Science of the Total Environment 628–629 (2018) 509–516

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Study of the spatial and temporal distribution of accumulated solids in an experimental vertical-flow constructed wetland system

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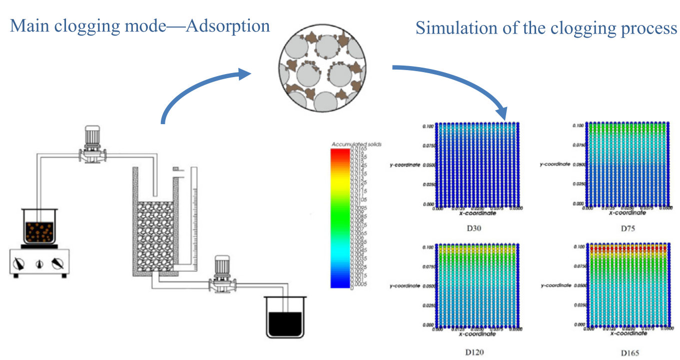
HIGHLIGHTS

- Solids accumulation process was monitored in experimental VF CW systems.
- Adsorption was the major accumulation mode for particles ($d_{50} = 8.26$ μm).
- Particles were intercepted or adsorbed into the matrix at a constant rate.
- The proportion of particles (>20 μm) kept increasing in the top layer of medium.
- The accumulation of particles could be simulated by a first-order kinetics model.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 18 December 2017
Received in revised form 7 February 2018
Accepted 8 February 2018
Available online xxxx

Editor: Jay Gan

Keywords:
Vertical flow constructed wetland
Clogging
Accumulated solids
Spatial and temporal change

ABSTRACT

Clogging is the most serious problem in the operation of subsurface flow constructed wetlands (SSF CWs) and is caused by the accumulation of solids in substrates. Study of the solids accumulation process can provide a more accurate reference for the management and maintenance of SSF CWs. In this study, an experimental vertical-flow constructed wetland system was recreated in the lab, and substrates with different depth were sampled through different operation time to reveal the spatial and temporal distribution of accumulated solids. During the study, particulates mainly accumulated through adsorption along the gravel surface. Therefore, the matrix could still provide sufficient space for the particles to pass through and be intercepted or adsorbed into the system at a constant rate. At the end of the study, an increasing number of large particles had been intercepted and were accumulated in the 0–2 cm layer of the matrix, indicating a significant decrease in the pore diameter at the top substrate layer. The spatial and temporal accumulation of substrate particulates during the study period was accurately simulated by first-order kinetics models, and the simulated results were in good agreement with measured values.

1. Introduction

Subsurface flow constructed wetlands (SSF CWs) have been used worldwide for sanitation, especially in small communities, because of their natural design and low operational and maintenance costs (Cooper et al., 1990; Vymazal, 2010). However, clogging is the most

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https://doi.org/10.1016/j.scitotenv.2018.02.086
0048-9697/© 2018 Published by Elsevier B.V.

serious but inevitable problem that is faced when using this technology (Blazejewski and Murat-Blazejewska, 1997; Caselles-Osorio et al., 2007; Pedescoll et al., 2013; Al-Isawi et al., 2015). This phenomenon is due to the build up of solids in substrate, which mainly come from biofilms, roots, and macrophytes, macrophyte litter, as well as any undissolved matter present in raw wastewater (Knowles et al., 2011; Nivala et al., 2012). Accumulated solids can be divided into organic and inorganic parts. Due to high moisture content and low density, organic matter occupies more pore volume comparing with inorganic solids (Matos et al., 2017; Miranda et al., 2017). However, researches conducted by Matos et al. (2017) and Miranda et al. (2017) also suggested that most of the accumulated solids were inorganic, which was confirmed by previous studies (Caselles-Osorio et al., 2007; De Paoli and von Sperling, 2013). Although Nguyen (2000) concluded that organic matter was the main factor in clogging, his study revealed that up to 90% of the organic solids were recalcitrant parts. In anaerobic conditions, only little organic matter is biodegradable, and aeration can promote the decomposition of accumulated organic matter in CWs (Carballeira et al., 2017). Therefore, in the SSF CWs that provide appropriate conditions for organic matter to decompose completely, mineral composition plays a dominant role in the accumulation of solids (García et al., 2007; Ruiz et al., 2010).

SSF CW performance indicators, such as contaminant removal efficiency, porosity, and hydraulic conductivity, change during the process of solids accumulation (Langergraber et al., 2003; Hua et al., 2010; Ranieri et al., 2013; Aiello et al., 2016). Thus, research on solids matter accumulation is critical for understanding and forecasting the performance of SSF CWs. There are two modes of accumulation for solids in substrates: on the substrate surface or within the pores, depending on the size of solid particles involved (Caselles-Osorio et al., 2007; De Paoli and von Sperling, 2013). Particles with a larger diameter clog substrate pores, whereas solids absorbed on substrate surfaces mostly have a diameter <100 μm (Hua et al., 2010). These two accumulation modes result in varying effects on their hydraulic parameters and behaviors. Solids embedded into pores have a stronger influence on hydraulic conductivity than adsorbed solids (Pan and Yu, 2015). Therefore, it is important to consider the dynamic change of distribution modes influenced by accumulated particle size when studying the accumulation of solids in substrates.

Some studies already exist that focus on the quantification of these accumulated solids (Caselles-Osorio et al., 2007; Pedescoll et al., 2013). Temporal changes occur in the dynamics of accumulated solids with a significant increase in the amounts of accumulated solids over operation time (Pedescoll et al., 2011; Fu et al., 2013; Zhong et al., 2013). And the distribution of solids in SSF CWs declines along the length of the flow path (Ye et al., 2008; Lancheros et al., 2017). In vertical-flow CW systems, where hydraulic behavior is less complicated, the accumulation of solids is negatively correlated with depth (Yan et al., 2008; Hua et al., 2010), with an obstructing layer of substrate existing no deeper than 20 cm (Todt et al., 2014; Xie et al., 2010). In horizontal-flow CWs, which have more complicated hydraulic behavior, the variation in accumulated solids distribution is less significant (Lancheros et al., 2017).

However, there is little study on the process of solids accumulation in CWs, which could not be elucidated clearly by just measuring the content change of accumulated solids. The temporal and spatial variance of accumulation mode together with particle diameter of accumulated solids should be taken into account. Due to the lack of real-time monitoring technology in SSF CWs, accumulated solids can be measured only through substrate sampling, which has significant limitations as the sampling process itself disrupts the internal environment in the substrate around the sampling sites. And data based on regular substrate sampling in a SSF CW system over time to reveal the temporal inner changes is still sparse (Corbella et al., 2016).

This study aimed to investigate the accumulation process of solids in an experimental vertical-flow constructed wetland system. To achieve this goal, the spatial and temporal changes in quantity and particle size distribution of accumulated solids, both in pores and on the substrate surface, were monitored and analyzed. Further, based on the observed data, a model was established to describe the spatial and temporal dynamics of accumulated solids distribution, which could help better understand the clogging process in SSF CWs.

2. Material and methods

This study was conducted in an experimental laboratory system over a period of 180 days. Because inorganic solids and recalcitrant organic solids account for the vast majority of accumulated solids in the current literature (García et al., 2007; Ruiz et al., 2010), insoluble inorganic particles in the inflow entering the SSF CWs were focused on to study the accumulation process. To exclude any contribution from biofilms or macrophytes, organic matter and nutrients were not added into the inflow of experimental systems. In addition, macrophytes were not planted.

2.1. Experimental system

Due to the disruptive effect of the sampling process on substrates, 12 identical systems were set up to allow for the sampling of 12 stages within the operational period without interference. At the end of each operational stage, substrates were collected from a system for the measurement of accumulated solids. The same conditions were used for all systems.

Fig. S1 shows the configuration of each experimental vertical flow constructed wetland system. The suspensions were prepared using zeolite powder (consisting of aluminosilicate) with the particle size distribution shown in Fig. S2, and then uniformly mixed with tap water using a magnetic stirrer in the upstream tank. This mixture was pumped up through the influent pipe to an experimental column filled with uniform gravel, which was sieved to 3 mm–4 mm in diameter and carefully cleaned in water using ultrasonic waves. The experimental column was 5 cm in diameter and 15 cm in height and made of Perspex with scales marked on the lateral wall. As mentioned before, in vertical-flow CWs systems the accumulation of solids is negatively correlated with system depth (Yan et al., 2008). And Hua et al. (2010) established that 80%–90% of total accumulated solids in vertical-flow CWs were distributed in the top 6 cm of substrates. Considering this, the height of packed gravel was set to be 10 cm. The column was equipped with a manometer connected near the bottom to monitor the water head. The outflow was sent to a downstream tank through an effluent pipe at the same rate as the inflow and controlled by pump-2.

2.2. Operation

All 12 systems, as shown in Fig. S1, had the same gravel packing and mode of operation. Steady inflow conditions were maintained throughout the whole experimental period. The concentration of total suspended solids (TSS) was about 500 mg/L, and the inflow rate to the experimental column was 37 mm/day in height, resulting in a value of 36.5 mg/day for the TSS load. Initial substrate effective porosity and infiltration rates were 0.372 and 0.458 cm/s, respectively. The air temperature in the laboratory where the apparatuses were installed was kept at 20 °C throughout the experiment.

2.3. Measurements

2.3.1. Quantity of accumulated solids

According to Caselles-Osorio et al. (2007), there are two types of accumulated solids in substrates: interstitial solids that are trapped in the empty spaces between the gravel and easily released when the spatial structure is lost, and adhered solids that are tightly adsorbed onto the surface of the gravel particles and are not easily released. Both types of accumulated solids were considered in this study. Every 15 days,