CLOGGING IN VERTICAL FLOW CONSTRUCTED WETLANDS: CAUSES FOR CLOGGING AND INFLUENCE OF DECONTAMINATION

Abstract: With the continuous operation of constructed wetlands, substrate clogging is an issue. In order to solve the problem, it is practical to understand the causes for clogging in constructed wetlands. Two pilot-scale vertical flow constructed wetlands were established, namely, CW-B and CW-C. By studying the relationship between the accumulation of different substances and the banked-up water area, it was found that the accumulation of non-filter substances and total solids was an important reason for the clogging of the substrate, and the accumulation degree of non-filter inorganic substances was more obvious than that of non-filter organic substances, and the blockage was mainly located in the 10-20 cm layer. In the vertical flow constructed wetland with river sand as the main substrate, water accumulation will occur when the content of total solids and non-filter substances exceeds 67.233 g and 101.228 g per cubic meter of substrate, respectively. Therefore, it is important to pay attention to the substrate particle size matching of the 0-20 cm layer to reduce the clogging in the vertical flow constructed wetland. The clogging has little effect on chemical oxygen demand (COD) removal, but great effect on total phosphorus (TP) removal. Compared with the control wetland (CW-C), the biomass content in the CW-B with biochar increased by 334.26 nmol P/g, which can improve the removal efficiency of total nitrogen (TN) and total phosphorus (TP), but also increase the risk of clogging in the vertical flow constructed wetland. Future research should try to combine the anti-blocking research results of biochar constructed wetlands to improve the purification effect, which is of great significance to promote the sustainable development of constructed wetlands.

Keywords: substrate clogging, vertical flow constructed wetland, substances accumulation

Introduction

Constructed wetland (CW) is a mature treatment technology with good treatment results and low cost [1-3]. However, blockage has become an inevitable and important problem with the operation of the constructed wetland [4, 5]. It is also one of the major factors affecting sustainable decontamination in wetland [6]. The blockage problem greatly restricts the popularization and application of constructed wetland. Therefore, it is of practical significance to study the blockage mechanism of constructed wetland and the influence of blockage on the removal of target pollutants for the scientific operation and management of constructed wetland. According to the different flow patterns, CW can be divided into three types: surface flow constructed wetland, subsurface flow constructed wetland and vertical flow constructed wetland. Vertical flow constructed wetland (VFCW)
is widely used in sewage treatment because it covers a small area and has strong oxygen transport capacity [7, 8], and has a good effect on the removal of organic pollutants [9]. However, in the practical application process, VFCW is more prone to clogging [10]. Substrate clogging can hinder oxygen transport seriously, result in the reduction of effective pores, which can lead to the reduction of the pollution removal effect [5, 11-16]. Porosity can be used as an indicator of matrix clogging [5]. It is concluded that the clogging mechanism of constructed wetland is generally divided into three aspects: physical, chemical and biological. Tanner found that the blockage of CW was mainly due to the accumulation of organic matter in the surface layer above 10 cm of the substrate [17]. But the study has found that the main cause of the blockage of CW was the accumulation of unfiltered substances in the matrix layer [18]. In order to find out the cause of VFCW clogging and the influence of clogging on pollutant removal, two VFCWs were simulated in this experiment. Wetland vegetation was not planted in the experimental wetland to eliminate the interference of plant roots in the substrate. The main filler of the two wetlands was river sand. Biochar was mixed on the surface of CW-B system, and CW-C was the control (without biochar). During the experiment, the difference of decontamination effect between the two wetlands, the substances accumulation between different substrate layers and the relationship with the banked-up area were compared. The main factors of VFCW clogging and the influence of clogging on the removal effect of chemical oxygen demand (COD), total nitrogen (TN) and total phosphorus (TP) in wetland were determined, and the corresponding mitigation measures were sought on this basis.

**Materials and method**

**Construction of VFCWs**

In the experiment, two parallel VFCWs were set, namely CW-B and CW-C. The size of the two wetlands are uniformly 88 cm × 67 cm × 65 cm (length × width × height).
From bottom to top, the gravel layer (the particle size of gravel range is 2.5-5 cm) is 15 cm, the river sand layer (the particle size of river sand range is 0.35-1 mm) is 30 cm, and left 20 cm for sewage irrigate area. Biochar was mixed to the surface matrix of the CW-B and the CW-C (no biochar) is the blank control. Biochar is a carbon-rich product obtained from the anaerobic pyrolysis of waste biomass [19, 20], the biochar used in this experiment was crop straw, which was carbonised at 600 °C. After two weeks of film hanging in trial operation, the systems began formal operation on September 13, 2020 and end with January 14, 2021. Sewage was irrigated by metering pump, and the hydraulic load was 10 cm/day. The water quality was monitored once a week.

**Inflow water quality**

The experimental sewage is synthetic sewage, and the composition simulation is close to domestic sewage. Parameter values are as followed: the variation range of redox potential and pH values are 56.40-23.40 mV and 7.30-7.96. The average values of total nitrogen (TN), total phosphorous (TP) and chemical oxygen demand (COD) are 33.91-40.73, 5.59-6.21, 238.03-504.25 mg/L. TN, TP and COD were monitored by national standard method [21].

**Analytical methods**

**Substrate porosity in VFCW**

10 mL (volume) of substrates were taken from (0-10) cm, (10-20) cm and (20-30) cm in VFCW and weighed after drying. Equation (1) was used for calculation:

\[
n = 1 - \frac{\rho_d}{G_s} \cdot \frac{\rho_w}{\rho_d}
\]

where \(G_s\) is the specific gravity of the substrate; \(\rho_w\) is the density of distilled water when in 4 °C; \(\rho_d\) is the dry density, \(\rho_d = \frac{m_s}{V}\), and \(m_s\) is the weight of the dried substrate, while \(V\) is the volume of the substrate.

The specific gravity of the substrate was determined by the specific gravity flask method: several grams of the dried substrate were put into a specific gravity bottle, filled with distilled water, and weigh the bottle, the substrate and the water. The specific gravity was determined according to the equation:

\[
G_s = \frac{m_s}{m_1 + m_s - m_2}
\]

In the formula, \(m_1\) is the weight of water and flask, \(m_2\) is the weight of water, substrate and flask.

**Determination of the content of non-filtrable substances between substrates**

A certain amount of substrate was taken from (0-10) cm, (10-20) cm, and (20-30) cm of the matrix layer of the VFCW. The substrate was gently washed with 200 mL of distilled water, and then the content of organic matter trapped by the substrates in the aqueous solution was determined by the filter membrane method [21]. The calculation method was as followed. Total solid weight (take 25 mL water solution to steam dry) = filtered organic matter + non-filter organic matter + filtered inorganic matter + non-filter inorganic matter; Total solid burning weight (600 °C burning) = filtered inorganic + non-filter inorganic; Soluble solid weight (filtrate the aqueous solution at 0.45 μm and take 25 mL to steam dry)
= Filtered organic matter + Filtered inorganic matter; Soluble solid burning weight (600 °C burning) = filtered inorganic.  

Among them, the total substances content between the matrix is the total solid weight; the content of non-filter substances includes non-filter organic matter and non-filter inorganic matter, and the content of organic matter includes filtered organic matter and non-filter organic matter.

**Detection of biomass**

A certain amount of substrate was taken from (0-10) cm, (10-20) cm and (20-30) cm of the VFCW and put into a 100 mL triangle flask with stopper. 19 mL of extraction solution of chloroform, methanol and water (volume ratio: 1 : 2 : 0.8) was added, and placed in an oscillating chamber for 10 min and then left standing for 12 h. Add 5 mL chloroform and 5 mL water to the triangle flask, so that the proportion of chloroform, methanol and water was 1 : 1 : 0.9, and let stand for 12 h. 5 mL of the lower chloroform containing lipid components were transferred to a 10 mL calibrated tube with stopper for evaporation in water bath. 0.8 mL 5 % potassium persulfate solution was added to the calibrated tube, and water was added to 10 mL. The solution was digested at 121 °C for 30 min in a high-pressure steam sterilization pot, and the phosphate concentration in the digestion solution was determined according to the method of making standard curve. The results were expressed as nmol P/g or nmol P/cm$^3$ [22].

**Measurement of backed-up water area**

Using the grid method: backed-up water area was measured by equal sized grids, and count the number of cells and multiply by the area of each cell, and the sum of the area is considered the total area of the backed-up water area.

**Analysis of the data**

The mean and standard errors of the analysis were calculated using Excel 2007 and SPSS(IBM)® 26.0 software. Duncan’s method was used to analyse and compare multiple comparisons. The statistical analysis duplication in this paper was absolute sample duplication not system duplication.

**Results**

**Factors of blockage in VFCW**

_The relationship between the banked-up water area and the substances in the substrate_

With the operation of the two VFCWs, there were different degrees of clogging in the two systems. Catchment water area, total solids, non-filter matter and total organic matter contents in substrates were shown in Table 1.

As can be seen from Table 1, the total solids and non-filter matter content in the CW-B system with biochar mixed to the surface substrate were significantly higher than those in the control system (CW-C), and there was no significant difference in organic matter content between the two systems. According to the correlation analysis in Table 2, the total solid content was significantly correlated with the area of water in the wetland ($p = 0.003 < 0.01$), and the non-filterable substances content was significantly correlated with the area of water ($p = 0.011 < 0.05$), indicating that the content of non-filterable...
substances and the total solid were important reasons for the substrate blockage in the VFCW.

### Table 1

<table>
<thead>
<tr>
<th>Systems</th>
<th>Banked-up water area [m²]</th>
<th>Total solids [g/m³]</th>
<th>Non-filter matter [g/m³]</th>
<th>Total organic matter [g/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW-B</td>
<td>0.589</td>
<td>136.4 ±2.6</td>
<td>116.4 ±2.6</td>
<td>49.1 ±8.4</td>
</tr>
<tr>
<td>CW-C</td>
<td>0.236</td>
<td>112.0 ±2.4</td>
<td>80.6 ±7.4</td>
<td>56.6 ±2.4</td>
</tr>
</tbody>
</table>

The letters a and b represent the difference between the two CWs.

### Table 2

<table>
<thead>
<tr>
<th>Banked-up water area [m²]</th>
<th>Total solids [g/m³]</th>
<th>Non-filter matter [g/m³]</th>
<th>Total organic matter [g/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson correlation</td>
<td>0.957**</td>
<td>0.915*</td>
<td>0.397</td>
</tr>
<tr>
<td>Sig (Double tail)</td>
<td>0.003</td>
<td>0.011</td>
<td>0.435</td>
</tr>
</tbody>
</table>

** represent a very significant difference, * represent a significant difference.

According to the fitting analysis, in this experiment, the correlation expressions of the total solid, the non-filter matter and the water area are respectively:

\[ y = 96.800 + 67.233x \quad (R^2 = 0.916) \quad (3) \]

\[ y = 56.777 + 101.228x \quad (R^2 = 0.837) \quad (4) \]

In equation (3), where \( y \) is the total solid content, and \( x \) is the banked-up water area [m²]; In the formula (4), \( y \) is the content of non-filter matter, and \( x \) is the banked-up water area [m²]. It can be seen from equations (3) and (4) that when the total solid content and non-filtered matter content in the substrate exceed 67.233 and 101.228 g per cubic meter, respectively, water accumulation will occur in the substrate.

**The vertical accumulation of substances in VFCW**

From the perspective of the different systems, it was found that the biomass, filtered organic matter, non-filter organic matter, non-filter inorganic matter, and total solid content in 0-10 cm layer of the CW-B were higher than the content of CW-C in the same layer (seen from Table 3). The results indicated that the addition of synthetic biochar was beneficial to interception and adsorption of various organic and inorganic substances, and was conducive to the adhesion and growth of biofilm in the substrate. From the perspective of different layers of the same system, it was found that the contents of non-filter organic matter, non-filter inorganic matter and total solid in 10-20 cm layer were the highest in the two VFCWs, which were significantly different from those in the other two layers (0-10 cm and 20-30 cm). This indicated that the non-filter substances and total solid substances in the vertical flow constructed wetland are mainly located in the layer of 10-20 cm, which proves that the layer of 10-20 cm is more prone to substrate blockage. Figure 2 also verifies this guess. It can be seen from Figure 2 that the porosity of the 10-20 cm layer of the two systems is the lowest among the three layers, and significantly lower than that of the 0-10 cm layer.
Table 3

<table>
<thead>
<tr>
<th>Accumulation of substances</th>
<th>CW-B 0-10 cm</th>
<th>CW-B 10-20 cm</th>
<th>CW-B 20-30 cm</th>
<th>CW-C 0-10 cm</th>
<th>CW-C 10-20 cm</th>
<th>CW-C 20-30 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass [nmol P/g]</td>
<td>592 ±112&lt;sup&gt;a&lt;/sup&gt;</td>
<td>94.4 ±4.1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>67.3 ±9.4&lt;sup&gt;b&lt;/sup&gt;</td>
<td>257 ±60&lt;sup&gt;a&lt;/sup&gt;</td>
<td>115 ±11&lt;sup&gt;b&lt;/sup&gt;</td>
<td>75 ±10&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Filtered organic matter [g/mL]</td>
<td>0.005 ±0.002&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>0.007 ±0.002&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.004 ±0.004&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.033 ±0.013&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.012 ±0.004&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.021 ±0.002&lt;sup&gt;ab&lt;/sup&gt;</td>
</tr>
<tr>
<td>Filtered inorganic matter [g/mL]</td>
<td>0.015 ±0.002&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.013 ±0.002&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.012 ±0.004&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.009 ±0.002&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.010 ±0.002&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.009 ±0.003&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Non-filter organic [g/mL]</td>
<td>0.026 ±0.009&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.060 ±0.030&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>0.012 ±0.004&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.016 ±0.014&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.052 ±0.011&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.032 ±0.004&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Non-filter inorganic [g/mL]</td>
<td>0.060 ±0.004&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>0.087 ±0.042&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.048 ±0.007&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.037 ±0.005&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.056 ±0.004&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.039 ±0.006&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Total solids [g/mL]</td>
<td>0.106 ±0.009&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.167 ±0.015&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.076 ±0.004&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.096 ±0.004&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.129 ±0.006&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.101 ±0.002&lt;sup&gt;bc&lt;/sup&gt;</td>
</tr>
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</table>

<sup>a, b and c</sup> in the table represent the differences of matters between different substrate layers in each wetland system.

Fig. 2. Substrate porosity changes vertically in VFCW

**Variation of pollutant removal efficiency in VFCW**

With the operation of the two VFCWs, complete backwater of the upper matrix appeared in CW-B and only a small area of backwater appeared in CW-C on November 21 (the 70<sup>th</sup> day). It can be seen from Figure 3 that the average removal rates of TN in CW-B and CW-C were 23.8 and 20.8 %, respectively.
The average removal rates of COD were more than 77%. The average removal rates of TP were 29.5 and 26.8%, respectively. In the experiment, the removal effect of CW-B with biochar was higher than that of the CW-C without biochar. In this experiment, the clogging
has little effect on the removal of COD. Until the end of the experiment, the COD removal rate of CW-B with serious clogging was still as high as 87.2%, and the COD removal rate of CW-C system was up to 71.8%. The blockage had the greatest effect on TP removal, and the TP removal rate was 4% in CW-B and –9.8% in CW-C at the end of the experiment.

Discussion

Influences of clogging on pollutant removal in VFCW

As shown in Table 3, the biomass content of 0-10 cm layer in the CW-B was 591.53 nmol P/g, while the biomass content of 0-10 cm layer in the CW-C was 257.27 nmol P/g. The biomass in surface layer of CW-B was 334.26 nmol P/g higher than that of CW-C. In this experiment, the blockage of CW-B was more serious and lasted longer, but the average removal rates of COD, TN and TP in the CW-B were slightly higher than those in the CW-C. The reason for these results may be that the addition of biochar matrix was more conducive to the adhesion and growth of microorganisms and the retention and adsorption of pollutants. Many studies have shown that biochar has a large specific surface area, a high porous structure and a strong cation exchange capacity, which can effectively remove pollutants from wastewater [23-26] and also proved that the addition of biochar could change the microbial community structure, thus improving the nitrogen removal [24]. Both CW-B and CW-C have good COD removal efficiency. Even if there was blockage in both systems, the average COD removal rates were greater than 75%, indicating that the blockage of matrix has little influence on the COD removal effect. The survey of horizontal subsurface flow constructed wetland with water accumulation after 15 years of operation has no significant influence on effluent COD [14]. Because the removal of COD is mainly by microbial action [27], and the high biomass level in these two systems in the experiment is conducive to the continuous removal of the COD. The average TN removal rates of two VFCWs were low, the reason is due to the degradation of TN depend mainly on biological nitrification and denitrification [28], and the denitrification is the main way to remove N completely, but the average content of dissolved oxygen in these two systems were higher than 3 mg/L, which lead to the low overall average TN removal rate. Creating a good anaerobic environment in the wetland is conducive to the denitrification of TN, thus achieving the complete removal of TN. Therefore, construction of composite vertical flow constructed wetlands in karst areas of Guizhou in China is more conducive to improving the removal of TN of sewage by taking advantage of topography. In this experiment, the time of blockage in CW-B was longer than that of CW-C, but the average removal rate of TP in CW-B was higher, for two reasons: (1) the content of upper biofilm in CW-B was 334.26 nmol P/g higher than that in CW-C, and the microbial biomass was larger, so it needed to obtain more phosphorus sources for its own growth; (2) The phosphorus content in the 0-10 cm substrate layer of CW-B was significantly higher than that in CW-C, and the addition of biochar was more conducive to the adsorption and interception of phosphorus in the surface matrix.

Analysis of clogging cause of VFCW

In this experiment, river sand was the main substrate in CW-B and CW-C, with a particle size range of 0.35-1 mm. Biochar was mixed to the surface substrate of CW-B, and the particle size range of biochar was about 2-5 mm. With the operation of the wetland,
the blockage area of CW-B is significantly larger than that of CW-C. The reason for this (see Table 1) was that the content of total solid and the non-filter matter in CW-B were higher than that in CW-C. The same operating conditions resulted in different experimental results, which may be caused by the addition of biochar in CW-B. It indicated that the addition of biochar in the vertical flow constructed wetland can improve the removal efficiencies of N and P, but it is more likely to cause blockage. It was found that the porosity of the 0-10 cm layer in CW-B and CW-C was significantly higher than that of the other two layers, and the porosity of the 10-20 cm layer was the smallest, indicating that the main substances causing the clogging were concentrated in the 10-20 cm layer, and the content of total solid and non-filter matter were the main reasons for the clogging of the matrix. Among them, the accumulation degree of non-filter inorganic substances in the matrix was more serious than that of organic substances. This result was similar to the study that found that the accumulation of non-filter substances was the main cause of matrix blockage [18], while differ from the study that blockage of constructed wetland was mainly due to the accumulation of organic matter in the surface layer above 10 cm of the substrate [17]. The experimental result confirmed that the 10-20 cm layer was the main blockage site in the VFCW with river sand as the main substrate. Therefore, construction of VFCW with river sand as the main substrate, the substrate particle size should be arranged in term of different layers and appropriately increased the particle size of the 10-20 cm layer, and it can effectively avoid the clogging of the substrate.

Conclusion

In this experiment, two VFCWs were constructed to study the clogging causes, and it was found that the content of total solid and non-filter matters in VFCW are the important reason of blockage, and mainly located in the 10-20 cm layer. Therefore, the pretreatment of sewage to remove part of the total solids and non-filter substances play an important role in avoiding wetland blockage. Reasonable arrangement of substrate particle size and moderate increase of substrate particle size in 10-20 cm layer can effectively alleviate substrate clogging and prolong the life of VFCW. In addition, adding biochar to the VFCW can improve the removal effect of N and P, but it is more likely to cause substrate blockage. Therefore, it is of practical significance to study the dosage and form of biochar in the future to improve the removal effect of VFCW.

Acknowledgements


References


