Bioclogging alleviation for constructed wetland based on the interaction among biofilm growth and hydrodynamics

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Research Article

Keywords: constructed wetland, bioclogging, biofilm growth, hydraulic loading

Posted Date: July 19th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1757080/v1

Abstract

Bioclogging is the most crucial operation problem of the constructed wetlands, which reduce its removal efficiency and life span. A strategy through properly increasing hydraulic loading is proposed in this study to alleviate the bioclogging for CWs. The two-dimensional porous media flow cell (2D PMFC) test indicated that a quadratic correlation was found between local biofilms growth rate and the near-wall Reynolds number ($r > 0.765$, $p < 0.05$). The biofilm growth rate declined with the flow rate when *Re* exceeded 6. It was also found that the higher flowrate (6 mL/min) lead to the homogeneous biofilm and velocity distribution in the PFMC. The column test indicated that the highest hydraulic loading (9.2 cm/h) produced the smallest decrease in hydraulic conductivity, which was 80 times more than that of low hydraulic load (3.0 cm/h) at the end (40 days) of experiment. Moreover, the relatively homogenized distribution of biofilm was found along the column with the highest hydraulic loading, which confirmed that the proper increase in hydraulic loading can alleviate bioclogging.

Introduction

Constructed wetlands, as a low-tech and low-cost water treatment technology, have been used worldwide in the wastewater treatment or stormwater disposal or reclaim (Kong et al. 2021; Chai et al. 2019). However, clogging is one of the most crucial operation problems that reduce the removal efficiency and life span of the constructed wetland, especially bioclogging, which was due to the accumulation of biomass in the porous media and considered to be the primary reason for the clogging of the infiltration system (Zhou et al. 2018). Bioclogging will occur inevitably in the substrate layer (Liu et al. 2019a), and thus, its mitigation or elimination is an urgent issue in the operation of the constructed wetlands (CWs).

Prevention and restoration are the two general strategies to control clogging in CWs management. Preventative strategies aim to delay or alleviate the negative effects of clogging, such as optimizing operational conditions (Pedescoll et al. 2011), size selection and filling strategies of substrate (Suliman et al.2007, Zhong et al. 2022), and applying resting operation (Hua et al. 2014). Physical and chemical pre-treatment is also an effective preventative strategy, such as adding flocculants, biological pretreatment (De la Varga et al. 2013), which can postpone clogging by removing organic and suspended solids loads (Srivastava et al. 2021).

Restorative strategies are objective to solve the clogging-related hydraulic problems or poor treatment efficiency of CWs (Nivala et al. 2012). The restoration of bioclogging CWs is traditionally through renovation, such as substrate replacement and backwashing. On the other hand, in situ restorations is also becoming widely used, such as adding wetland animals (e.g., earthworms and loaches) (Chiarawatchai et al.2007, Ye et al. 2018), or dosing chemicals (e.g., H_2O_2, HCl, NaOH and NaClO). Recently, several innovative dosing strategies were presented, such as addition of *B. subtilis* (Ping et al. 2021), enzymes (Tang et al. 2018), biosurfactants (Du et al. 2016) and rhamnolipids-citric acid compound (Cao et al. 2021), which have good solubilizing effect and environmental friendliness. Although there have been many technologies for prevention and recovery of the bioclogging for CWs, they will increase investment, operating costs, or the land occupation in practical applications. Therefore, it is still imperative to explore the in situ, non-intrusive, environmental friendly and cost saving method to alleviate bioclogging.

Bioclogging is induced by the biofilm accumulation in the porous media. Recent research found that the interactions between the biofilm growth and liquid flow hydrodynamics affected the biofilm accumulation in the porous media (Zhou et al. 2021). An increase in fluid flow velocity facilitates cells and nutrients transport but also triggers biofilm detachment events (Krsmanovic et al. 2021). Thus, it is hypothesized that effectiveness of bioclogging control in CWs may be enhanced by optimizing hydraulic loading. In this paper, we investigated the biofilm distribution and hydrodynamic characteristics in the porous media under the different hydraulic loadings through two-dimensional (2D) flow cell. Besides, the effectiveness of hydraulic loading on bioclogging alleviation was also evaluated through column testing. The results will provide a safe and effective method for solving bioclogging issue in CWs.

Methods And Measurement

2.1 Experimental setup and procedure

The 2D porous media flow cell (PMFC) was used for direct observation of the interaction between fluid flow and biofilm growth. The PMFC was produced according the X-CT images of gravel column according to Zhou et al. (2020). Three identical PMFCs, named Cell 1–3, were mounted on a platform vertically in the dark as illustrated in Fig. 1. The PMFCs were fed with artificial wastewater from the top at room temperature (20–25°C). The artificial wastewater was made by adding glucose and other components in the ultra-pure water according to Zhou et al. (2020). The flow rates of Cell 1, Cell2 and Cell3 were 2 mL/min, 4 mL/min and 6 mL/min, respectively.

The column tests were carried out through three identical saturated columns made of Perspex as shown in Fig. 2. The columns, 55 cm in height and 10 cm in diameter, were filled with identical gravel (4-8mm) to a depth of 40 cm. At the bottom of each column, there was a 5 cm large pebbles layer to collect the treated wastewater. Two piezometer tubes were positioned at the upper and bottom layer to measure total hydraulic conductivity. To prevent algal growth, light–tight cloth was used to wrap the outside surface of the columns.

The artificial wastewater was fed into the columns through a peristaltic pump. The hydraulic loading, COD concentration of the influent wastewater, and the COD pollution load in each column was presented in Table 1.

Table 1
the parameters of the columns test.

No.	Influent flowrate (ml/min)	Surface hydraulic load (cm/h)	Influent COD concentration (mg/L)	Surface pollution load (mg COD/h cm^2)
Column A	6.0	4.6	30	0.14
Column B	12.0	9.2	15	0.14
Column C	3.0	2.3	60	0.14

2.2 Measurement and methods

(1) hydraulic conductivity of the columns

The water head difference of each column was measured every three days. The saturated hydraulic conductivity K of the columns was calculated using Darcy's flow equation (Eq. 1)

$$K = \frac{Q * L}{A_w * \Delta h} (1)$$

where A_w is the cross-sectional area of the columns (cm^2); Δh is the hydraulic head difference of the porous media; Q is the flow rate (ml/min), and L is the vertical distance between the two piezometers.

(2) 2D imaging

Greyscale images of the 2-D PMFCs were taken every three days. These images were segmented into three categories by the gray value histogram according to Yang et al. (2001), which corresponds to the fluid, biofilm in the porous media and filter media. The biofilm was quantified according to the areal parameters of the biofilm proportion (Kim et al. 2010).

The flow patterns in the porous media with the biofilm growth was visualized through injection of dye tracer, which was prepared by mixing brilliant blue solution with a small amount of xanthan gum and ethanol to lower its diffusivity in water (references). According to the movement of the front of dye tracer, the velocity in each pore throat can be calculated. Dye tracer tests were carried out every 3 days. Images of dye tracer were analyzed using Matlab according to Zhou et al. (2020).

(3) biomass dry mass

After the column tests, the gravel media was sampled from four different layers along the each column at the depth of 0-10cm, 10-20cm, 20-30cm, 30–40 cm from the column top. The gravel samples were immersed in a beaker containing 1L of distilled water, which was then placed into the sonic bath for 5 minutes. In order to accelerate detachment, the gravel was stirred gently. After the sonic bath, the suspended solid (SS) was collected and dried. The quantity of the attached biomass was expressed as SS dry mass per volume of gravel.

Results And Discussion

3.1 The interaction between biofilm growth and hydrodynamic

The biofilm growth rate during the 3rd to 10th day and the hydrodynamics in the different pores throat of the PMFC were analyzed, and their interaction is presented in Fig. 3. A quadratic correlation was found between local biofilm growth rate and the Reynolds number (*Re*) of the throats ($r > 0.765$, $p < 0.05$). We found in our experiment that the biofilm growth rate increased with the *Re* when it was below about 6. At this stage, the result was consistent with the results of the Zhou et al. 2020 that bacterial growth and accumulation were positively correlated with the seepage flowrate. However, the growth rate of biofilm declined when *Re* exceeded 6 as shown in Fig. 3. The biofilm thickness is attributed to the balance between the nutrient transfer and the local hydrodynamics, and the increase of the local shear forces induced by higher flow rate make the biofilm more vulnerable to detachment (Bottero et al. 2013). As the consequence, the quadratic correlation of biofilm growth with near-wall hydrodynamic appeared in the experiment, and similar results were also reported by Liu et al. (2019b) and Zhou et al. (2021). This result indicated that proper hydraulic loading can potentially alleviate the bioclogging problem and promote the hydraulic efficiency of the CWs.

3.2 The influence of hydraulic loading on biofilm distribution and flow field

According the grayscale image of biofilm development (Fig.S1), the biofilm distribution in the PMFCs with time is illustrated in the Fig. 4. In the Cell 1 (2 ml/min), it can be observed that the biofilm grows thicker and thicker with the time and began to clog the pore throat on the 9th day. After 12 days' operation, the biofilm distributed in the whole cell and its distribution along the cell was inhomogeneous. The upper layer near the inlet accumulated much more biofilm, which is more obvious in the Cell 2 (4 ml/min). The upper layer of the Cell 2 presented more dense biofilm distribution, while the lower layer near the outlet showed almost no biofilm. This is because the spatial distribution of biofilm depended on the nutrient supply (Bottero et al. 2013). In the upper layer, the biofilm colonies expanded due to continuous nutrient supply. While the biofilm stopped growing in the downstream bottom layer because of the limited nutrients. This is in agreement with the experimental observations of biofilm growth in the previous studies (e.g., Simoni et al. 2001, Zhou et al. 2020).

Notably, it was found that the homogeneity of biofilm increased both in the distribution and magnitude in the Cell 3 under the higher flowrate (6 ml/min) condition as shown in Fig. 3, which suggested that the higher flowrate induced the nutrient homogeneity in the entire PMFC. This may be because that the presence of shear force induced by higher flowrate limited the further growth of biofilm in the pore of the upper layer (Bottero et al. 2013). Moreover, the amount of biomass in Cell 3 was less than half of that in Cell 1 (Fig.S2). As the consequence, the higher flowrate made the nutrient transfer in the lower layer and thus biomass gradient along the cell decreased.

Figure 5 presented the flow velocity distribution in the PMFCs with the biofilm development. The velocity magnitude heat map was generated to visualize flow between pores and the velocity distribution becomes more heterogeneous with biofilm growth in the Cell 1 and Cell 2. The preferential flow path and stagnant regions formed after 12 days' operation in both cells. This resulted from the enhancement of pore space heterogeneity with the biofilm development (Von Der Schulenburg et al. 2009). As for the higher flowrate condition, the velocity distribution in the Cell 3 was remarkably homogeneous, which was beneficial to improve the treatment efficiency of CWs (Suliman et al. 2006).

3.3 The performance of hydraulic loading on bioclogging alleviation

The column tests were performed to evaluate the effect of the hydraulic loading on bioclogging alleviation. Figure 6 presented the change of *k* of the columns with different hydraulic loading. After 40 days operation, the *k* of Column A and Column B decreased from 16.65cm/s to 0.86 cm/s and from 17.53 cm/s to 1.58cm/s, respectively; while a significant decline from 16.65 cm/s to 0.02 cm/s was observed in Column C. In the low hydraulic loading condition (Column C), decreases in hydraulic conductivity of up to 3 orders of magnitude were observed due to biofilm growth, while the column with the highest hydraulic loading (9.2 cm/h, Column B) produced the smallest decrease in hydraulic conductivity. This result proved further that proper hydraulic loading can alleviate the bioclogging in the porous media.

We observed the vertical distribution of biomass in the columns with the highest (Column B) and lowest (Column C) surface hydraulic loading at the end of the experiment, and the result is presented in the Fig. 7. The biomass content in the upper layer of Column C were far higher than that of lower layers. The biomass content in the upper layer reached 0.044mg/cm^3, and decreased greatly to below 0.01 mg/cm^3 in the deeper layer (20-40cm). The result agrees with Lianfang et al. (2009) that the reduction of effective porosity of upper layer was significant. While the biomass in Column B was relatively homogenous throughout the column although a light gradient of biomass content is inevitable. This result was consistent with the previous result in the 2-D PMFC. The relatively homogenized distribution of biofilm in the columns ensured the pollution removal efficiency (Fig.S3), although the higher hydraulic load means a shorter hydraulic retention time

3.4 Potential practice application

This study confirmed that properly increasing the hydraulic load of the CWs can alleviate bioclogging effectively. There was no obvious difference in the treatment performance of the three columns under the condition of the same pollution load. Generally, chemical dosing strategy for bioclogging alleviation is not feasible due to its inconvenience and possible negative effects. Hereby, this study testified the feasibility of hydraulic loading optimization to control bioclogging. Therefore, a strategy through properly increasing hydraulic loading by returning the treated wastewater can be proposed to alleviate biclogging for CWs, as illustrated in Fig. 8.

Briefly, the return pipe is required to return the treated wastewater to the influent system, which can increase the hydraulic loading of the CWs and reduce and stabilize the influent concentration. The flowrate of returned water (q) can be determined according to the optimal hydraulic load. Moreover, the higher hydraulic loading led to the increase of the seepage hydraulic gradient in the porous media. Thus, the constructed wetland beds can be set at a certain slope. This strategy will not require dosing any chemical agent and thus has no negative effects of the performance of the CWs.

Conclusion

This study reported and demonstrated a new bioclogging alleviation approach for CWs, based on hydraulic loading optimization. The main conclusions are as follows:

(1) The quadratic correlation of biofilm growth with near-wall hydrodynamic was observed in the 2D PMFC experiment. The growth rate of biofilm in the porous media increased with the *Re* when it was below about 6, However, the growth rate of biofilm declined when *Re* exceeded 6.

(2) The biofilm was distributed in the whole cell and its distribution along the cell was inhomogeneous when flowrate was 2 or 4 ml/min. The upper layer near the inlet accumulated much more biofilm, while the biofilm was sparse in the downstream (bottom). When the flowrate reached 6 ml/min, the homogeneity of biofilm increased both in the distribution and magnitude in the PMFC. Moreover, the highest flowrate (6 ml/min) lead to more homogeneous velocity distribution in the PFMC.

(3) The column test found that the highest hydraulic loading (9.2 cm/h) produced the smallest decrease in hydraulic conductivity, while the decreases in hydraulic conductivity was up to 3 orders of magnitude observed in the low hydraulic loading condition. This confirmed that the proper increasing hydraulic loading can alleviate the issue of bioclogging.

(4) A strategy through properly increasing hydraulic loading by returning the treated wastewater was proposed in this study to alleviate biclogging for CWs. This strategy will not require dosing any chemical agent in the CWs and thus has no negative effects of the performance of the CWs nor to the environment.

Declarations

Acknowledgement

The authors are grateful to all research staff that contributed to the data collection required for this study.

Funding

The Project was supported by National Natural Science Foundation of China (51878597)

Financial interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception and design. **Ping Tang**: Conceptualization, Methodology. **Li Chen**: Investigation; Writing- Original draft preparation. **Wenming Zhang**: Co-supervision, Writing-Reviewing and Editing. **Yongchao Zhou**: Methodology, Writing- Original draft preparation and Supervision.

Ethical Approval and Consent to Participate

This article does not contain any studies with human participants or animals performed by any of the authors.

Availability of data and materials

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Consent to Publish

Not applicable.

Competing interests

The authors declare no competing interests.

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Figures

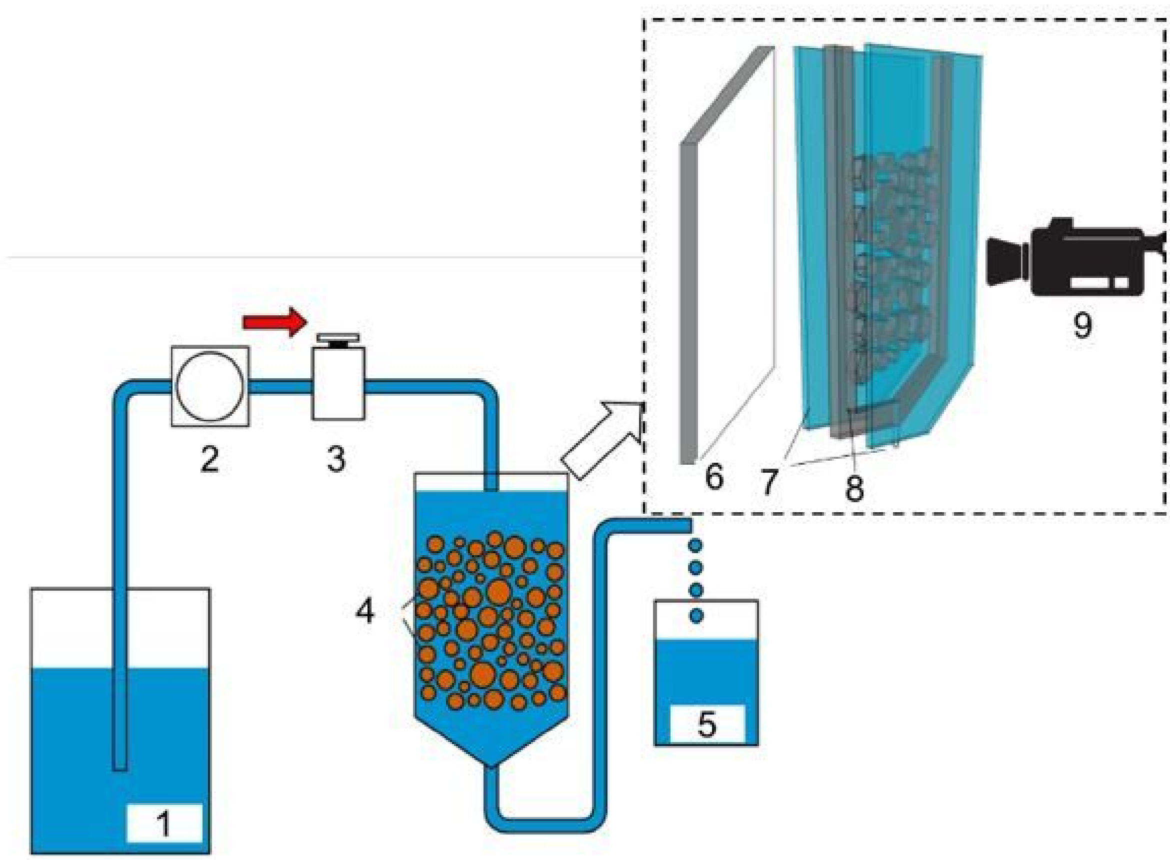

Figure 1

the experimental setup

1 Inflow tank; 2 Peristaltic pump; 3 Pressure regulator; 4 PMFC; 5 Outflow tank; 6 Backlight; 7 Back and front ultra-clear glass; 8 2D pore structure; 9 Camera

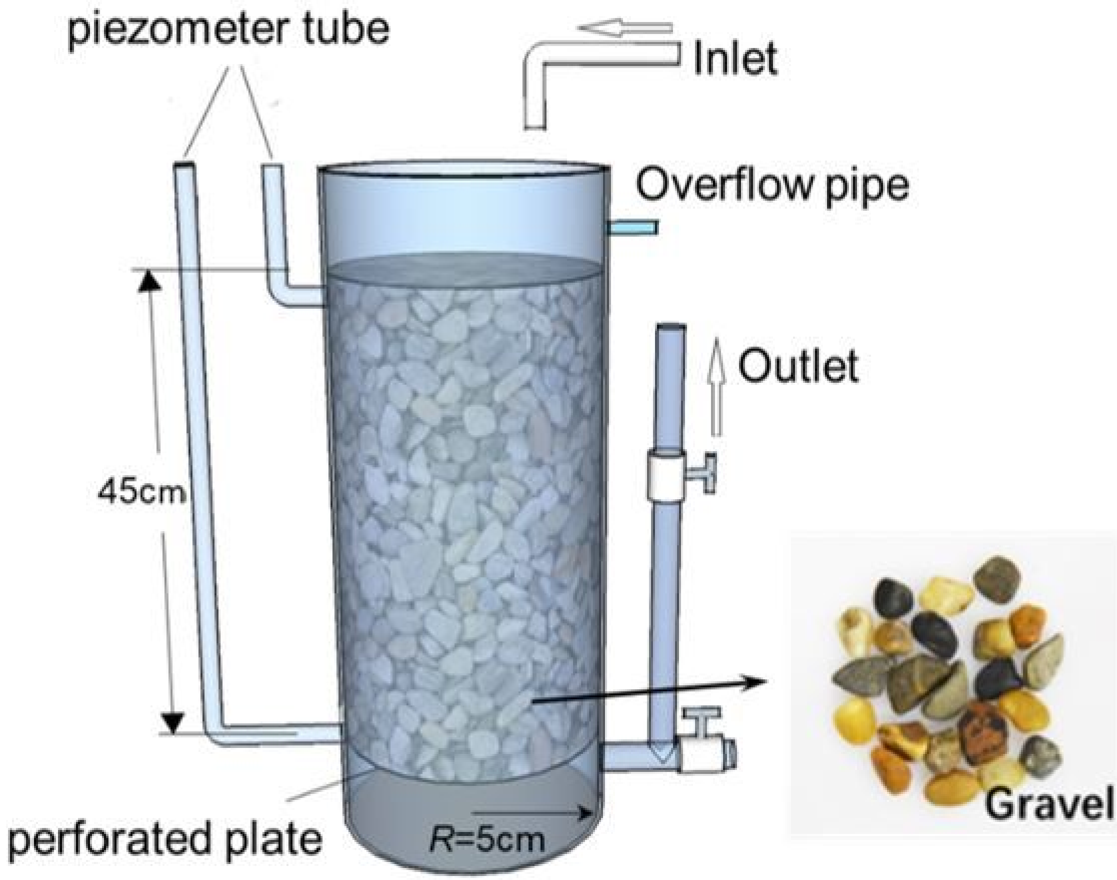

Figure 2

the experimental setup of the column test

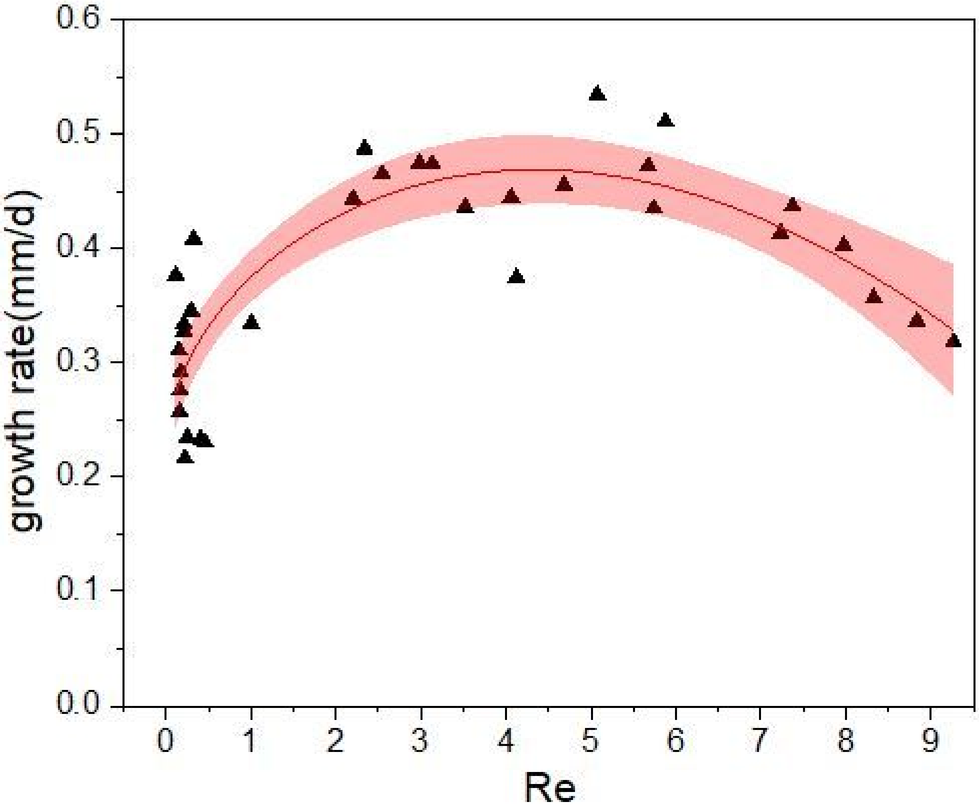

Figure 3

the interaction between biofilm growth rate and hydrodynamic characteristics

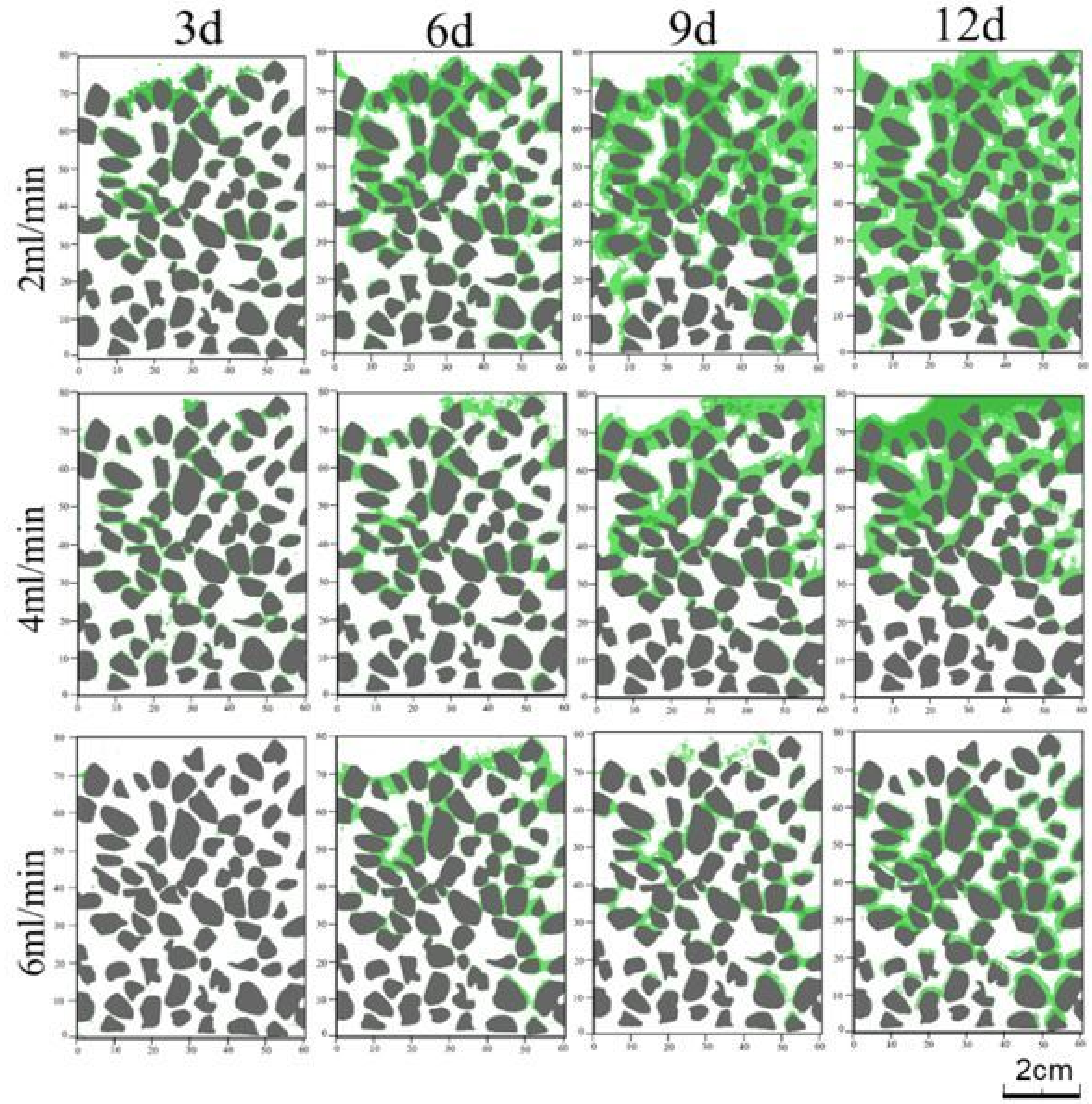

Figure 4

the change of biofilm distribution with time in the PMFCs

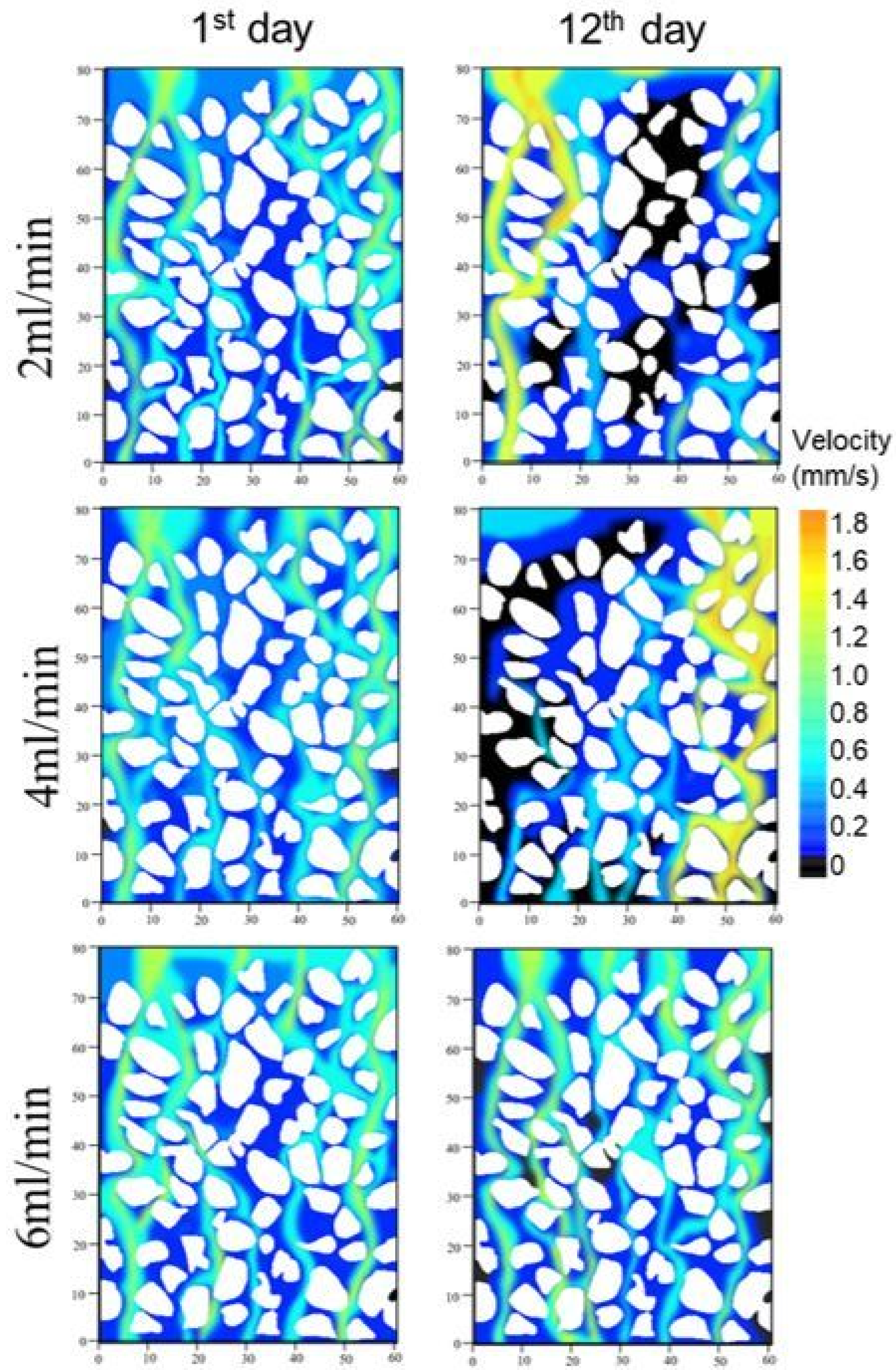

Figure 5

the flow velocity distribution in the PMFCs with the biofilm development.

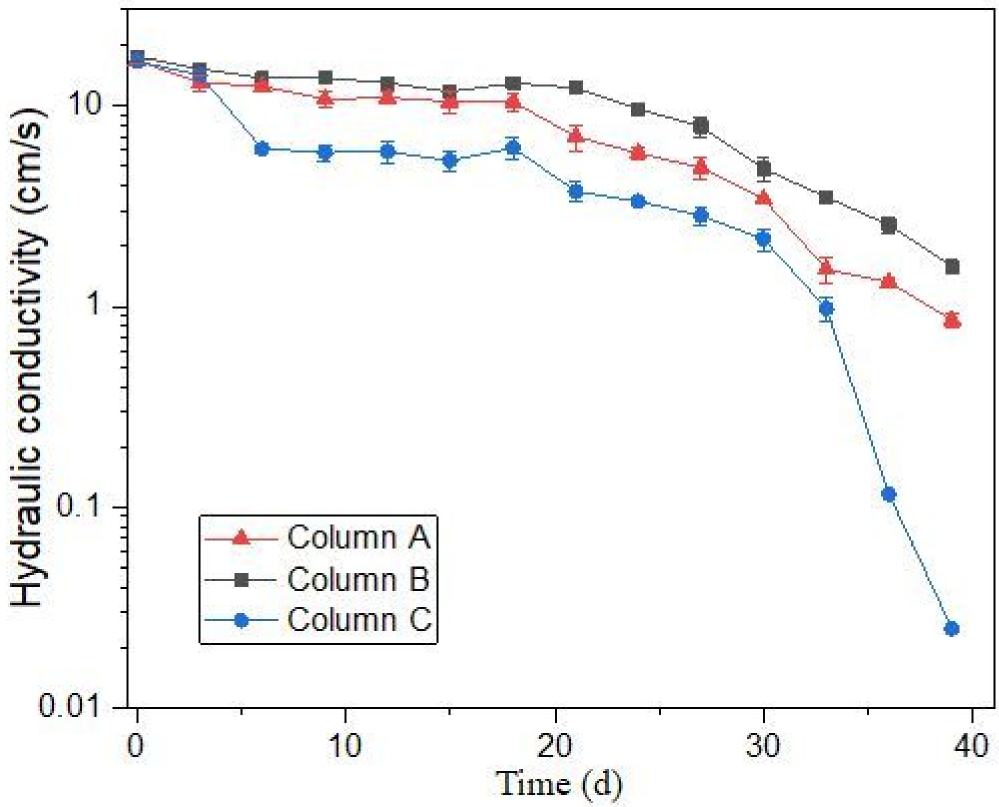

Figure 6

the hydraulic conductivity of the columns with different hydraulic loading

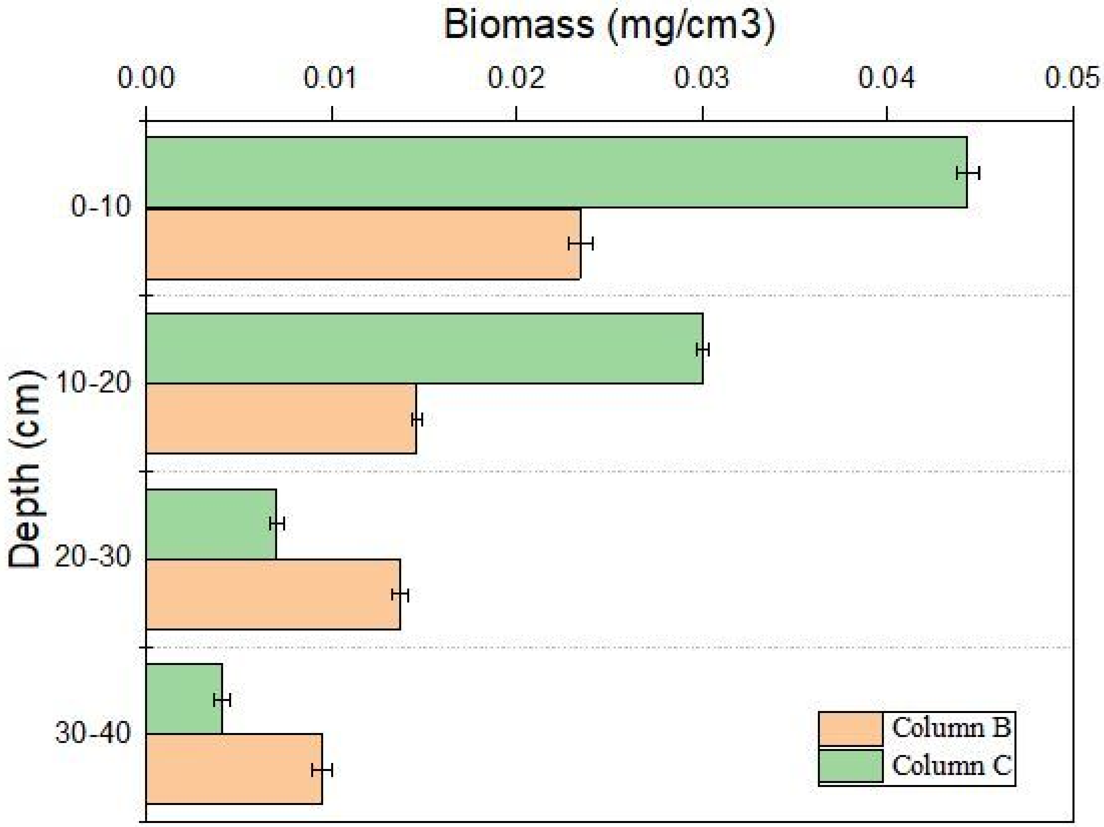

Figure 7

the biomass vertical distribution in the Column B and Column C

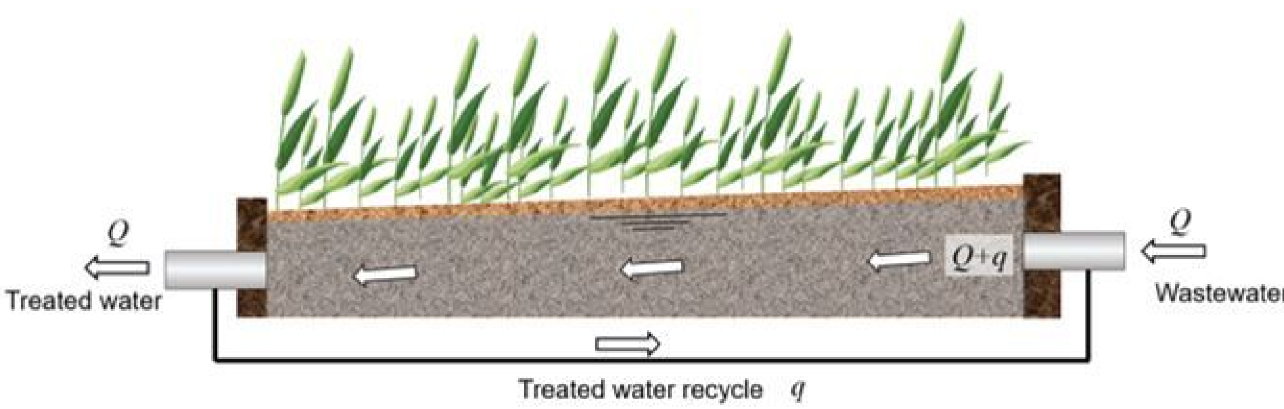

Figure 8

A conceptual diagram of applying hydraulic loading optimization for bioclogging alleviation.

Supplementary Files

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