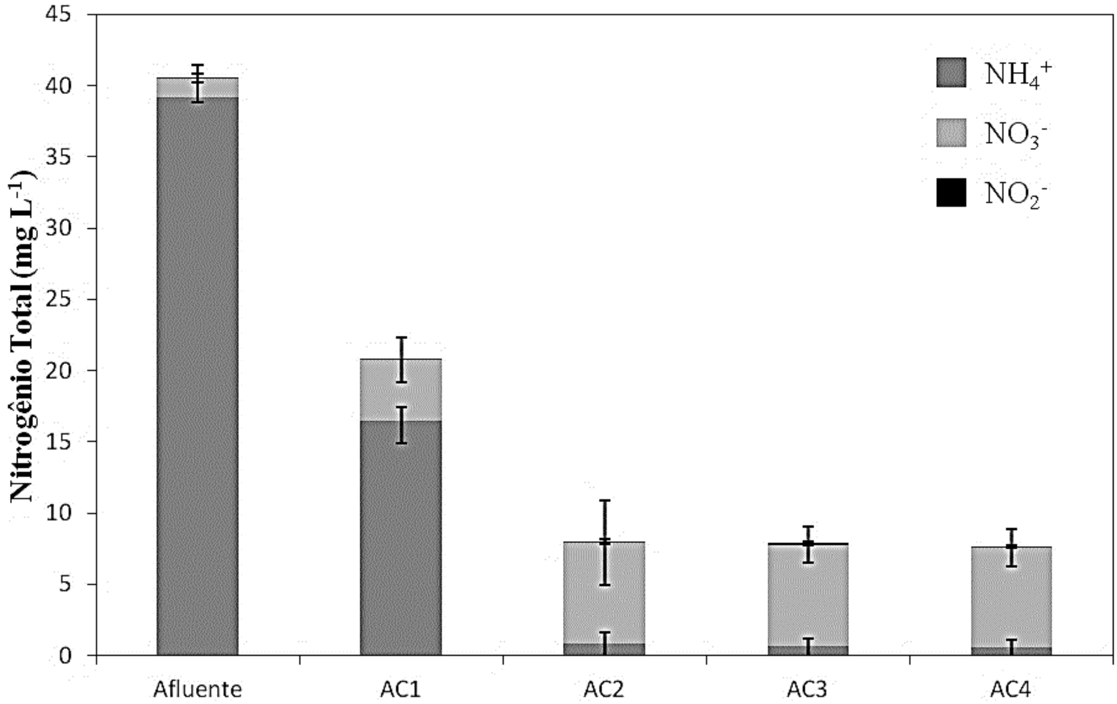


Figure 6 shows the NH^{4+}, NO_3^-, and NO $_2^-$ compositions of the influent and effluent of the four constructed wetlands. The average NO_2^- concentrations recorded during the experiment were very low (<0.3 mg L^{-1}), indicating that the transformation of NO_2^- to NO_3^- occurs rapidly. The effluent from AC1 is composed primarily of NH^{4+} due to limited nitrification. The effluents from the aerated systems (AC2--4) are composed almost exclusively of NO^{3-}, indicating that effective nitrification occurred. However, although the data indicate the simultaneous occurrence of nitrification and denitrification, the accumulation of NO_3 in these effluents shows that complete denitrification did not occur, probably due to a lack of organic carbon. Wu et al. (2016a) reported that carbon deficiency prevented complete denitrification of the effluent in intermittently aerated ACFVs.

Figure 6. Concentrations of NH^{4+}, NO_3^- and NO_2^- in the influent and effluent of the four constructed wetlands



5.1 Statistical analysis

ANOVA decomposes the variance of the analyzed parameters into two distinct components: 1) a between-group component and 2) a within-group component. The F-index, which in this case is 12.35 for COD and 50.14 for TN, is the ratio of the between-group estimate to the within-group estimate. Because the P value for the F test is less than 0.05 ($p < 0.0000$), there is a statistically significant difference between the COD and TN means of one constructed wetland and another at the 5% significance level. Tukey's test was performed to determine which means were significantly different from the others (Table 2).

Table 2. Tukey test of the COD and NT parameters obtained from the four constructed wetlands

Parameter	Tukey 's test			
	System	Count	Average	Homogeneity*
COD	1	20	61.93	the
	2	20	12.80	b
	3	20	13.93	b
	4	20	13.53	b
NT	1	20	25.58	the
	2	20	9.73	b
	3	20	10.50	b
	4	20	9.55	b

* Equal letters indicate that there is no significant difference at the 5% probability level.

The test results for the COD and TN parameters revealed statistically significant differences between the wetlands constructed without aeration and the other systems. However, the same test revealed no significant difference between the aerated systems; that is, the different aeration rates did not affect the COD or TN removal efficiency.

4 CONCLUSIONS

Intermittent aeration allows nitrification and denitrification to occur simultaneously, thus improving the performance of ACFH in TN removal. Additionally, compared with nonaerated systems, intermittently aerated ACFH systems have higher COD removal rates. However, a lack of organic carbon can limit the denitrification process in intermittent aerated systems.

In the present study, increasing aeration rates did not significantly alter the COD and TN removal efficiencies, likely because of the aeration pattern adopted (1 h aeration/7 h nonaeration) and the low oxygen transfer efficiency to the effluent. Finally, our results show that intermittently aerated ACFHs present high efficiencies in removing COD (>97%), TN (>80%), and NH_{4+} (>97%) and, therefore, are a viable option for efficient wastewater treatment in isolated communities.

5 ACKNOWLEDGMENTS

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