Evaluation of unclogging aspects in horizontal subsurface flow constructed wetlands

Suymara Toledo Miranda, Antonio Teixeira de Matos, Gheila Corrêa Ferres Baptestini and Alisson Carraro Borges

ABSTRACT

In horizontal subsurface flow constructed wetlands (HSSF-CWs), the main operational problem is clogging of the porous medium. In this study, the unclogging of HSSF-CWs was evaluated, at rest, by adding a nitrogen-based nutrient solution to the influent. For this, six HSSF-CWs were used, consisting of two uncultivated (CW-C), two cultivated with Tifton 85-grass (*Cynodon* spp.) (CW-T) and two cultivated with alligator weed (*Alternanthera philoxeroides*), which were fully clogged after being used for the treatment of swine wastewater. The results indicated that passage of the nutrient solution for 55 days through the bed of the HSSF-CWs resulted in reductions of 11 and 33%, respectively, in the total volatile solids (TVS) concentration of fine clogging material in the CW-T and CW-A. With regard to the TVS content of the coarse clogging material, the reduction was even greater, being 33% for CW-T and 62% for CW-A. Measurements of $K_0$, made along the beds (thirds 1, 2 and 3) before and after passage of the nutrient solution in the CWs indicated respective increases of 7, 13 and 0.1% in CW-C; 21, 11 and 7% in CW-T; and 52%, 6% and – 6% (decrease) in CW-A. Runoff of the nutrient solution decreased gradually over time, presenting at the beginning of the experiment 26, 35 and 150 cm, and at the end (after 55 days of application) 0, 0 and 50 cm in the flow direction of the CW-C and CW-T and CW-A, respectively.

Key words | clogging, hydraulic conductivity, porous media, treatment system

INTRODUCTION

Horizontal subsurface flow constructed wetlands (HSSF-CWs) have been widely used as an effective alternative for treating wastewater around the world. It has been intensively studied due to its lower potential for generating odors and attraction of vectors, potential to continuously treat wastewater and also its simple operation. However, several studies have indicated operational problems, including clogging of the porous medium. Clogging can result in decreased hydraulic conductivity in the porous media, generating surface runoff of wastewater and the appearance of dead zones or short circuits (Pedescoll et al. 2009), as well as reduce the hydraulic retention time (HRT) in the system (USEPA 2000) that could lead to lower treatment efficiency. These problems affect the overall performance of the treatment system as well as its operational lifetime.

When there is clogging of the porous medium in HSSF-CWs, one of the traditional restoration procedures is its removal and replacement. Another option to restore porosity of the medium is to remove and wash the filtration medium, returning it back to the system (Kadlec & Wallace 2008; Knowles et al. 2011; Nivala et al. 2012). Although these methods are the most efficient, they are expensive, highly invasive and require a prolonged system recovery period for establishment of a new biofilm and readaptation of plants, both of which are essential in the treatment of effluents in CWs (Kadlec & Wallace 2008; Hua et al. 2014).

In recent years, studies on unclogging have been performed in situ, applying minimally invasive reparative techniques to systems which avoid taking them out of operation for prolonged periods of time, which have included: aeration (Ouellet-Plamondon et al. 2006; Nivala et al. 2007; Chazarenc et al. 2009; Zhang et al. 2010), addition of chemicals such as hydrogen peroxide (Behrends et al. 2006a; Nivala & Rousseau 2009) or worms (Li et al. 2011).
Other strategies are also used to prevent the negative effects associated with clogging of the porous medium, including approaches such as best management practices (Turon et al. 2009), pre-treatment of wastewater (La Varga et al. 2015) and backwashing (Fei et al. 2010), in addition to the use of processes including system rest (Nivala et al. 2012; Hua et al. 2014).

Based on observations in literature on the subject, there is a need for further studies on techniques for unclogging of HSSF-CWs in order to enable their operation for a longer period of time. For a biological treatment system to function properly, the main nutrients, nitrogen and phosphorus, should be available in adequate quantities. So, hypothetically considering that the main clogging material in the CWs is organic, it would be advisable to create a means to increase the material degradation rate, one being adaptation of a C:N:P relationship that results in growth and accelerated microbial and root activity of the plants in the porous media, and therefore more accelerated unclogging. In this sense, the present study sought to evaluate unclogging of the HSSF-CW at rest by adding a nutrient solution to the affluent, and cultivation of two plant species.

MATERIAL AND METHODS

Characterization of the experiment

The experiment consisted of six HSSF-CWs deployed in a greenhouse, made of fiberglass boxes measuring 0.6 m high × 0.5 m wide × 2.0 m long. These boxes were filled with gneiss gravel \( (D_{50} = 9.1 \text{ mm}, \text{uniformity coefficient} \ - \ UC = D_{60}/D_{10} = 3.1 \text{ and initial void volume of } 0.398 \text{ m}^3 \text{ m}^{-3}) \) to a height of 0.55 m, leaving a freeboard of 0.05 m (the water level was kept to 0.05 m below the surface of the support material). The evaluated units had no bottom slope and were in operation from July 2011 until December 2013, for the treatment of swine wastewater (Baptestini et al. 2016).

The six HSSF-CWs were divided into three different treatment groups: two uncultivated (HSSF-CW 1 and HSSF-CW 4), called CW-C, two cultivated with Tifton 85-grass (Cynodon spp.) (HSSF-CW 2 and HSSF-CW 5), referred to as CW-T, and two cultivated with alligator weed (Alternanthera philoxeroides) (HSSF-CW5 and HSSF-CW 6), denominated CW-A.

Selection of the plant species was based on previous experiences (Fia et al. 2011; Baptestini et al. 2015, 2016) which demonstrated the efficiency of these plants in HSSF-CWs operated in tropical environments, presenting good rooting, high dry matter yield and great ability to remove nutrients, as well as adaptation and survivability in extreme environments, such as reducing or saline conditions.

All HSSF-CWs, at the end of the experiment conducted by Baptestini et al. (2016), were fully clogged and characterization of the clogging material was performed for further evaluation of the dynamics of unclogging via application of a nitrogen-based nutrient solution to the system influent.

In formulation of the nutrient solution, the most favorable nitrogen:phosphorus ratio (N:P) for development of microorganisms in the medium was considered, which according with Metcalf & Eddy (2005) is 5:1. Based on results of previous chemical characterization of the clogging material in all CWs, it was verified that there is a need to add nitrogen to the medium to obtain the said N:P ratio. The solution was prepared weekly by mixing 8 kg of urea fertilizer (45% N) with 3.5 L of distilled water. It was stored in tanks and pumped through metering pumps of the brand Concept Plus (Prominent) into the systems, at a flow rate of 46.06 mL min\(^{-1}\), calculated based on the working volume of the HSSF-CWs divided by the HRT, fixed at 3 days. The pore volume of the HSSF-CWs corresponds to the product of the total volume \((2.0 \text{ m long } \times 0.50 \text{ m wide } \times 0.55 \text{ m deep})\) by the drainable porosity, which are pores of larger diameter in the support material where water and the solution permeate, and are subject to clogging by accumulated solids. Confirmation of flow from the pumps was performed daily and, if necessary, was adjusted.

The experiment was initiated on December 7, 2013 with application of the nutrient solution continuously for 24 h at the inlet of each of the HSSF-CWs, and was maintained until February 1, 2014. During this period there was no passage of residual water and two cuttings of the plants were performed, one at the beginning of the experiment and the other on day 40.

Sampling and characterization of solids present in the porous medium

For characterization of the clogging material in each experimental unit, three samples were collected of the support material along with solids retained in its interstices, one from each third of the bed. For this purpose, a PVC pipe measuring 100 mm in diameter and 60 cm in length was inserted into the bed, followed by manually removing all material contained therein. The material was passed through sieves of different size mesh (19.1, 12.7, 9.25, 6.35, 4.76 and 2.58 mm, 1 mm and 0.212 mm) for separation.
by particle size, enabling the removal of most of the interstitial solids and part of those adhered to the solid support medium (gneiss gravel). The material retained on and which passed through the 0.212 mm sieve was packaged in separate recipients. The remainder of the material was washed using a maximum volume of 1.5 L of distilled water, so as to provide the largest possible removal of adhered organic material. The suspensions generated when washing each support material sample were placed in 2 L beakers and dried on a heated plate at 60 °C. Then, drying of the residue contained in the beakers was completed in a forced air ventilation oven at a temperature of 65 °C for 24 h. Finally, the material that passed through the 0.212 mm mesh sieve was denominated ‘fine material’ and the material that passed through the 1 mm sieve and remained on the 0.212 mm sieve was called ‘coarse material’. It was opted to perform this separation since after the washing of all support material, the presence of organic material adhered to the smallest particles of the support material was observed.

Characterization of the solids was carried out by the method described in APHA/AWWA/WEF (2012) for analysis of total solids (TS), total fixed solids (TFS), total volatile solids (TVS) and easily oxidizable carbon (EOC).

Hydraulic conductivity test and monitoring the reduction in surface runoff

To perform the hydraulic conductivity tests in the saturated medium \( K_0 \), PVC tubes measuring 75 mm in diameter and 0.50 m in length were used. The tubes were permanently inserted to a wet depth of 10 cm at distances of 0.33, 1.0 and 1.67 m from the inlet of each of the HSSF-CW beds (Figure 1), having previously made two measurements, one before and another after passage of the nutrient solution through the system.

The procedure consisted of the application of clean water to the tube (piezometer), obtaining a head of 0.40 m in the form of a pulse by measuring the time it took water to infiltrate/percolate through the porous medium of the HSSF-CWs. To measure the water level difference inside the tube over time, a hydrostatic level transmitter HYTRONIC® model TSH/100M/E/02 (0 to 1 m of water column) was used, connected to the converter modules 7520 and A/D 7018, and these to a computer. For data collection and storage the computer program ‘Data Acquisition System’ was used, developed by Batalha (2011).

Hydraulic conductivity at each point was estimated using Equation (1), obtained by combining the conservation of mass principle and Darcy’s law (NAVFAC 1986):

\[
K_o = \frac{\pi D + 11L}{11t} \ln \frac{h_0}{h}
\]

where, \( K_o \) = hydraulic conductivity of the saturated medium \( (m \ s^{-1}) \); \( h_0 \) = initial height of water in the tube \( (m) \); \( h \) = height of the water level in the tube at time \( t \) \( (m) \); \( D \) = internal diameter of the tube \( (m) \); \( L \) = height of the submerged tube \( (m) \); \( t \) = time \( (s) \).

To monitor the unclogging process in the HSSF-CWs, monitoring the advance of surface runoff was performed to determine if there was reduction after the nutrient solution was applied.

Statistical analysis of the data

The statistical analysis consisted of application of the ‘t’ test for the paired data, adopting the probability levels of 5 and
10%, aiming to compare the solid concentration means (total, volatile fixed, easily oxidized) in the pore medium system before and after passage of the nutrient solution. In order to assess the unclogging process of the systems, a descriptive analysis was carried out based on the physical, chemical and biological phenomena.

RESULTS AND DISCUSSION

Evaluation of the physical alterations in the bed of the CWs resulting from the unclogging process

To evaluate the effects of applying the nutrient solution for the HSSF-CW unclogging process, a comparison was made between the solids fractions (TS, TVS and TFS) and EOC in the clogging material, before and after performing the treatment. The mean values of the variables are shown in Table 1, as well as the difference between them, performing a statistical analysis of the differences so that it would be possible to evaluate the contribution of the system treatment with the nutrient solution in the HSSF-CW unclogging process.

According to the results shown in Table 1, passage of the nutrient solution through the bed of the HSSF-CWs resulted in significant reductions in the volatile solids content, i.e. part of the organic material present in the medium was degraded, thus contributing to unclogging pores in the filter medium.

It was observed that in the cultivated systems the reduction in TVS concentrations in the fine material after passage of the nutrient solution was more significant, being 11 and 33% in the CW-T and CW-A, respectively. With regard to TVS in the coarse material, this reduction was even greater, being 33% in CW-T and 62% in CW-A. A potential hypothesis for further reduction of TVS in CW-A is the presence of a root aeration system, consisting of aerenchyma more adapted to the flooded environments with alligator weed than with Tifton 85-grass.

The larger reduction in TVS levels of the coarse material was associated with the fact that this material is more labile than the fine material (see EOC of the materials presented in Table 1). Thus, degradation of organic matter from the coarse material was predominant in the unclogging of the systems under study.

The mass removed from the coarse clogging material was 20.6, 30.3 and 33.0 g cm⁻³ of sample collected, respectively, for the control HSSF-CWs (CW-C), those cultivated with Tifton 85-grass (CW-T) and cultivated with alligator weed (CW-A), i.e. mass of coarse material in the cultivated CWs was 32 and 37% higher, respectively, in CW-T and CW-A, in relation to the uncultivated CWs.

Thus, it can be inferred that the mass of the coarse clogging material present in the cultivated CWs is predominantly made up of dead plant tissue, corroborating with the results of Knowles et al. (2010) and Pedescoll et al. (2011), according to which the obstruction of the porous medium in the CWs can be caused by the growth of rhizomes and roots and by the senescence of plants that produce large quantities of plant debris. However, just as clogging is faster in the cultivated CWs, unclogging also occurs in an accelerated manner, considering that the plant material is readily degradable. Rosmann et al. (2015) added that the root zone is an environment conducive to

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Mean values in (dag kg⁻¹) of TS, TFS, TVS and EOC, before (B) and after (A) the period of passing the nutrient solution through the HSSF-CW and the difference between them (B-A)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Treat.</strong></td>
<td><strong>TS (dag kg⁻¹)</strong></td>
</tr>
<tr>
<td><strong>Fine material</strong></td>
<td></td>
</tr>
<tr>
<td>CW-C</td>
<td>98.77</td>
</tr>
<tr>
<td>CW-T</td>
<td>97.18</td>
</tr>
<tr>
<td>CW-A</td>
<td>97.20</td>
</tr>
<tr>
<td><strong>Coarse material</strong></td>
<td></td>
</tr>
<tr>
<td>CW-C</td>
<td>99.32</td>
</tr>
<tr>
<td>CW-T</td>
<td>96.97</td>
</tr>
<tr>
<td>CW-A</td>
<td>96.77</td>
</tr>
</tbody>
</table>

ns, *; #-non-significant; significant at 5 and 10% by the ‘t’ test, respectively, comparing after and before addiction of nutrient solution.

CW-C, CW-T and CW-A – HSSF-CWs unplanted, cultivated with Tifton 85-grass and cultivated with alligator weed, respectively.

*dag kg⁻¹ unit of concentration (mass of the variable per total dry mass of the material).
greater microbial diversity, providing better conditions for degradation and transformation of organic material, which results in faster unclogging of the pores.

**Measure of hydraulic conductivity in saturated medium**

Two hydraulic conductivity measurements were carried out in the saturated medium ($K_0$), one before (measurement 1) and one after (measurement 2) the application period of the nutrient solution in the CWs. Figures 2–4 show, respectively, the results of $K_0$ along the control HSSF-CW (CW-C), those cultivated with Tifton 85-grass (CW-T) and those cultivated with alligator weed (CW-A). Figure 5 presents a graph of the average values of $K_0$ in a HSSF-CW through which only water was passed (clean gravel before starting the treatment of wastewater). The values were measured by Ferres (2012).

It was noted that CW-C, CW-T and CW-A showed lower $K_0$ values than the system containing ‘clean’ gravel, even after the period of passing the nutrient solution. When comparing the $K_0$ values of measurement 2 for the HSSF-CWs studied with the HSSF-CW receiving only clean water presented by Ferres (2012), there were recoveries of 11, 19 and 19%, respectively, in thirds 1, 2 and 3 of the uncultivated HSSF-CWs; 56, 58 and 59%, respectively, in thirds 1, 2 and 3 of the HSSF-CWs cultivated with Tifton 85-grass; and 87, 76 and 53%, respectively, in thirds 1, 2 and 3 of the HSSF-CWs cultivated with alligator weed for restoration of the initial hydrodynamic conditions of the systems.

It may be noted that the CW-C (without plants), even after passage of the nutrient solution, also showed higher $K_0$ values than the planted systems (CW-T and CW-A), which was indicated in both measurement 1 and measurement 2. It was assumed that this difference is due to the contribution of dead organic matter deposits by plants in the cultivated CWs, which may have contributed to the clogging process of the systems, and consequently the decrease in hydraulic conductivity of the porous medium.

A comparison was performed of the $K_0$ values before (measurement 1) and after the period of passing the nutrient solution (measurement 2) along the systems, verifying that there was an increase of 7, 13 and 0.1% in this variable when measured in thirds 1, 2 and 3, respectively, of the CW-C; and 21, 11 and 7% in the same thirds in CW-T. In CW-A, an increase in $K_0$ was observed only in the first (52%) and second (6%) thirds, while in the third there was a decrease in hydraulic conductivity. It was assumed that the lower recovery of $K_0$ in the final third of CW-A was
due to greater accumulation of organic debris resulting from the attack and death of many alligator weed plants. With application of the nutrient solution, the organic material accumulated in the first thirds of CW-A were degraded and transported to the system output (final third).

**Surface runoff of the nutrient solution applied to the HSSF-CWs**

Runoff of the nutrient solution applied to the HSSF-CWs is a phenomenon resulting from the advanced degree of clogging of the system pores and which occurred while there was no clearing of organic material accumulated in the drainable pores. Figure 6 shows the length of the bed in which there was surface runoff during the nutrient solution application period in the HSSF-CWs.

The first measurement of runoff length, performed on the seventh day of application of the nutrient solution, indicated that the CW-C (uncultivated) presented less runoff than the cultivated systems CW-T and CW-A. This fact was evidenced throughout the monitoring period, which may be the contribution of dead organic matter deposits by plants, which formed a layer of about 15 cm of organic material accumulation, the main factor influencing runoff. According to Pedescoll et al. (2011), the roots constituted, after 3 years, 35 to 70% of the occupant material from the drainable pore spaces, and according to Knowles et al. (2011) it has been demonstrated that the presence of roots creates greater resistance to water flow.

Therefore, the reduction in runoff length of the nutrient solution occurred gradually over the treatment time of the CWs, where runoff was no longer observed in CW-C as of the fourth week, and in the CW-T as of the fifth week. Regarding CW-A, the reduction in runoff was gradual, reaching a maximum value of 72% on the seventh week of treatment (49 days of nutrient solution application), but at no time was runoff completely eliminated. However, after the forty ninth day (eighth week of application of nutrient solution) there was a 39% increase in runoff compared to what was observed on the seventh week. This coincided with the period in which there was a new pest attack and death of alligator weed plants. These results indicated that the presence of dead plant tissues on the surface of the bed greatly influences runoff in the HSSF-CWs, as has previously been reported.

Figure 7 shows surface runoff before passage of the nutrient solution and at the end of the experiment, after performing the referred treatment.

Ferres (2012) found that in the same HSSF-CWs used in this experiment, the plants generated a larger accumulation
of organic matter in the upper layers, which resulted in accelerated fouling of the systems. In contrast, it was observed that, in the cultivated CWs, the reduction in surface runoff and increase in $K_0$ were proportionately greater than those measured in the non-cultivated CWs. It appeared that the accumulated material presented great lability and the plants and their residues resulted in a more suitable environment for growth of the microbial community, contributing to faster degradation of the organic material retained in the porous medium of the systems.

The supply of nutrients may be a strategy used to enhance the action of microorganisms for the degradation of accumulated organic material, and thereby unclog the porous medium. Behrends et al. (2006a), at the laboratory scale, obtained a 50% reduction in volatile material trapped in porous media when removing the surface layer of the bed and adding nitrogen fertilizer to the system. On the other hand, Hanson (2002) and Behrends et al. (2006b) found that under field conditions nutrient addition resulted in only the displacement of clogging from one area to another downstream in the CWs.

Based on the results obtained, it was found that passage of the nitrogen-based nutrient solution was effective in reducing runoff in cultivated CWs and may be used as an unclogging technique whenever the accumulated organic material presents an unfavorable N:P or C:N nutrient ratio for microbial degradation.

### CONCLUSIONS

The application of a nitrogen-based nutrient solution contributed to reduce surface runoff on the beds of the HSSF-CWs, where the reduction in concentration of organic material in the surface layers is one of the main factors for this decline.

Application of the nutrient solution resulted in recovery of the saturated hydraulic conductivity in the HSSF-CWs, being more expressive in the first third of the beds.

Clogging was faster in the cultivated CWs and unclogging also occurred in an accelerated manner, considering that the plant material is readily degradable. A decrease in the extent of surface runoff was observed in the HSSF-CW cultivated with Tifton-85 grass and also in the uncultivated HSSF-CW. Only in the HSSF-CW cultivated with alligator weed did surface runoff persist due to the fact that plants died as a result of pest attack.

Runoff of the nutrient solution decreased gradually over time, which at the beginning of the experiment extended 26, 35 and 150 cm and at the end (after 55 days of application) 0, 0 and 50 cm in the flow direction of the CW-C and CW-T and CW-A, respectively.

### REFERENCES


Hanson, A. 2002 Unplugging the bed of a subsurface-flow wetland using $\text{H}_2\text{O}_2$. In: Wetlands and Remediation II (K. W.
Nehring & S. E. Brauning, eds). Battelle Institute, Columbus, OH, USA. pp. 281–287.


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