Acta Scientiarum

http://www.uem.br/acta
ISSN printed: 1806-2563
ISSN on-line: 1807-8664
Doi: 10.4025/actascitechnol.v34i4.13990

Efficiency of constructed wetland systems cultivated with black oats treatment of domestic sewage

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ABSTRACT. The objective of the present work was to evaluate the efficiency of a constructed wetland system cultivated with black oat (*Avena strigosa* Schreb) for the treatment of domestic sewage effluent from a septic tank, with emphasis on removal of carbonaceous matter, nutrients (N, P and K) and sodium. The experiment was conducted in four constructed wetland system (CWS) with horizontal subsurface flow for secondary/tertiary treatment domestic sewage. The CWS 1, 2, 3 and 4 received, respectively, organic load rates (OLR) of 100, 200, 400 and 600 kg ha^{-1} day^{-1} of BOD. Average efficiencies for removal of BOD, COD, total nitrogen, phosphorus, sodium and potassium were, respectively, 69.5, 70.2, 17.8, 26.2, 14.9 and 16.6%. Low efficiency in the removal of nutrients (N, P and K) was due a high OLR applied which provided also a large input of nutrients to the system. Sodium removal efficiency was low because it is a highly soluble ion and is poorly absorbed by plants. In general, lower OLR result in greater pollutant removals from the domestic sewage.

Keywords: constructed wetlands, wastewater, pollution control.

Eficiência de sistemas alagados construídos cultivados com aveia preta no tratamento de esgoto doméstico

RESUMO. Com a realização deste trabalho, objetivou-se avaliar a eficiência do sistema alagado construído, cultivado com aveia preta forrageira (*Avena strigosa* Schreb), no tratamento de esgoto domestico, efluente de um tanque séptico, com ênfase na remoção de matéria carbonácea, nutrientes (N, P e K) e sódio. O experimento foi conduzido em quatro Sistemas Alagados Construídos (SACs) de escoamento subsuperficial horizontal para tratamento secundário/terciário de esgoto doméstico. Os SACs 1, 2, 3 e 4 receberam, respectivamente, taxas de carregamento orgânico (TCO) de 100; 200; 400 e 600 kg ha^{-1} dia^{-1} de DBO. A eficiência média na remoção de DBO, DQO, nitrogênio total, fósforo, sódio e potássio, foram, respectivamente, de 69,5; 70,2; 17,8; 26,2; 14,9 e 16,6%. A baixa eficiência na remoção de nutrientes (N, P e K) foi devida à alta TCO aplicada que proporcionou, também, grande aporte de nutrientes ao sistema. A eficiência de remoção de sódio foi baixa por ser um íon de grande solubilidade e devido à baixa absorção pelas plantas. No geral, menores TCOs proporcionaram maiores remoções de poluente do esgoto doméstico.

Palavras-chave: leitos cultivados, águas residuárias, controle da poluição.

Introduction

With the objective of preserving water resources and protecting public health, new technologies for the treatment of domestic sewage have been sought, especially those of low cost. One of these that may be highlighted is the constructed wetland system (CWS) due to its low operational and maintenance costs (KONNERUP et al., 2009), also allowing for production of plant species of commercial interest and/or food. This method of wastewater treatment has proven to be efficient in removing organic matter (BOD and COD), total suspended solids (TSS), nitrogen and phosphorus or raw effluent or domestic sewage (CHAGAS, et al. 2011; GHOSH; GOPAL, 2010; ZURITA et al., 2009).

Among the key components of these systems are the plant species to be cultivated, the substrate and the bacteria biofilm formed in the medium, which are responsible either directly or indirectly for the removal of pollutants in wastewater. Selection of the plant species is, along with other design variables, of fundamental importance for the successful treatment of wastewater in CWS. The functions of macrophytes include not only the extraction of nutrients from the wastewater, but also the transfer of oxygen to the substrate, providing support (rhizomes and roots) for the growth of biofilm bacteria, and improving the permeability of the substrate and aesthetics of the environment (MATOS et al., 2009a).

Several plant species naturally adapted to flooded environments have been deployed in these systems, such as cattail (*Typha latifolia* L.) (BRASIL et al., 2007a and b; FIA et al., 2008, 2011; MATOS et al., 2009a and b; WANG et al., 2009), plant species of the grass family, such as Tifton-85 (*Cynodon* sp.) (FIA et al., 2011, MATOS et al., 2008, 2009a and b, 2010a and b), elephant grass (*Pennisetum purpureum*)(MATOS et al., 2008), ryegrass (*Lolium multiflorum*) (FIA et al., 2010a, b and c), and ornamental plants such as heliconia (*Heliconia psittacorum*) (KONNERUP et al., 2009), arum (*Zantedeschia aethiopica*) (BELMONT; METCALFE, 2003; ZURITA et al., 2009), agapanto (*Agapanthus africanus*) (ZURITA et al., 2009) and others.

The cultivation of oats (*Avena strigosa* Schreb) in CWS was evaluated by Fia et al. (2010a and b). It is a forage originally from Europe which presents rapid initial growth, with high production in the first cut and/or grazing (FEROLLA et al., 2007). Oats have been used for management and conservation of soil, such as cover and green manure, or for direct seeding because it produces large amounts of biomass and decomposes slower than legumes used as green manure. This grass grows and develops rapidly, helping to control erosion and weeds (ROSSETTO; NAKAGAWA, 2001).

Considering that the black oat is a grass that has characteristics indicated for plant species to be grown in CWS during the winter and has value as an animal feed, it is important to obtain information regarding its adaptability to the environment, productivity and capacity to provide conditions for the removal of pollutants in the system. Thus, the objective of this study was to evaluate the efficiency of constructed wetland systems planted with oat forage for the treatment of domestic sewage.

Material and methods

The experiment was conducted in the Experimental Area for Treatment of Urban Waste (AETRU) at the Department of Agricultural Engineering, Universidade Federal de Viçosa - DEA/UFV, Viçosa, Minas Gerais State, Brazil, located at the geographic coordinates: latitude 20º45’14”S, longitude 42º52’53”W and average elevation of 650 m.

The AETRU receives raw sewage from the residential complex Bosque Acamari, located in the city of Viçosa, Minas Gerais State, Brazil, between 8:00 am and 6:00 pm. Raw sewage passes through primary treatment (grit chambers, flow meter and mixing box) and then is sent to the various forms of treatment available at the AETRU.

The experiment was conducted in four subsurface horizontal flow CWS to treat secondary/tertiary sewage. Each measured 0.35 m high x 1.0 m wide x 24.0 m long, and all were sealed with a polyvinyl chloride (PVC) geomembrane with thickness of 0.50 mm. Pea gravel was used for support (diameter - D_{60} = 7.0 mm, Cu D_{60}/D_{10} = 1.6 and air voids of 48.4%, saturated hydraulic conductivity K_{S20} = 7.970 m day^{-1}) which was placed in the CWS to a height of 0.30 m, leaving 0.05 m along the top of the beds.

Supply and distribution of the influent in the CWS was performed by a ball valve and PVC pipe measuring 50 mm diameter, perforated longitudinally in order to apply the influent across the width of the CWS. Distribution of the effluent occurred at the saturated entry zone filled with gravel (diameter of 19 to 25 mm), while the rest of the CWS bed was filled with pea gravel. The system was equipped with a drainage system which occupied the entire width of the bed, made of PVC pipe measuring 50 mm in diameter and with transverse slits of 2 mm in width. The discharge device and level control was connected to this drainage system.

Black oats (*Avena strigosa* Schreb) were grown in the CWS, sown by broadcasting on the support medium (pea gravel) saturated with primary domestic sewage from the septic tank at a density of 80 kg ha^{-1} of seed on April 7, 2008. As of April 14, 2008 application of the effluent was initiated for 24 hours a day, 7 days a week for two months.

CWS 1, 2, 3 and 4 received organic loading rates (OLR) of 100, 200, 400 and 600 kg ha^{-1} day^{-1} of BOD, respectively, which were obtained from the results of the BOD concentration analysis of the influent to the CWS, quantified every 15 days. Based on these results, the flow of primary domestic sewage to be applied to each CWS was regulated. The hydraulic retention times (HRT) corresponding to these OLR were 2.62, 1.31, 0.66 and 0.43 days, respectively.

Values of flow for each CWS were calculated using Equation 1, based on the BOD in the influent which was monitored during the experimental period.

$$Q = \frac{A_s \times TCO \times 1000}{C} \quad (1)$$

where,

Q: influent flow rate (m^3 day^{-1});

A_s: surface area of the tank (ha);

TCO: organic loading rate (kg ha^{-1} day^{-1}) and,

C: BOD of the influent (mg L^{-1}).

Samples were collected at the inlet (0 meters) and outlet (24 meters) of each CWS, where for each analysis three repetitions were obtained.

To evaluate the performance of the CWS for removal of pollutants, the following variables were analyzed: potential of hydrogen (pH), electric conductivity (EC) and turbidity using a pH meter, conductivity meter and bench-top turbidity meter, respectively, total nitrogen via the semimicro Kjeldahl process, phosphorus by spectrophotometry, sodium and potassium by flame photometry, BOD_5 (biochemical oxygen demand) by quantifying dissolved oxygen by the iodometric method (Winkler procedure) and COD (chemical oxygen demand) using the method of chemical oxidation in open reflux. Laboratory analyses were performed at the Laboratory and Water Quality of the UFV, in accordance with recommendations of the *Standard Methods for Wastewater Examination* (APHA/AWWA/WEF, 2005).

The mean values and standard error of potential of hydrogen (pH), electrical conductivity (EC), turbidity, total nitrogen (N_{total}), total phosphorus (P_{total}), potassium (K), sodium (Na), biochemical oxygen demand (BOD) and chemical oxygen demand (COD) in the influent of the CWS are presented in Table 1.

Table 2 presents the mean quantity of nutrients applied to the CWS.

Table 2. Mean quantity of nutrients applied to the CWS (kg ha^{-1} day^{-1}).

SAC	N	P	K
	kg $ha^{-1}day^{-1}$		
1	22.0±2.6	3.8±0.3	13.3±2.7
2	42.2±11.1	8.4±0.7	28.3±4.5
3	68.0±15.7	14.2±2.4	55.4±11.9
4	121.5±26.5	27.0±2.3	83.5±12.9

The data was subjected to analysis of variance where the means of the qualitative factors (CWS) were compared using the Duncan test, adopting a probability level of 5%. Average efficiency for removal of pollutants was calculated based on average efficiencies observed in each sampling performed.

Results and discussion

Table 3 shows the mean values and standard error of the physical, chemical and biochemical characteristics of the effluent from the CWS and Table 4 the average percentages (%) of removal efficiency in function of OLR applied to CWS.

There was no significant variation in pH among the influents (Table 1) and effluents from the CWS (Table 3) where the values found are close to neutrality, conditions considered ideal for the development of organic material degrading microorganisms which is in the range of 6.0 to 7.2, as well as improved performance of plant species (BRIX et al., 2002). The pH values of the effluent (Table 3) are within the limits of 6 to 9 set by the Joint Resolution Normative COPAM/CERH No. 01/2008 (MINAS GERAIS, 2008), for characteristics of effluents to be released to water bodies.

Table 1. Mean values and standard deviation of the physical, chemical and biochemical characteristics of the influent of the CWS

pH	CE	Turbidity	N_{total}	P_{total}	K	Na	BOD	COD
	dS m^{-1}	UNT	mg L^{-1}					
7.0±0.04	0.6±0.02	66.5±5.4	36.4±7.4	7.2±0.7	25.0±4.6	31.5±3.5	181.1±13.3	508.4±78.4

Table 3. Mean values and standard error of the physical, chemical and biochemical characteristics of the effluent of the CWS

SAC	pH	EC	Turbidity	N_{total}	P_{total}	K	Na	BOD	COD
		dS m^{-1}	UNT	mg L^{-1}					
1	7.0±0.05	0.5±0.07	8.7±1.5	24.1±5.4	4.6±1.3	21.6±3.4	29.6±4.1	40.9±13.6	90.9±37.4
2	7.1±0.04	0.5±0.02	12.1±2.9	32.3±6.2	6.4±1.5	21.4±5.0	29.0±5.7	63.7±15.1	177.9±57.8
3	7.1±0.05	0.6±0.02	18.8±3.1	31.9±7.4	6.3±0.7	19.8±4.6	26.6±4.8	46.9±13.8	134.0±46.0
4	7.1±0.06	0.6±0.02	19.2±3.0	34.8±8.1	6.8±0.6	22.0±4.6	29.2±4.5	41.3±5.5	166.1±39.6

Table 4. Mean percentages (%) of removal efficiency of EC, Turbidity, N_{total}, P_{total}, K, Na, BOD and COD in the CWS evaluated

SAC	EC	Turbidity	N_{total}	P_{total}	K	Na	BOD	COD
	%							
1	14.7±4.0a	84.5±5.0 a	42.6±11.2 a	39.8±12.9 a	9.3±4.7 a	7.1±4.4 a	78.0±7.8 a	76.7±13.1 a
2	9.4±2.4 ab	81.4±4.7 ab	14.3±8.9 b	28.5±13.9 a	22.2±12.9 a	20.6±12.6 a	67.0±8.1 a	66.7±10.1 a
3	3.4±1.3 b	69.2±4.9 b	1.2±1.2 b	15.9±9.2 a	21.5±12.9 a	18.2±12.8 a	72.1±5.8 a	66.5±8.3 a
4	3.6±2.1 b	73.1±3.2 ab	13.2±9.7 b	20.4±8.6 a	13.6±10.3 a	13.7±10.3 a	64.8±4.8 a	70.9±10.2 a

*Means followed by the same letter do not differ among themselves by the Duncan test ($p \le 0.05$).

According to the electrical conductivity value of the domestic sewage in Tables 1 and 3, the sewage before and after treatment can be classified as water with average salinity - C2 (electrical conductivity between 0.250 and 0.750 dS m^{-1} at 25°C), allowing for its utilization in drip irrigation of crops with moderate salt tolerance and in most cases without special practices for salinity control. Similar results were obtained by Brasil et al. (2005) who, when treating domestic sewage after passing through a CWS cultivated with cattail, obtained EC values lower than 0.7 dS m^{-1}, considering use of this wastewater in agriculture without restriction.

The CWS were not very effective in reducing the electrical conductivity (Table 4), indicative of low removal of total dissolved solids (TDS) which was to be expected considering that the degradation of organic material results in the release of many ions to the solution. However, there was a clear upward trend in TDS removal efficiency with the lower OLR. The black oats may have efficiently extracted the ions liberated in the application of lower rates (100 and 200 kg ha^{-1} day^{-1} BOD), which did not occur when applying the higher rates (400 and 600 kg ha^{-1} day^{-1} BOD), since there were excess ions released by the degradation of organic matter in solution.

According to data on the efficiency of turbidity removal (Table 4), the variable indicative of the concentration of suspended solids (TSS) in wastewater, it appears that the lower the OLR applied, greater is the removal of suspended solids in the system, which confirms what was observed in relation to the TDS.

For the CWS of 100, 200, 400 and 600 kg ha^{-1} day^{-1}, efficiencies of 84.50, 81.42, 69.17 and 73.09%, respectively, were obtained for the removal of turbidity. This high efficiency is attributed to the physical processes occurring in the CWS since the support media of CWS is very effective in retaining particles (sizes ranging from colloidal to millimeters), mainly due to the development of the plant root systems in the media. In addition to reducing the pore space of the medium, the roots also create conditions that minimize the formation of preferential pathways of wastewater in CWS. According to Metcalf and Eddy (2003), CWS are effective in removing TSS as a result of sedimentation in the interstices, retention by flow restriction (filtration) and adherence to the granules of support material (due to van der Waals forces). The lower rates also had the largest hydraulic detention time, allowing more time for sedimentation and, consequently, removal by the system.

Brasil et al. (2005) encountered an average turbidity removal efficiency of 80% in CWS planted with *Typha* sp. used for the treatment of domestic sewage effluent from a septic tank with OLR_v of 116 to 210 g m^3 day^{-1} COD.

For the OLR of 100, 200, 400 and 600 kg ha^{-1} day^{-1} BOD, which corresponded to 22.00, 42.2, 68.0 and 121.5 kg ha^{-1} day^{-1} total-N (Table 2), average efficiencies of 42.6, 14.3, 1.2, and 13.2% were obtained, respectively, for the removal of total nitrogen. The lower OLR (100 kg ha^{-1} day^{-1} BOD) resulted in greater total-N removal efficiency, contrary to what was observed by Matos et al. (2010c), who observed increase in removal efficiency with the increasing OLR applied, which were 66, 130, 190, 320 and 570 kg ha^{-1} day^{-1} BOD. However, for these OLR the total nitrogen loads applied, corresponded to 3.01, 4.93, 6.84, 10.68 and 18.63 kg ha^{-1} day^{-1} total N, respectively, i.e., total-nitrogen loads were substantially lower than those applied in this experiment.

The lowest OLR used in this study resulted in greater contact time between the primary sewage effluent and the biological film, composed of the microorganisms responsible for degradation of pollutants which may have contributed to the greater removal efficiencies of total nitrogen in different CWS. Furthermore, higher retention times resulted in greater N removal, considering that they are associated with lower intakes of the nutrient. Brasil et al. (2005) obtained a total N removal of 33% in CWS planted with cattails, using a HRT of 1.9 days in the treatment of domestic sewage. When the same authors used an HRT of 3.8 days a total nitrogen removal efficiency of 57% was obtained. Gosh and Gopal (2010) also achieved the highest removal efficiency in CWS receiving the highest HRT. The authors obtained total-N removal efficiencies of 21.86, 63.66, 72.03 and 83.99% for HRT of 1, 2, 3 and 4 days, respectively, in CWS planted with cattail for the treatment of a domestic secondary sewage effluent.

Comparing the results with those of other works in which forage species were planted in the CWS, it was found that in the present experiment the N removal was relatively low. Matos et al. (2010a) obtained 64% removal of total N in CWS cultivated with Tifton-85 in the treatment of wastewater from swine, when applying a OLR of 155 kg ha^{-1} day^{-1} BOD (93.3 kg ha^{-1} day^{-1} total N) and HRT of 4.8 days. Matos et al. (2010c) obtained removal efficiencies ranging from 51 to 70% and 14 to 50% in CWS planted with Tifton-85 grass and elephant grass, respectively, for the treatment of dairy wastewater, applying an OLR of 130 kg ha^{-1} day^{-1}.

It is believed that the lower development of oat plants, due to failure of emergence of plants, may have contributed to this occurrence.

Based on the pH values measured in the wastewater subjected to treatment it can be inferred that the volatilization of ammonia (NH_3) was negligible in the CWS, where these losses become significant only at pH greater than 9.

Although there is no statistical difference between the removal efficiencies of total phosphorus, this result obtained from the high coefficient of variation, common in domestic wastewater samples, it can be seen that the lowest OLR and hence lower P loads result in more efficient total phosphorus removal (Table 4), similar to what was observed in relation to total nitrogen. The results confirm what was observed in relation to total nitrogen and electrical conductivity, i.e., lower OLR should be recommended for application of domestic sewage submitted to treatment in CWS cultivated with oats since it indicates the highest removal (39.8%). Matos et al. (2010a) observed removals of 33, 55, 55 and 55% in the treatment of wastewater from swine in CWS planted with cattail, Alternanthera, Tifton-85 and a mixture, respectively, with an average application rate of 155 kg ha^{-1} day^{-1} BOD, HRT of 4.8 days and average phosphorus load of 22.1 kg ha^{-1} day^{-1}. Brasil et al. (2005) obtained phosphorus removal rates of 35 and 48% (total-P) in CWS used in the treatment of primary sewage effluent and planted with cattail (*Thypha* sp.), subjected to application rates of 26 to 118 kg ha^{-1} day^{-1} BOD_5, respectively. Matos et al. (2010c) did not obtain significant phosphorus removal, where the effluent concentration was greater than that of the influent applied to CWS cultured with Tifton and elephant grass for the treatment of dairy wastewater.

The effluent concentrations (Table 3) followed the same pattern of variation observed in the influents (Table 1), denoting the sensitivity of the system to rates of potassium intake. Considering the high solubility of potassium and its non-association with organic material (LO MONACO et al., 2009), which was effectively removed from the system, it may be considered that the CWS were able to remove only small portions of this nutrient (Table 4). This fact may be confirmed by the low efficiencies obtained for the OLR of 100, 200, 400 and 600 kg ha^{-1} day^{-1} BOD, i.e., K loads of 13.81, 27.66, 55.25 and 82.87 kg ha^{-1} day^{-1}, with efficiencies of 9.29, 22.20, 21.46 and 13.63%, respectively. These values were lower than those found by Brasil et al. (2005) who obtained, in CWS planted with cattail (*Thypha* sp.) for treatment of domestic primary sewage effluent, removals of 35 and 52% for HRT of 1.9 days and 3.8 days, respectively, under application rates of 26 to 118 kg ha^{-1} day^{-1} of BOD_5. However, the obtained values were higher than those encountered by Matos et al. (2010c), who observed practically no removal of potassium when applying K loads of 2.46, 3.89, 5.31, 8.19 and 13.89 kg ha^{-1} day^{-1} in CWS cultivated with Tifton and elephant grass for the treatment of dairy wastewater.

Considering that sodium is not an essential nutrient for the plants and when present in excess in the media may be toxic to them, high concentrations present in the wastewater are detrimental factors to system performance. It may be considered that, in general, sodium was little removed in some CWS (Table 4). Despite the relatively high concentration present in the wastewater under study in relation to other nutrients (Table 1), Brasil et al. (2005) pointed out that the factors that contribute most to failure of the system in the removal of sodium are the solubility of this chemical element, low absorption by plants and low association of the cation with organic material, which is efficiently removed by physical processes in the CWS. Low efficiencies of sodium removal (4%) were observed by the same authors, in CWS grown with cattail for the treatment of domestic sewage; by Matos et al. (2010a) who obtained removals of 18, 25, 18 and 24% in CWS planted with cattail, Alternanthera, Tifton and a mixture (planted with cattail, Alternanthera and Tifton), treating swine wastewater under average loading of 11.3 kg ha^{-1} day^{-1} of Na; and Matos et al. (2010c) when applying 4.65, 6.85, 9.04, 13.69 and 22.74 kg ha^{-1} day^{-1} of Na found that, similar to potassium, the effluent concentrations were very close to those of the influent in CWS cultivated with Tifton and elephant grass for the treatment of dairy wastewater.

Good performance was observed in the CWS with regard to BOD removal, but there were no significant differences in effectiveness between treatments according to the data presented in Table 4, taking into consideration the high variability of BOD in the influent. However, it may be affirmed that there was a trend of increased removal with decrease in OLR, as also observed by Fia et al. (2010b), considering that these authors worked with loads ranging from 653 to 1513 kg ha^{-1} day^{-1}. For the OLR of 600 kg ha^{-1} day^{-1} the lowest BOD removal was observed since there was no vegetation growth in this system, possibly due to the high OLR applied, creating an unsuitable environment for germination of the oat seeds. Matos et al. (2010c) observed an increase in the BOD removal efficiency with the increase in OLR until it reached a peak at which point there was a decrease in efficiency. The authors attributed this behavior to the likely accumulation of particulate matter in the system since this material would have worked as a filter to allow for further removal of particulate BOD. These authors also assumed that increasing the formation of biofilm on the support medium, resulting in the increase in TCO, may also have increased the capacity of the system to remove BOD. Fia et al. (2012) observed no significant difference in removal of BOD when applying increasing OLR to CWS cultivated with Tifton-85 grass in the treatment of domestic sewage and swine wastewater, respectively.

Considering the discharge limits for BOD (60 mg L^{-1} or treatment with minimal BOD removal efficiency of 60% and annual average greater than 70% for sewage systems), established by environmental legislation of the Brazilian state of Minas Gerais, it can be verified according to Table 3 that the effluents of all CWS, with the exception of CWS 2, met the discharge standards (MINAS GERAIS, 2008). Although not meeting the required standards, the BOD of CWS 2 was close to the satisfactorily value of 60 mg L^{-1}.

The high BOD removal efficiencies obtained in this study, 64.8% (OLR of 600 kg ha^{-1} day^{-1} BOD) to 78.0% (OLR of 100 kg ha^{-1} day^{-1} BOD) were similar to those observed by Fia et al. (2010b) who, for a OLR of 686 kg ha^{-1} day^{-1} COD, obtained removals of 60.9 and 70.8% in CWS grown with black oat and ryegrass, respectively, for the treatment of wastewater from the processing of coffee fruits.

According to the results presented in Table 4, there was no significant difference in COD removal efficiencies when applying increasing OLR to the CWS. However, similar to the BOD, a tendency for greater removal efficiency at lower OLR was observed (100 kg ha^{-1} day^{-1} BOD).

Considering the discharge standards for COD (180 mg L^{-1} or treatment with COD removal efficiency of at least 55% and annual average greater than or equal to 65% for sewage systems) established by environmental legislation of Minas Gerais State, Brazil, according to Tables 3 and 4 the effluents of all CWS met the discharge standards (MINAS GERAIS, 2008).

The results of this study were similar to those of Chagas et al. (2011), who encountered COD removals ranging from 63.7 to 72.15% in CWS cultivated with yellow lily for treatment of the same effluent used in the present study. However, removals were lower compared with the results found by Brasil et al. (2005) who obtained 85% COD removal efficiency when growing cattail, independent of the volumetric load applied for the treatment of domestic primary sewage effluent. To evaluate the performance of the CWS cultivated with black oats, the results obtained in this study were compared to those reported by Fia et al. (2010b), who obtained COD removals of 78.3 and 79.5% in CWS grown with oat and ryegrass, respectively, applying OLR of 653 and 686 kg ha^{-1} day^{-1} COD. Matos et al. (2010a) obtained a minimum COD removal of 87% in CWS with Alternanthera and a maximum of 92% in the mixed CWS (grown with cattail, Alternanthera and Tifton 85 grass) for treatment of swine wastewater. Fia et al. (2012) obtained COD removal ranging from 66 to 80% and 69 to 79% in CWS planted with Tifton-85 grass and cattail, respectively, for the treatment of swine wastewater. Matos et al. (2010c) achieved an average minimum removal of 84.7% and maximum of 97.1% in CWS cultivated with Tifton 85 grass and submitted to the OLR of 66.0 and 570 kg ha^{-1} day^{-1}, respectfully.

It must be stressed that the failure to consider evapotranspiration, not quantified in CWS, results in an underestimation in the calculation of pollutant removal efficiency from treatment of domestic primary sewage effluent. Brasil and Matos (2008), working with systems constructed wetlands planted with cattail, in Viçosa, State of Minas Gerais, Brazil, obtained evapotranspiration values of up to 18.7 mm day^{-1} and values from 2.2 to 4.6 times the reference rate of evapotranspiration (ET_0) at the site. Thus, a mass balance of pollutants would be more appropriate to obtain the actual efficiency for removal of pollutants from wastewater.

Conclusion

Based on the obtained results, it may be concluded that:

- The average efficiency of constructed wetlands systems (CWS) cultivated with black oat forage for the treatment of wastewater from septic tanks in the removal of BOD, COD, total nitrogen, phosphorus, sodium and potassium, was, respectively, 70.5, 70.2, 17.8, 26.2, 14.9 and 16.6% obtained for application of OLR between 100 and 600 kg ha^{-1} day^{-1} BOD and TDH between 0.43 and 2.62 days;

- The low efficiency for removal of nutrients (nitrogen, phosphorus and potassium) is associated with the relatively high loads of nutrients applied;

- Removal efficiency of sodium was low because it is a highly soluble ion, is little absorbed by plants and is applied in relatively high loads;

- There was no significant difference in the removal of organic matter, but an increasing trend in removal was observed with reduction in the OLR applied, and

- Under the operational conditions of the system, it was found that lower OLR (100 and 200 kg ha^{-1} day^{-1}) generally resulted in greater pollutant removals of domestic sewage, indicated for the treatment of domestic sewage with oats.

References

APHA-American Public Health Association; AWWA–American Water Works Association; WEF-Water Environment Federation. **Standard methods for the examination of water and wastewater**. 21th ed. Washington, D.C.: APHA/AWWA/WEF, 2005.

BELMONT, M. A.; METCALFE, C. D. Feasibility of using ornamental plants (*Zantedeschia aethiopica*) in subsurface flow treatment wetlands to remove nitrogen, chemical oxigen demand and nonylphenol ethoxylate surfactants – a laboratory-scale study. **Ecological Engineering**, v. 21, n. 4, p. 233-247, 2003.

BRASIL, M. S.; MATOS, A. T. Avaliação de aspectos hidráulicos e hidrológicos de sistemas alagados construídos de fuxo subsuperfcial. **Engenharia Sanitária e Ambiental**, v. 13, n. 3, p. 323-328, 2008.

BRASIL, M. S.; MATOS, A. T.; SILVA, C. M.; CECON, P. R.; SOARES, A. A. Modeling of pollution removal in constructed wetlands with horizontal subsurface flow. **Agricultural Engineering Research**, v. 13, n. 2, p. 48-56, 2007a.

BRASIL, M. S.; MATOS, A. T.; SOARES, A. A. Plantio e desempenho fenológico da taboa (*Thypha* sp.) utilizada no tratamento de esgoto doméstico em sistema alagado construído. **Engenharia Sanitária e Ambiental**, v. 12, n. 3, p. 266-272, 2007b.

BRASIL, M. S.; MATOS, A. T.; SOARES, A. A.; FERREIRA, P. A. Qualidade do efluente de sistemas alagados construídos, utilizados no tratamento de esgoto doméstico. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 9, supl., p. 133-137, 2005.

BRIX, H.; DYHR-JENSEN, K.; LORENZEN, B. Root-zone acidity and nitrogen source affects *Typha latifolia* L. growth and uptake kinetics of ammonium and nitrate. **Journal of Experimental Botany**, v. 53, n. 379, p. 2441-2450, 2002.

CHAGAS, R. C.; MATOS, A. T.; CECON, P. R.; LO MONACO, A. T.; FRANÇA, L. G. F. Cinética de remoção de material organic em sistemas alagados construídos cultivados com lírio amarelo. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 15, n. 11, p. 1186-1192, 2011.

FEROLLA, F. S.; VÁSQUEZ, H. M.; SILVA, J. F. C.; VIANA, A. P.; DOMINGUES, F. N.; AGUIAR, R. S. Produção de matéria seca, composição da massa de forragem e relação lâmina foliar/caule + bainha de aveia preta e triticale nos sistemas de corte e de pastejo. **Revista Brasileira de Zootecnia**, v. 36, n. 5, p. 1512-1517, 2007.

FIA, F. R. L.; MATOS, A. T.; FIA, R.; LAMBERT, T. F.; MATOS, M. P. Remoção de nutrientes por *Typha latifólia* e *Cynodon* spp. Cultivadas em sistemas alagados construídos. **Ambi-água**, v. 6, n. 1, p. 77-89, 2011.

FIA, F. R. L.; MATOS, A. T.; FIA, R.; BORGES, A. C.; TEIXEIRA, D. L. Remoção de matéria orgânica e determinação de parâmetros cinéticos em sistemas alagados construídos em escala laboratorial. **Acta Scientiarum. Technology**, v. 34, n. 2, p. 149-156, 2012.

FIA, R.; MATOS, A. T.; FERREIRA, P. A.; TEODORO, P. E. P.; SCHUERY, F. C.; LUIZ, F. A. R. Desempenho agronômico da *thypha* sp. e *alternanthera philoxeroides* mart utilizadas no tratamento de águas residuárias da lavagem e descascamento/despolpa dos frutos do cafeeiro em sistema alagado construído. **Engenharia na Agricultura**, v. 16, n. 4, p. 436-448, 2008.

FIA, R.; MATOS, A. T.; FIA, F. R. L.; MATOS, M. P.; LAMBERT, T. F.; NASCIMENTO, F. S. Desempenho de forrageiras em sistemas alagados de tratamento de águas residuárias do processamento do café. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 14, n. 8, p. 842-847, 2010a.

FIA, R.; MATOS, A. T.; MATOS, M. P.; ABREU, E. C.; FIA, F. R. L. Tratamento das águas do processamento dos frutos do cafeeiro em filtro anaeróbio seguido por sistema alagado construído: I - remoção de matéria orgânica. **Engenharia Agrícola**, v. 30, n. 6, p. 1191-1202, 2010b.

FIA, R.; MATOS, A. T.; LAMBERT, T. F.; FIA, F. R. L.; MATOS, M. P. Tratamento das águas do processamento dos frutos do cafeeiro em filtro anaeróbio seguido por sistema alagado construído: II - remoção de nutrientes e compostos fenólicos. **Engenharia Agrícola**, v. 30, n. 6, p. 1203-1213, 2010c.

GHOSH, D.; GOPAL, D. Effect of hydraulic retention time on the treatment of secondary effluent in a subsurface flow constructed wetland. **Ecological Engineering**, v. 36, n. 8, p. 1044-1051, 2010.

KONNERUP, D.; KOOTTATEP, T.; BRIX, H. Treatment of domestic wastewater in tropical, subsurface flow constructed wetlands planted with Canna and Heliconia. **Ecological Engineering**, v. 35, n. 2, p. 248-257, 2009.

LO MONACO, P. A. V.; MATOS, A. T.; SARMENTO, A. P.; LOPES JÚNIOR, A. V.; LIMA, J. T. Desempenho de filtros constituídos por fibras de coco no tratamento de águas residuárias de suinocultura. **Engenharia na Agricultura**, v. 17, n. 6, p. 473-480, 2009.

MATOS, A. T.; ABRAHÃO, S. S.; PEREIRA, O. G. Desempenho agronômico do capim tifton 85 (*Cynodon* spp.) cultivados em sistemas alagados construídos utilizados no tratamento de água residuária de laticínios. **Ambi-Água**, v. 3, n. 1, p. 43-53, 2008.

MATOS, A. T.; FREITAS, W. S.; LO MONACO, P. A. V. Capacidade extratora de diferentes espécies vegetais cultivadas em sistemas alagados utilizados no tratamento de águas residuárias da suinocultura. **Ambi-Água**, v. 4, n. 2, p. 31-45, 2009a.

MATOS, A. T.; FREITAS, W. S.; FIA, R.; MATOS, M. P. Qualidade do efluente de sistemas alagados construídos utilizados no tratamento de águas residuárias da suinocultura visando seu reuso. **Engenharia na Agricultura**, v. 17, n. 5, p. 383-391, 2009b.

MATOS, A. T.; FREITAS, W. S.; LO MONACO, P. A. V. Eficiência de sistemas alagados construídos na remoção de poluentes de águas residuárias da suinocultura. **Ambi-Água**, v. 5, n. 2, p. 119-132, 2010a.

MATOS, A. T.; FREITAS, W. S.; MARTINEZ, M. A.; TÓTOLA, M. R.; AZEVEDO, A. A. Tifton grass yield on constructed wetland used for swine wastewater treatment. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 14, n. 5, p. 510-516, 2010b.

MATOS, A. T.; ABRAHÃO, S. S.; BORGES, A. C.; MATOS, M. P. Influência da taxa de carga orgânica no desempenho de sistemas alagados construídos cultivados com forrageiras. **Engenharia Sanitária e Ambiental**, v. 15, n. 1, p. 83-92, 2010c.

METCALF, E.; EDDY, H. **Wastewater engineering**: treatment and reuse. 4th ed. New York: MacGraw-Hill, Inc., 2003.

MINAS GERAIS. **Deliberação Normativa Conjunta Copam/CERH-MG**. n. 1, de 5 de maio de 2008. Belo Horionte: Diário do Executivo, 2008.

ROSSETTO, C. A. V.; NAKAGAWA, J. Época de colheita e desenvolvimento vegetativo de aveia preta. **Scientia Agricola**, v. 58, n. 4, p. 731-736, 2001.

WANG, R.; KORBOULEWSKY, N.; PRUDENT, P.; BALDY, V.; BONIN, G. Can vertical-flow wetland systems treat high concentrated sludge from a food industry? A mesocosm experiment testing three plant species. **Ecological Engineering**, v. 35, n. 2, p. 230-237, 2009.

ZURITA, F.; ANDA, J. D.; BELMONT, M. A. Treatment of domestic wastewater and production of commercial flowers in vertical and horizontal subsurface-flow constructed wetlands. **Ecological Engineering**, v. 35, n. 5, p. 861-869, 2009.

Received on July 12, 2011.
Accepted on September 29, 2011.