Bioresource Technology 220 (2016) 26–33

Contents lists available at ScienceDirect

Bioresource Technology

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

An enhanced anaerobic membrane bioreactor treating bamboo industry wastewater by bamboo charcoal addition: Performance and microbial community analysis

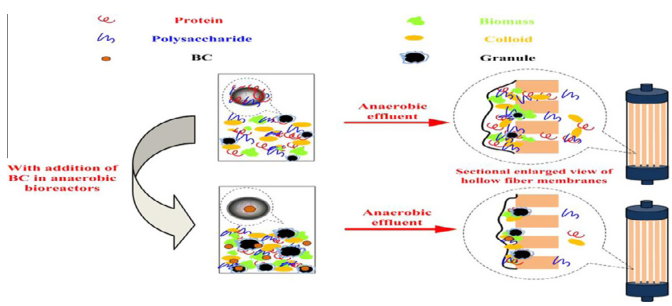
Tian Xia [a], Xinyi Gao [a], Caiqin Wang [a], Xiangyang Xu [a,b], Liang Zhu [a,b,*]

[a] *Department of Environmental Engineering, Zhejiang University, Hangzhou 310058, China*
[b] *Zhejiang Province Key Laboratory for Water Pollution Control and Environmental Safety, Hangzhou 310058, China*

HIGHLIGHTS

- A novel process for BIWW treatment was built with addition of BC.
- Addition of BC enhanced the COD removal and methane yield.
- Addition of BC decreased the cake layer resistance and pore blocking.
- Addition of BC could increase the microbial diversity and activity.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 30 June 2016
Received in revised form 11 August 2016
Accepted 13 August 2016
Available online 17 August 2016

Keywords:
Anaerobic membrane bioreactor
Bamboo charcoal
Performance
Membrane fouling
Microbial community

ABSTRACT

In this study, two anaerobic membrane bioreactors (AnMBRs) were operated for 150 days to treat bamboo industry wastewater (BIWW), and one of them was enhanced with bamboo charcoal (B-AnMBR). During the steady period, average chemical oxygen demand (COD) removal efficiencies of 94.5 ± 2.9% and 89.1 ± 3.1% were achieved in B-AnMBR and AnMBR, respectively. The addition of bamboo charcoal (BC) increased the amount of biomass and improved the performance of the systems. A higher biogas production and methane yield were also observed in B-AnMBR. Regarding the issue of membrane fouling, BC lowered the soluble microbial product (SMP) content by approximately 62.73 mg/L and decreased the membrane resistance, thereby mitigating membrane fouling. Analysis of the microbial communities demonstrated that BC increased the microbial diversity and promoted the activity of *Methanosaeta*, *Methanospirillum*, and *Methanobacterium*, which are dominant in methane production.

1. Introduction

Bamboo is an important forest resource in China, and the area covered by bamboo forest has reached 6.01 million hectares, ranking the largest China's bamboo forest in the world. With the rapid development of the bamboo industry, wastewater from the production process has brought great challenges to the ecological environment. Bamboo industry wastewater (BIWW) is characterized by a high chemical oxygen demand (COD 16,000–18,000 mg/L) and NH_4^+-N concentration (470–520 mg/L) with low pH values (2.5–3.2) (Wu et al., 2013a,b). Moreover, the complex composition of the wastewater aggravates the treatment difficulty. Physical, chemical and combined anaerobic and aerobic treatments are carried out for domestic BIWW treatment (Xin et al., 2009; Wu et al., 2013a,b). Anaerobic biological treatment has been widely used for industrial wastewater and municipal wastewater because

* Corresponding author at: Department of Environmental Engineering, Zhejiang University, No. 866 Yuhangtang Road, Hangzhou 310058, China.
E-mail address: felix79cn@hotmail.com (L. Zhu).

http://dx.doi.org/10.1016/j.biortech.2016.08.057
0960-8524/

it can treat high volume loads with low energy consumption and low sludge generation (Astals et al., 2012). However, Meyer and Edwards (2014) found that the reduction of COD was only above 50% when treating pulp and paper mill wastewater. High strength sewage treatment in a one-stage UASB reactor was COD removal efficiency of 32% (Mahmoud, 2008). Another study illustrated that methanogenic bacteria in an anaerobic reactor could grow faster at 35 °C than at 10 °C (Bhuptawat et al., 2007). Therefore, poor water quality, slow microbial growth and high environmental standards for pH and temperature represent problems that remain to be addressed for anaerobic biological treatment (Chen et al., 2015). Following the development of a new generation of membranes (Zayen et al., 2010), the anaerobic membrane bioreactor is a very promising option for BIWW treatment due to the double advantages of improved anaerobic biological treatment and improved membrane technology (Li et al., 2015).

The anaerobic membrane bioreactors (AnMBRs), which combine an anaerobic bioreactor and a membrane unit, use a membrane to retain the biomass in the reactor and achieve independence of the hydraulic retention time (HRT) and sludge retention time (SRT) (Smith et al., 2014). Furthermore, membrane modules can significantly improve the water quality and replace the traditional settling pond to reduce the space and footprint (Bakonyi et al., 2014). In recent years, AnMBRs have been widely reported for the treatment of, for example, textile wastewater, oil grease wastewater, and landfill leachate (Zayen et al., 2010; Yurtsever et al., 2015). Xiao et al. (2015) discovered that the COD removal efficiency was over 99% after regulation of SRT when using an AnMBR to treat kitchen wastewater. An AnMBR could also treat municipal wastewater at low temperatures with the COD removal efficiency reaching 87 ± 1% when the volume loading rate (VLR) was 2–2.5 kg COD/(m^3·d^{-1}) (Gouveia et al., 2015). However, membrane fouling is still an unavoidable issue (Ng et al., 2015), and causes a reduction in throughput, shortens the membrane life and ultimately increases the costs. The membrane fouling process can be divided into three stages. The first stage is rapid fouling caused by colloids, small organic molecules and flocculent sludge. They quickly gather on the membrane surface and block pores. The second stage is steady fouling and occurs due to biofilm formation on the membrane surface, which is mainly attributed to soluble microbial products (SMPs) and extracellular polymeric substances (EPSs). In the third stage, cake layer deposition continues leading to a compaction layer and a jump in trans-membrane pressure (TMP).

To mitigate membrane fouling and strengthen performance of the AnMBR, adding filter was reported to be a promising option. For example, it has been confirmed that adding granular activated carbon (GAC) to an AnMBR resulted in a reduction in the cake layer resistance by approximately 53.5%. GAC can promote increases in the particle sizes and adsorption of colloids and solutes (Ding et al., 2014). Montalvo et al. (2014) also observed that the addition of zeolite could achieve a COD removal efficiency of 60%, which was higher than a removal efficiency of 40% without zeolite. Moreover, zeolite decreased nitrogen concentrations and generated larger granules. Apart from filters, reagents were also utilized. Dong et al. (2015) also found that operation without $FeCl_3$ dosing resulted in more rapid membrane fouling, which was attributed to increased concentrations of proteins and carbohydrates. In contrast, dosing with $FeCl_3$ reduced the colloidal matter and inhibited proteins and carbohydrates, which ultimately resulted in the formation of a thicker fouling layer on the membrane. However, the novel filters have the issue of being difficult to regenerate, costly and may cause secondary pollution to the environment.

Bamboo charcoal (BC), which is produced as a plentiful residual by-product of the bamboo processing industry, is a biochar. It has a high surface area and microporous structure. Low-cost BC was reported to have a stronger adsorption than activated carbon because BC has a relatively large number of oxygen-containing functional groups and relatively low graphite structure (Mizuta et al., 2004). In this study, a control system of an AnMBR and an AnMBR system with BC added (B-AnMBR) were established to investigate whether the addition of BC enhances the removal of pollutants. A comprehensive characterization of the mixed liquor properties and membrane fouling was conducted with and without the addition of BC. Microbial communities and the strength mechanism were analyzed in this study.

2. Materials and methods

2.1. Wastewater characteristics

The wastewater was collected from a BIWW treatment plant located in Anji County (Zhejiang Province, China). Table 1 summarizes the main characteristics of the wastewater. It illustrates that BIWW has a high concentration of organic matter and NH_4^+-N. The influent pH was adjusted to 6.8–7.2 by adding sodium bicarbonate ($NaHCO_3$).

2.2. Experimental setup and operation

The AnMBR system (Fig. 1), which consisted of an expanded granular sludge blanket reactor (EGSB) and a polyvinylidene fluoride (PVDF) hollow membrane module with a surface area of 0.07 m^2 and a pore size of 0.02 μm were operated to treat the BIWW. The effective working volume of the EGSB was 5.5 L, and the recirculation flow ratio was 10. The gas discharged from the top of the reactor passed through a water-sealed bottle and was collected in a wet gas flow meter. Both reactors were inoculated with 16 g VSS·L^{-1} originating from an upflow anaerobic sludge blanket from an urban sewage treatment plant in Hangzhou, China. The particle size of the BC was 0.5 mm, which was bought from Watson Bamboo Charcoal Products Company in Anji. BC (100 g) (1: 1 for MLSS) was added to the reactor with the sludge and the system was referred to as B-AnMBR. The reactor without the addition of BC was the control reactor (AnMBR). The HRT was set to 3d during the whole operation, and the temperature was maintained at 32 ± 2 °C. At the initial stage, the two reactors were operated with 9-times diluted BIWW. During the start-up period, the dilution factor was reduced to that of the real BIWW and the organic loading rate (OLR) reached approximately 6 kg COD/(m^3·d). Both membrane systems were set to 20 min with 5 min of relaxation. The permeate was withdrawn by a suction pump. At 50 and 108 days, the membranes were removed for physical and chemical cleaning.

2.3. Analytical methods

The COD, NH_4^+-N, oxidation–reduction potential (ORP), and volatile fatty acids (VFAs) were determined according to standard methods for the examination of water and wastewater (Gilcreas, 1955). The biogas composition was measured via a gas chro-

Table 1
Characteristics of BIWW.

Water quality	Value
COD (mg/L)	17,160 ± 814
NH_4^+-N (mg/L)	507 ± 25
TN (mg/L)	598 ± 17
TOC (mg/L)	5790 ± 121
Chroma	400 times
SS (mg/L)	400 ± 12
pH	3.23 ± 0.1