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Key factors in the clogging process of horizontal subsurface flow constructed wetlands receiving anaerobically treated sewage

M.P. Matos[a,*], M. von Sperling[b], A.T. Matos[b], S.T. Miranda[c], T.D. Souza[c], L.M. Costa[d]

[a] Department of Engineering, Nucleus of Environmental and Sanitary Engineering, Federal University of Lavras, Lavras, Minas Gerais, Brazil
[b] Department of Sanitary and Environmental Engineering, Federal University of Minas Gerais, Minas Gerais, Brazil
[c] Agricultural Engineering, Federal University of Viçosa, Viçosa, Minas Gerais, Brazil
[d] Soil Department, Federal University of Viçosa, Viçosa, Minas Gerais, Brazil

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ABSTRACT

The influent solids load, biofilm formation and occupation of void spaces by precipitates have been identified as major contributors to clogging the pores of horizontal subsurface flow constructed wetlands (HSSF-CWs). Several publications suggest that most of the accumulated material is inorganic, and this indicates that wear of the substrate may be an important constituent of clogging. The objective of this study was to characterize, in mineralogical, physical (specific mass) and chemical terms (neutralization power and volatile and fixed solids) the clogging material from the pores and the substrate medium (blast furnace slag) in two small full-scale HSSF-CWs, one planted with cattail (*Typha latifolia*) and another kept unplanted. The system received urban wastewater pre-treated in an upflow anaerobic sludge blanket reactor, was operating for seven years and showed signs of heavy clogging leading to overland flow. Samples were collected at intermediate points along the two units in order to identify the origin of the accumulated material and thereby enable the proposition of a conceptual model for the clogging process of these systems. The results indicated that most of the mass of clogging solids were inorganic and originated from wear of the substrate. However, the volume occupied by the organic solids was larger, and those were the major contributors to the clogging process.

1. Introduction

Clogging, when referring to horizontal subsurface flow constructed wetland systems (HSSF-CWs), can be defined as the phenomenon of progressive solids accumulation in their porous media (Kadlec and Wallace, 2009), and is considered by many researchers and practitioners as their main operational problem.

For authors, such as Zhao et al. (2009), the load of suspended solids (SS) applied was the factor that most contributed to clogging, being therefore mainly associated with sedimentation and filtration mechanisms. On the other hand, Hua et al. (2010), when stating that pores are much larger than the diameter of SS in wastewaters, suggested that other factors must be involved in the accumulation of solids, otherwise the particles would exit in the effluent. The greater filtration capacity is therefore dependent on the formation of retaining cores, adsorption sites of solids (filter maturation), implying in reduction of pores spaces, that can result from, for example, the formation of biofilms. Analysis of the material collected in the pores also allowed for observing that the characteristics of the accumulated solids were different from the suspended material entering the filter bed (Caselles-Osorio et al., 2007).

According to Caselles-Osorio and García (2006) the biofilm formation could be a more important factor for clogging. However, this phenomenon is progressive throughout the system operation time (Kadlec and Wallace, 2009), while the development of biofilm is not continuous. There is a certain balance between bacterial growth and decay as a function of nutrient transfer at the center of the biofilm, which can lead to weakening and loss of adhesion to the support medium, causing it to be lost in the effluent (Okabe et al., 1998). Seifert and Engesgaard (2007) concluded that there were also other factors that contributed to reduce the available or effective porosity.

Inside the porous medium there may occur the formation of precipitates associated with sulfides, carbonates, silicates, hydroxides and phosphates of iron, calcium, magnesium, aluminum and

* Corresponding author.
E-mail addresses: mateus.matos.deg@ufla.br (M.P. Matos), marcos@desa.ufmg.br (M.v. Sperling), atmatos@desa.ufmg.br (A.T. Matos), suymara.miranda@ufv.br (S.T. Miranda), tamara.souza@ufv.br (T.D. Souza), liovandomc@yahoo.com.br (L.M. Costa).

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heavy metals (Marshall, 2009). However, the importance of pore clogging by precipitates depends, among other variables, on the redox potential and characteristics of the filter material (Korkusuz et al., 2005; Suliman et al., 2006). According to Guofen et al. (2010), the trapped gases, for example, H_2S and CH_4, could also be factors hindering the water permeability in CWs.

Authors, such as Caselles-Osorio et al. (2007) and Paoli and von Sperling (2013), for example, found that only 20–25% of the solids present inside the bed were organic, and thus the higher inorganic fraction could be associated with the wear of the support material. Pedescoll et al. (2009) encountered similarity between the inorganic solids associated with clogging and powder of the substrate.

The participation of the plants in the clogging process is controversial. Some authors state that the network of roots and rhizomes occupy pore space and also contribute to greater retention of solids, in addition to the contribution of debris resulting from senescence and death of plant parts which could contribute to accelerated clogging (Tanner and Sukias, 1995; Knowles et al., 2010; Paoli and von Sperling, 2013). However, other researchers suggest that plants mitigate this effect by expansion of the pore space caused by the growth of roots and rhizomes, in the mechanism known as "swelling", besides the formation of secondary channels after death and subsequent degradation of roots and rhizomes. The presence of plants can also provide conditions for a richer and more favorable microbial community to improve the degradation rate of accumulated interstitial solids (Turon et al., 2009; Seeger et al., 2013; Matos et al., 2015).

Given the points presented above, it is clear that the need to investigate the origin of clogging solids is evident, including the characterization of the clogging solid materials and the medium substrate. The objective of this study was therefore to characterize, mineralogically, physically and chemically, the clogging material of the pores and the contribution of the substrate, blast furnace slag, wear when used as medium for a small full-scale HSSF-CWs treating sewage previously treated in a UASB reactor. The aim is to identify the origin of the clogging material and thereby propose a conceptual model for the clogging process in these systems.

2. Materials and methods

The tests were developed at the Center for Research and Training in Sanitation (CePTS UFMG/Copasa), located at 19°53′42"S and 43°42′52"W, in the Arrudas Wastewater Treatment Plant (WWTP) in the city of Belo Horizonte, Brazil. The area has a tropical climate, with an average annual temperature of 22.1 °C and rainfall of 1540 mm $year^{-1}$.

Part of the sewage from the Arrudas WWTP, after preliminary treatment (coarse and fine screens followed by grit removal), is diverted to feed the experimental units in CePTS, among which is the system composed of a UASB reactor and two HSSF-CWs. The beds are in operation since 2007, working in parallel, continuously receiving 7.5 m^3 d^{-1} each.

The CWs were filled with blast furnace slag, with diameter d_{10} equal to 19.1 mm and uniformity coefficient (UC) equal to 1.2 (Dornelas et al., 2009), except for the first 1.0 m and last 0.5 m. These sections were filled with larger stones (between 10 and 15 cm) to facilitate the distribution and collection of wastewater. As can be observed in Fig. 1, the HSSF-CWs have an effective length of 25.0 m and a width of 3.0 m. Table 1 shows other design and operational details for each of the CWs. One of the HSSF-CWs (P-CW) was cultivated with cattail (*Typha latifolia*), while the other (U-CW) remained uncultivated.

In the last operation phase, the planted CW presented removal efficiencies (median) of 82, 80, 78 and 48%, respectively, of total suspended solids (TSS), BOD, COD and total Kjeldahl nitrogen (TKN).

Table 1
Constructive and operational characteristics of each HSSF-CW unit.

Parameter	Unit	Value
Total height (h_t)	m	0.4
Useful (liquid) height (h_u)	m	0.3
Useful length (top) (L)	m	25.0
Total length (top) (L_t)	m	25.5
Width (top) (B)	m	3.0
Longitudinal bottom slope (i)	%	0.5
Total bed volume (V_t)	m^3	30.0
Bed volume with liquid (V_u)	m^3	22.5
Bed surface area (top) (A_s)	m^2	72.0
Porosity of the filter medium (ϵ)	$m^3\,m^{-3}$	0.40
Volume of voids or pores (V_p)	m^3	9.0
Theoretical hydraulic retention time (HRT)	d	1.20
Median of suspended solids loading rate (surface)	gTSS $m^{-2}\,d^{-1}$	5.6
Median of organic loading rate (surface)	gBOD $m^{-2}\,d^{-1}$	4.6
Hydraulic loading rate (surface)	$m^3\,m^{-2}\,d^{-1}$	0.1

In the same order, the efficiencies in the unplanted CW were of 80, 75, 66 and 30%, but having significant difference only for the nitrogen removal. Other details of this treatment system can be found in the following references: performance and loading rates (Dornelas et al., 2009; Costa et al., 2013, 2015; Matos, 2015); determination of hydraulic conductivity (Matos et al., 2016b); hydrodynamic characterization by tracer studies (Matos et al., 2015); and determination of the clean porosity with the use of Georadar (Matos et al., 2016a).

Both units were already operating for seven years and showed a high degree of clogging, with large amount of sludge and the appearance of wastewater above the substrate. It is observed that there is less surface flow in the planted CW, but this unit had the worst initial conditions (with highest water level), while the zone of the unplanted CW with the most critical situation is close to its center (Matos et al., 2016a, 2016b). Analysis of the hydraulic retention time (HRT) (Matos et al., 2015) and the clean porosity (Matos et al., 2016a) indicate overall better conditions in the planted CW.

2.1. Granulometric characterization of the filter medium and solids

Fig. 1 also shows the positions for sampling of the solids and substrate, at 3.0, 6.0, 11.0, 16.0 and 21.0 m from the system inlet. Sampling was performed manually in 2014, seven year after the start of operation, by inserting a 100 mm PVC tube with handle to facilitate penetration and removal of the crimped tube. Markings were made on the tube, defining the depths of 0.15 and 0.40 m (maximum depth of the HSSF-CWs). Rotation of the tube with the help of handles allowed for forcing them down to a depth of 0.15 m where sampling was performed by transferring the material to properly labeled plastic bags. To sample the deeper layer of the porous medium, the tube was forced to penetrate up to the 0.40 m depth mark, repeating the sampling operation in the same manner as performed in the upper layer (0.15 m depth). Differentiation was also made by the side of the marked section, with sampling positions to the left and right of the imaginary traced transversal axis of the filter bed (see Fig. 1).

The samples of material collected were left under ambient temperature and subsequently forwarded for granulometric separation. Materials were obtained with granulometry greater than 12.70, from 9.25 to 12.70, from 6.35 to 9.25, from 4.76 to 6.35, from 2.38 to 4.76 from 1.00 to 2.38 and less than 1.00 mm. The fine material not retained on the 1.00 mm sieve was considered to be the clogging material, while the remainder was considered substrate. With construction of the granulometric curves the diameter was calculated which allowed for passage of 10, 30 and 60% of all samples, respectively, D_{10}, D_{30} and D_{60}, and the coefficient of uniformity (UC) and curvature (CC), calculated by Eq. (1) and Eq. (2). In