Journal of Environmental Management 217 (2018) 363–372

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Recycling of drinking water treatment residue as an additional medium in columns for effective P removal from eutrophic surface water

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ARTICLE INFO

Article history:
Received 4 January 2018
Received in revised form
27 March 2018
Accepted 30 March 2018

Keywords:
Drinking water treatment residuals
Eutrophication control
Wastes recycling
Phosphorus

ABSTRACT

This study assesses the feasibility of recycling drinking water treatment residue (DWTR) to treat eutrophic surface water in a one-year continuous flow column test. Heat-treated DWTR was used as an additional medium (2%–4%) in columns in case excessive organic matter and N were released from the DWTR to surface water. The results indicated that with minimal undesirable effects on other water properties, DWTR addition substantially enhanced P removal, rendering P concentrations in treated water oligotrophic and treated water unsuitable for *Microcystis aeruginosa* breeding. Long-term stable P removal by DWTR–column treatment was mainly attributed to the relatively low P levels in raw water (<0.108 mg L^{-1}) and high P adsorption capability of DWTR, as confirmed by increases in amorphous Al/Fe in DWTR after the tests and low adsorption of P in the mobile forms. The major components of DWTR showed minimal changes, and potential metal pollution from DWTR was not a factor to consider during recycling. DWTR also enriched functional bacterial genera that benefitted biogeochemical cycles and multiple pollution control (e.g., *Dechloromonas*, *Geobacter*, *Leucobacter*, *Nitrospira*, *Rhodoplanes*, and *Sulfuritalea*); an apparent decrease in *Mycobacterium* with potential pathogenicity was observed in DWTR–columns. Regardless, limited denitrification of DWTR–columns was observed as a result of low bioavailability of C in surface water. This finding indicates that DWTR can be used with other methods to ensure denitrification for enhanced treatment effects. Overall, the use of DWTR as an additional medium in column systems can potentially treat eutrophic surface water.

1. Introduction

Drinking water treatment residue (DWTR) is an inevitable byproduct largely generated during potable water production (Dassanayake et al., 2015). DWTR has long been dumped in landfills, but the cost and availability of land needed for this disposal are likely to increase because of the increased generation of the residue (Babatunde and Zhao, 2007; Ahmad et al., 2016a). Accordingly, the alternative option for final disposal of DWTR has drawn worldwide interest in recent decades (Nimwinya et al., 2016; Krishna et al., 2017). In conventional water treatment methods, Al/Fe salts are used as coagulants for water purification, leading to high concentrations of Al and Fe in DWTR (Ahmad et al., 2016b; Jung et al., 2016). Al and Fe in DWTR mainly occur in amorphous phases, endowing DWTR with porosity and high adsorption capability (Ippolito et al., 2011). On the basis of these properties, many potential approaches have been developed for DWTR recycling in environmental remediation. DWTR has been found to be an effective adsorbent of many contaminants, such as P (Makris et al., 2005;

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https://doi.org/10.1016/j.jenvman.2018.03.128
0301-4797/

Oliver et al., 2011), hydrogen sulfide (Wang and Pei, 2012), perchloric acid (Makris et al., 2006), toxic metals (Chiang et al., 2012; Ippolito et al., 2009; Lin et al., 2017; Zhou and Haynes, 2011), and toxic organic substance (Hu et al., 2011; Punamiya et al., 2013). Efforts have also been devoted to recycling DWTR for remediation of soil (Agyin-Birikorang et al., 2009), water (Hu et al., 2012; Krishna et al., 2016), and sediment (Wang et al., 2013a).

DWTR has been typically reused in column systems to treat wastewater (Babatunde and Zhao, 2007). Column systems are a type of filtration systems commonly used to remove contaminants from polluted water on the basis of various physicochemical and biologic functions during environmental remediation (Li et al., 2018). A representative column system is constructed wetland. The DWTR-column systems exhibited high efficiencies in P removal, denitrification, and degradation of chemical oxygen demand during treatment of various types of wastewater, such as livestock wastewater (Hu et al., 2012), domestic wastewater (Park, 2009), secondary effluent (Bai et al., 2014), and urban runoff (Ippolito, 2015), among others (Leader et al., 2005). Such performance suggests that DWTR-constructed column systems may effectively treat eutrophic surface water. Eutrophication, the over-enrichment of aquatic ecosystems with N and P, leading to algal blooms and anoxic events, is a persistent condition of surface waters and a widespread environmental problem (Carpenter, 2005). Numerous approaches have been developed to control eutrophication (Li et al., 2008; Ulrich et al., 2016), and surface water treatment using columns systems has been shown to be an effective approach (Li et al., 2008). Specifically, wetland systems in lake borders have often been adopted to ensure the quality of surface water from rivers to lakes (Dunne et al., 2012). Successful application of DWTR in column systems to treat eutrophic surface water can promote DWTR recycling (Ahmad et al., 2016a).

For eutrophic surface water treatment using column systems, total P concentrations in effluent would reasonably attain mesotrophic–oligotrophic states ($<0.03\ mg\ L^{-1}$), and total N in effluent would be at concentrations safe to the aquatic environment ($<1.0\ mg\ L^{-1}$) (Camargo, and Alonso, 2006). These concentrations are substantially lower than the discharge standards for wastewater treatment; e.g., total P and total N < 0.5 and $15\ mg\ L^{-1}$, respectively, in China. The properties of eutrophic surface water and wastewater vary; specifically, nutrients for microbial growth in eutrophic surface water are at lower levels than the nutrients in wastewater. DWTR is also composed of impurities from raw water and chemical agents used during treatment of drinking water. A previous study observed the slow release of ammonium N (NH_4^+-N) during treatment of secondary effluent by DWTR-constructed columns (throughout the 260 d-tests), although total N concentrations decreased after treatment (Bai et al., 2014). The release of organic matter from DWTR also has been reported (Liu et al., 2016). Accordingly, for eutrophic surface water treatment, DWTR-column systems have higher requirements, compared with wastewater treatment. The feasibility of recycling DWTR-column systems to control surface water eutrophication has to be assessed.

Therefore, this study aimed to determine the performance, stability, and characteristics of the microbial community of DWTR constructed columns for eutrophic surface water treatment in a one-year continuous flow test. The results of this study could provide theoretical support for DWTR recycling in eutrophication control.

2. Materials and methods

2.1. Sample collection and preparation

Dewatered DWTR was collected from a drinking-water treatment plant (No. 9 Waterworks) in Beijing, China. In this plant, both Al and Fe salts were used as coagulants for water purification. Fresh DWTR was air-dried, ground, and sieved to a diameter of less than 0.147 mm. Eutrophic surface water was collected at a tributary of Lake Xuanwu, China (N 32°04′16″, E 118°48′18″). Lake Xuanwu is a typical urban lake with an area of 378 ha in the southern part of Yangtze River in China. Surface water was sampled at a depth of approximately 0.5 m and filtered through a 0.45 μm glass fiber filter to remove impurities. Glass beads with a diameter of 2 mm were heated under 500 °C for 4 h, washed with deionized water to remove impurities, and oven-dried for further tests.

2.2. The experimental design

The experimental designs are presented in Fig. 1 and Table S1. Raw eutrophic surface water was treated using DWTR constructed columns. The performance was evaluated by water quality analysis and cyanobacteria growth testing. The stability of DWTR during the column tests was analyzed based on X-ray fluorescence (XRF), Fourier transform infrared spectroscopy (FTIR), and other physicochemical methods. The characteristics of the microbial community in the columns were also determined by high-throughput sequencing analysis. Finally, recommendations for DWTR recycling in column systems to treat eutrophic surface water were presented.

In this study, raw DWTR was initially used as the main medium to prepare columns for the treatment of eutrophic surface water. Preliminary experiments were conducted (for approximately 1 month), and P concentrations in the effluent markedly decreased; the concentrations of total organic carbon (TOC) and total N (specifically, NH_4^+-N) increased from about 20 to 2 to 100 and $50\ mg\ L^{-1}$, respectively. In order to avoid such kinds of release, DWTR was used after being pretreated under a nitrogen atmosphere at 500 °C for 4 h (with a heating rate of 15 °C min^{-1} to reach 500 °C) (Wang et al., 2016). For repacking the columns, DWTR was applied as an additional medium (2%–4%) with glass beads in columns. The application of glass beads as an inert material helped elucidate the performance of DWTR in treating surface water; the relatively large diameter of glass beads can eliminate the formation of preferential flow paths in columns. In addition, 500 °C oxygen-limited treatment was applied to DWTR because at this temperature, most organic matter in the pretreated DWTR were transformed to the stable humin fractions without reducing the P adsorption capability of DWTR (Wang et al., 2016).

2.3. Column tests

Four columns with volumes of 12 L were used. Columns were packed with 10 L glass beads with 200 g DWTR (mixed completely), 5 L glass beads with 200 g DWTR, 10 L glass beads without DWTR, and 5 L glass beads without DWTR. Eutrophic surface water was supplied continuously from the bottom of the columns by using a peristaltic pump (Boyer et al., 2011). Hydraulic retention times (HRT) for the columns packed with 10 L media were set to 4 d, whereas those for columns with 5 L media were set to 2 d. Surface water was renewed every 3 d. Both influent and effluent were sampled and analyzed every week. Column tests were run for 1 year, and at the end of the tests, cyanobacteria growth tests were performed for the sampled surface water before and after treatment. After the tests, the media in the columns were vertically divided into 2 parts and completely homogenized. Glass beads, glass bead–DWTR mixtures, and DWTR in the columns were collected.