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UV-H$_2$O$_2$ based AOP and its integration with biological activated carbon treatment for DBP reduction in drinking water

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Abstract

The presence of disinfection byproducts (DBPs) such as trihalomethanes (THMs) and haloacetic acids (HAAs) in drinking water is of great concern due to their adverse effects on human health. Emerging regulation limiting the concentration of DBPs in drinking water has increased demands for technologies and processes which reduce the formation of DBPs in drinking water. In this study, UV-H$_2$O$_2$ based advance oxidation process (AOP) was used to treat raw surface water. Experiments were conducted using low pressure mercury vapor UV lamps in collimated beam and flow-through annular photoreactors. The effect of UV fluence (0–3500 mJ cm^{-2}) and hydrogen peroxide concentration (0–23 mg l^{-1}) in reducing the concentration of THMs and HAAs was examined. The UV-H$_2$O$_2$ AOP was then coupled with a downstream biological activated carbon (BAC) treatment to assess the synergetic benefits of combining the two treatments. It was observed that UV-H$_2$O$_2$ AOP was only effective at reducing DBPs at UV fluences of more than 1000 mJ cm^{-2} and initial H$_2$O$_2$ concentrations of about or greater than 23 mg l^{-1}. However, the combined AOP–BAC treatment showed significant reductions of 43%, 52%, and 59% relative to untreated raw water for DBPs, TOC, and UV$_{254}$, respectively.
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1. Introduction

The use of chlorine as a drinking water disinfectant produces halogenated byproducts that are known for their long-term adverse health effects (Komulainen, 2004). These compounds, referred to as disinfection byproducts (DBPs), form through the reaction between chlorine and natural organic matter (NOM), which is present in raw source waters. Trihalomethanes (THMs) and haloacetic acids (HAAs) are two prominent forms of DBPs that have been shown to be harmful and probable human carcinogens, thereby posing a serious threat to human health (Richardson, 1998; Toledano et al., 2005). Thus, health and environmental authorities have placed limits on the presence of THMs and HAAs in drinking water. The United States

Environmental Protection Agency (USEPA) allows for maximum 80 µg l^{-1} of THMs and 60 µg l^{-1} of HAAs based on its stage 2 disinfectants and disinfection byproducts rule (USEPA, 2006). THMs and HAAs are very difficult to eliminate once formed. Thus, any effective strategy to reduce their concentrations in drinking water should focus on hindering their formation by degrading and/or removing their precursors.

Advanced oxidation processes (AOPs) are promising technologies that utilize potent OH radicals to oxidize NOM and DBP precursors by removing hydrogen atoms or adding electrophiles to their double bonds (Sundstrom et al., 1986; Beltran et al., 1993). In particular, UV-H$_2$O$_2$ based AOP offers great potential because of the already wide acceptance and application of UV as effective disinfectant. UV-H$_2$O$_2$ based AOP could reduce the formation of DBPs in drinking water in two ways. Rigorous treatment results in the complete oxidation or mineralization of NOM to CO$_2$ and reduces the total organic carbon

(TOC) content. Intermediate UV-H_2O_2 treatment, on the other hand, partially oxidizes NOM and its large molecular weight constituents into smaller and more biodegradable compounds such as aldehydes and carboxylic acids (Tuhkanen, 2004). Such physical and/or chemical changes to the high molecular weight components, in turn, alter the overall NOM characteristics, potentially reducing its reactivity with chlorine. Each of these treatment options has implications on the application of UV-H_2O_2 AOP as a viable standalone treatment strategy. Rigorous treatment, although very effective, comes at the cost of high energy input to the UV system. Intermediate treatment and partial oxidation of NOM, may not sufficiently reduce TOC and/or alter the characteristics of DBP precursors to impact their behavior in reactions with chlorine. Also, formation of biodegradable oxidation byproducts (e.g. aldehydes and carboxylic acids) may lead to bacterial re-growth in the drinking water distribution system. Thus, implementing a UV-H_2O_2 AOP as a standalone treatment may not be practical because of the high-energy costs or insufficient reductions in the formation of DBPs.

Integrating UV-H_2O_2 with a downstream biological process may offer a promising alternative because it allows for the removal of the biodegradable intermediates formed as a result of partial oxidation of NOM. The intermediates of UV-H_2O_2 oxidation act as a major food source for microbial communities and are utilized as substrates in bioreactors (Charnock and Kjonno, 2000). Therefore, the application of a downstream biotreatment could complement UV-H_2O_2 AOP by taking advantage of the increased biodegradability of the DBP precursors for removing and/or degrading the organics completely. This could ultimately result in a net reduction of total carbon available for the formation of DBPs.

Other researchers have documented the potential benefits of coupled AOP-biotreatment. It has been reported that AOP pretreatment followed by biodegradation minimizes chlorine dosage and diminishes bacterial re-growth in the distribution system (Wu et al., 2003). Fahmi and Okada (2003) observed reductions in dissolved organic carbon (DOC) with H_2O_2-O_3 AOP followed by biological treatment. Furthermore, UV-H_2O_2 AOP followed by biodegradation has been shown to have significant impact on the reduction of THMs (Speitel et al., 2000). With these initial studies indicating the benefits of combined AOP and biotreatment, there comes the need for more comprehensive work focusing exclusively on the synergistic benefits of combining AOPs with downstream biotreatment at reducing THM and HAA formation potentials (FP). In particular, it is important to determine the optimum levels of pretreatment required for the enhanced degradation of DBP precursors.

This research focused on the evaluation of each UV-H_2O_2 and biological process as well as the synergistic effects of their combination for the reduction of DBP precursors in drinking water. Laboratory and bench scale experiments were carried out on raw surface water serving the Greater Vancouver in the province of British Columbia, Canada. The effectiveness of each treatment alternative was examined for reducing TOC, THM–FP, and HAA–FP.

2. Materials and methods

2.1. Apparatus and chemicals

The laboratory scale UV-H_2O_2 experiments were carried out in a collimated beam photoreactor equipped with a low pressure mercury vapour UV lamp (Trojan Technologies Inc.) and a stirred Petri dish (6 cm diameter, 70 ml working volume). Varying the distance between the UV source and the surface of the water allowed the UV irradiance and the UV fluence to be adjusted. The latter was determined by multiplying the UV irradiance by the exposure time. The irradiance of the UV at the surface of the water was determined using a research radiometer (International Light Inc., IL1700, sensor SED240 for $\lambda = 254$ nm). The volume averaged UV irradiance for the specific distance in the investigation was measured to be 0.193 mW cm^{-2}. This value was determined according to the standard protocol (Bolton and Linden, 2003) which accounts for the depth of the liquid in the reactor chamber and the properties of the raw water being treated (i.e. transmittance and H_2O_2 concentration).

The set-up for bench scale UV-H_2O_2 experiments consisted of a flow-through annular photoreactor equipped with a low pressure mercury vapour UV lamp (UVMax Model F, Trojan Technologies Inc.), centrifugal pump, feed reservoir, and fluid transfer devices (Fig. 1). The centrifugal pump (Type JP5, Grundfor) re-circulated the water from the polyethylene feed reservoir, through the UV reactor and back again. The flow rate was monitored by the flow meter and controlled by a gate valve.

The set-up for downstream biotreatment included two Plexiglas columns (2 cm diameter and 20 cm height) filled with granular activated carbon (SeaGram Matrix Carbon),
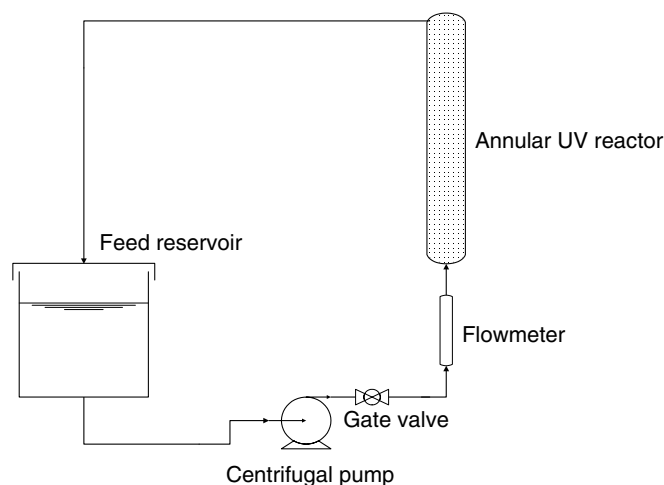

Fig. 1. UV-H_2O_2 bench scale setup.