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Characterization of bacterial community and iron corrosion in drinking water distribution systems with O₃-biological activated carbon treatment

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ABSTRACT

Bacterial community structure and iron corrosion were investigated for simulated drinking water distribution systems (DWDSs) composed of annular reactors incorporating three different treatments: ozone, biologically activated carbon and chlorination (O₃-BAC-Cl₂); ozone and chlorination (O₃-Cl₂); or chlorination alone (Cl₂). The lowest corrosion rate and iron release, along with more Fe₃O₄ formation, occurred in DWDSs with O₃-BAC-Cl₂ compared to those without a BAC filter. It was verified that O₃-BAC influenced the bacterial community greatly to promote the relative advantage of nitrate-reducing bacteria (NRB) in DWDSs. Moreover, the advantaged NRB induced active Fe(III) reduction coupled to Fe(II) oxidation, enhancing Fe₃O₄ formation and inhibiting corrosion. In addition, O₃-BAC pretreatment could reduce high-molecular-weight fractions of dissolved organic carbon effectively to promote iron particle aggregation and inhibit further iron release. Our findings indicated that the O₃-BAC treatment, besides removing organic pollutants in water, was also a good approach for controlling cast iron corrosion and iron release in DWDSs.

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Introduction

Cast iron pipes have been used in drinking water distribution systems (DWDSs) for over five centuries (McNeill and Edwards, 2001). The corrosion of cast iron pipes is the most common problem in DWDSs, which can cause pipe failures and the deterioration of potable water quality (Nawrocki et al., 2010; Liu et al., 2014). The chemical stability of iron corrosion scales and biofilm microbial communities in DWDSs can have a large influence on the release of iron and other corrosion products, which may result in 'red water' issues, particularly under the situation of source water switching (Yang et al., 2014).

Iron corrosion in DWDSs is influenced by many chemical factors in the finished water: pH, alkalinity and the concentrations of oxygen, sulfate, chloride, disinfectants, and natural organic matter (NOM) (McNeill and Edwards, 2001; Imran et al., 2005). Recently, microbiologically influenced corrosion (MIC) has attracted great interest due to its complicated role in the corrosion process, where it can either accelerate or inhibit corrosion (Li et al., 2014). Some research found that sulfate-reducing bacteria (SRB) could increase the corrosion rate (Yuan et al., 2013). However, an increasing number of studies have begun to show the protective effects of some bacterial biofilms on metal against corrosion. For example, some reports show that iron-reducing bacteria (IRB) could

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inhibit corrosion by reducing ferric ions to ferrous ions and enhancing the consumption of oxygen (Dubiel et al., 2002). Interestingly, the nitrate-dependent Fe(II) oxidation by some nitrate-reducing bacteria (NRB) was found to accelerate the formation of α -FeOOH, whereas the reduction of Fe(III) by other NRB promotes the formation of Fe₃O₄ to inhibit further corrosion and iron release (Zhang et al., 2005; Etique et al., 2014; Wang et al., 2015).

We found that the bacterial communities in DWDSs differed with different disinfectants (Wang et al., 2012; Zhu et al., 2014), which led to different cast iron corrosion patterns. Moreover, it was reported that cast iron corrosion was also different between DWDSs using ground water and DWDSs using surface water, because bacterial communities and dissolved organic carbon (DOC) concentrations were significantly different in the two water types (Li et al., 2015). As noted by Hong Wang et al., the relatively low concentrations of total organic carbon in feed water from biofiltration resulted in variations between microbial communities, such as a decrease of *Alphaproteobacteria* and *Acidobacteria* Gp3 and an increase of *Gammaproteobacteria* and *Sphingobacteria* in the biofilms of the simulated DWDSs (Wang et al., 2013). Many previous studies found that the presence of fulvic acid and humic acid (the majority components of NOM) could greatly affect the attachment or deposition of microbes on surfaces, especially metal-oxide coated surfaces (Yang et al., 2012a). Therefore, DOC could significantly influence the bacterial community in drinking water, causing differences in the further corrosion of cast iron pipes. The concentration and characteristics of DOC in distributed water depend on the source water and treatment processes of the drinking water treatment plants (DWTPs). Biological activated carbon (BAC) filtration has been used for many years in drinking water treatment, usually after ozonation (O₃), and has been proven to be capable of significantly removing NOM, as well as taste and odor compounds (Simpson, 2008). Under normal operating conditions, BAC can be colonized by microorganisms, which can eventually establish active biofilms, and the formation of such biofilms can contribute to NOM removal by biodegradation (Gibert et al., 2013). Meanwhile, BAC colonized by microbes could also influence microbial numbers and the bacterial community structure in water through the release of detached biofilm cells (Han et al., 2013). O₃/BAC coupling has been widely used as the main advanced drinking water treatment process prior to chlorination (Cl₂) to improve water quality in DWTPs, because of its relatively low cost and high removal capacity for organic pollutants. Given the above, O₃/BAC coupling may be a more promising process for improving water quality and maintaining the biological stability of water in DWDSs. However, to best of our knowledge, the previous studies have been limited to the effects of these advanced treatments on the organic matter changes in bulk water, and few studies have been conducted, thus far, to characterize their effects on bacterial communities and corrosion processes in DWDSs.

The objective of this study was to investigate the effects of O₃-BAC-Cl₂ on the corrosion of cast iron coupons and bacterial communities in DWDSs using annular reactors (ARs) with O₃-Cl₂ and Cl₂ treatments as references. In the three ARs, the corrosion products and corrosion process were characterized

by electrochemical and physicochemical measurements. High-throughput Illumina HiSeq DNA sequencing was used to monitor changes in the composition of the bacterial community, including corrosion-related bacteria. The quantitative real-time polymerase chain reaction (PCR) was used to monitor changes in the microbial community according to specific groups: total bacteria based on the 16S rRNA gene and denitrifiers based on the functional genes *nirS*, *nirK* and *nosZ*. Most probable number enumerations of NRB, IRB and nitrate-dependent Fe(II)-oxidizing microorganisms were carried out under different conditions for biofilms on corrosion scales. DOC was characterized using a total organic carbon analyzer and high-performance size exclusion chromatography (HPSEC). The relationships among organic matter, bacterial communities and corrosion were discussed.

1. Materials and methods

1.1. Materials, preparations and model distribution systems

The elemental composition (wt.%) of cast iron coupons in this study was C 3.24%, O 1.64%, Si 2.24%, P 0.08%, S 0.10%, Fe 90.47%, Cu 0.75%, Mn 0.71%, and Zn 0.77%. Prior to use, the coupons were exposed to UV light for 30 min and weighed. Granular activated carbon was washed with deionized water in an ultrasonic water bath to remove all the carbon fines, dried at 105°C for 2 days and cooled in a desiccator.

In the experiments, three annular reactors (ARs) (Model 1320LJ, BioSurface Technologies Co., USA) were used to simulate DWDSs. The schematic of the experimental set-up is shown in Fig. 1. In the ARs, there were two concentric glass cylinders and a rotating inner drum that supported 20 cast iron coupons. Three ARs were arranged in parallel and operated at 50 r/min rotational speed, which produced a shear stress of 0.25 N/m², corresponding to a flow rate of about 0.3 m/sec in a 100-mm-diameter smooth pipe (Wang et al., 2012). The hydraulic retention time (HRT) of the ARs was 6 hr. All exposed surfaces of the ARs were covered with aluminum foil during the whole experiment to inhibit phototrophic growth.

In one AR, the influent water was treated with O₃ for a contact time of 12 min, followed by BAC adsorption with a retention time of 30 min. Ozonation was carried out in a 6 L reactor. Approximately 46 mg of gaseous O₃/L oxygen-ozone was bubbled into the reactor through a porous plate in the reactor bottom at a flow rate of 200 mL/min. Then, the AR was exposed to free chlorine as the second disinfectant. Chlorine was dosed from a stock solution of sodium hypochlorite (NaClO). The second AR was treated with O₃ at the same contact time, and then exposed to free chlorine without BAC adsorption. The third AR experiment was conducted with only free chlorine as disinfectant. Moreover, before flowing into the ARs, the water treated with chlorine for the three systems entered an organic glass chlorine tank with 4 hr HRT to ensure sufficient mixing between water and disinfectant. The experiment was operated in two stages. Stage I was the initial corrosion stage. The ARs were given 40 days to form corrosion scales from zero-valent cast iron. During stage II, the stable corrosion stage (after 40 days), the corrosion scales underwent further transformation, and finally reached stable conditions.

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