Chemosphere 83 (2011) 661–667

Contents lists available at ScienceDirect

Chemosphere

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

Powdered activated carbon coupled with enhanced coagulation for natural organic matter removal and disinfection by-product control: Application in a Western Australian water treatment plant

Ina Kristiana *, Cynthia Joll, Anna Heitz

Curtin Water Quality Research Centre, Curtin University, Perth, Western Australia, Australia

ARTICLE INFO

Article history:
Received 26 October 2010
Received in revised form 7 February 2011
Accepted 7 February 2011
Available online 25 February 2011

Keywords:
Powdered activated carbon
Enhanced coagulation
Disinfection by-products
Natural organic matter
Trihalomethanes
Haloacetic acids

ABSTRACT

The removal of organic precursors of disinfection by-products (DBPs), i.e. natural organic matter (NOM), prior to disinfection and distribution is considered as the most effective approach to minimise the formation of DBPs. This study investigated the impact of the addition of powdered activated carbon (PAC) to an enhanced coagulation treatment process at an existing water treatment plant on the efficiency of NOM removal, the disinfection behaviour of the treated water, and the water quality in the distribution system. This is the first comprehensive assessment of the efficacy of plant-scale application of PAC combined with enhanced coagulation on an Australian source water. As a result of the PAC addition, the removal of NOM improved by 70%, which led to a significant reduction (80–95%) in the formation of DBPs. The water quality in the distribution system also improved, indicated by lower concentrations of DBPs in the distribution system and better maintenance of disinfectant residual at the extremities of the distribution system. The efficacy of the PAC treatment for NOM removal was shown to be a function of the characteristics of the NOM and the quality of the source water, as well as the PAC dose. PAC treatment did not have the capacity to remove bromide ion, resulting in the formation of more brominated DBPs. Since brominated DBPs have been found to be more toxic than their chlorinated analogues, their preferential formation upon PAC addition must be considered, especially in source waters containing high concentrations of bromide.

1. Introduction

Since the beginning of the 20th century, disinfection has been an integral part of drinking water treatment due to its crucial role in preventing the spread of waterborne diseases. While disinfectants are effective in inactivating harmful microorganisms, as powerful oxidants, they also react with organic and inorganic materials in treated waters, leading to the formation of disinfection by-products (DBPs). Through epidemiological studies, some DBPs have been associated with a number of adverse human health effects e.g. cancers of the urinary and digestive tracts, bladder and colon cancers, low birth weight, intrauterine growth retardation, and spontaneous abortion (Richardson et al., 2007), although some of these effects are still somewhat controversial and require further studies. Due to the potential adverse health effects associated with DBPs, in many countries the concentrations of DBPs in drinking waters are regulated. For example, the maximum contaminant level of trihalomethanes (THMs) (the total concentrations of four species of THMs: chloroform, bromodichloroacetic acid, chlorodibromoacetic acid, and bromoform) in the US is currently 80 $\mu g\ L^{-1}$, while the Australian Drinking Water Guidelines (ADWG) set the guideline value for the concentration of total THMs at 250 $\mu g\ L^{-1}$. Water utilities are therefore required to ensure that drinking water treatment processes are in place and adequate, such that the concentrations of DBPs in the distributed drinking water do not exceed the specified regulations and guidelines.

The formation of DBPs can be controlled and minimised using one, or a combination of, the following approach: removal of DBP precursors prior to disinfection, change of disinfectant, and removal of DBPs following disinfection (Karanfil et al., 2008). The removal of organic precursors of DBPs i.e. natural organic matter (NOM) prior to disinfection and distribution is considered to be the most effective approach to minimise the formation of DBPs. Due to the increasingly stringent DBP regulations, advanced precursor removal technologies are being used to maximise NOM removal. These include membrane filtration (microfiltration, nanofiltration, reverse osmosis), activated carbon (granular activated carbon, powdered activated carbon (PAC)), and ion exchange (MIEX resin).

---

* Corresponding author. Address: Curtin Water Quality Research Centre, GPO Box 1987, Perth, Western Australia 6845, Australia. Tel.: +61 08 9266 9389; fax: +61 08 9266 3547.

E-mail address: I.Kristiana@curtin.edu.au (I. Kristiana).

0045-6535/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.chemosphere.2011.02.017

In Australia, many source waters contain particularly high concentrations of NOM by international standards (up to 40 mg L^{-1} as dissolved organic carbon (DOC)), and sources in coastal locations may contain elevated levels of bromide ion (up to 2 mg L^{-1}). This poses challenges to Australian water utilities to produce drinking water which meets the ADWG. An important source water that presents a particularly difficult treatment process challenge is a reservoir in the southwest of Western Australia (WA) (referred to here as SW reservoir). The water from this reservoir contains elevated concentrations of DOC (ranging from 20–40 mg L^{-1}) and the bromide ion concentration is also high (300–600 μg L^{-1}). Water from this reservoir is treated at a nearby water treatment plant (SW WTP) for the removal of DOC. Historically, the treatment process has used enhanced coagulation (alum) and flocculation, followed by sedimentation and sand filtration, and disinfection with chlorine. This conventional treatment removed 80–90% of DOC from the raw water. However, since the initial DOC concentration was so high, the residual DOC in the treated water was still typically around 4–5 mg L^{-1}, which led to excessive chlorine consumption and the production of elevated concentrations of DBPs in the disinfected water. Occasionally, when disinfection levels needed to be increased to ensure residual throughout the distribution system, the concentrations of total THMs in the distribution system exceeded the ADWG value of 250 μg L^{-1}. In such cases, aeration was employed to volatilise the THMs formed, in order to reduce the concentrations of THMs in the distribution system. However, it was found that some of the chlorine residual was also lost during the aeration process.

After consideration of the best available technologies to manage the formation of THMs at the treatment plant and in the distribution system, PAC treatment was selected by the local water utility as the preferred technology to enhance NOM removal, and thus reduce the formation of THMs, at this particular treatment plant. In drinking water treatment, PAC is traditionally used for the removal of organic compounds that cause taste and odour (Najm et al., 1991). However, PAC has also been reported to be an effective adsorbent for organic precursors of DBPs, i.e. NOM (e.g. Najm et al., 1990, 1998; Amy et al., 1991; Jacangelo et al., 1995; Fabris et al., 2004). The extent of NOM removal by PAC has been found to largely depend on the type of PAC, as well as the quality of the source water which determines the dose of PAC required to achieve the desired NOM removal (Najm et al., 1991; Jacangelo et al., 1995). PAC treatment has also been used in conjunction with coagulation, enhanced coagulation, or ultrafiltration to improve the removal of NOM (e.g. Jacangelo et al., 1995; Najm et al., 1998; Uyak et al., 2007). In a pilot-scale study, Jacangelo et al. (1995) reported 12–80% removal of NOM from a US river water, depending on PAC dose, when PAC is added as a pre-treatment to ultrafiltration. Based on the results from a series of laboratory-scale jar test experiments, Najm et al. (1998) claimed that the combination of enhanced coagulation and PAC provides a more cost-effective treatment process than enhanced coagulation only, in order to produce drinking water that meets US water quality regulations. In another laboratory-scale study, Uyak et al. (2007) demonstrated that supplementing enhanced coagulation with PAC in the treatment of a Turkish lake water resulted in an increased DOC removal from 45% to 76% at an optimum PAC dose of 40 mg L^{-1}. Recently, in a laboratory-scale study on the effect of PAC addition on the removal of NOM, Álvarez-Uriarte et al. (2010) reported that the addition of small amounts (up to 50 mg L^{-1}) of PAC during coagulation increased the removal of THM precursors from 40% to 70%. However, Carrière et al. (2009) found that the application of PAC (11 mg L^{-1}) combined with enhanced coagulation at a WTP in Canada only resulted in a small increase (7%) in the reduction of DOC and did not improve the removal of THM precursors.

Preliminary laboratory-scale experiments using varying PAC types (Acticarb PS1000 and Acticarb PS1300), PAC dose rates and contact times were conducted by the local water utility to evaluate the effectiveness of PAC added into the enhanced coagulation step for enhancement of the removal of THM precursors in the source water from the SW reservoir. The laboratory-scale trials showed that Acticarb PS1300 performed better than Acticarb PS1000 for removal of THM precursors. Using Acticarb PS1300, a dose of 150 mg L^{-1} was sufficient to reduce the concentration of THMs in the treated water to well below the guideline value. Following successful plant trials using PAC dose equivalent to the optimum dose found in laboratory-scale trials (150 mg L^{-1}), PAC treatment was added to the existing WTP through addition of PAC into the enhanced alum coagulation step. The SW WTP is the only WTP in Australia that uses the combination of PAC and enhanced coagulation for the removal of NOM.

Here, we report the first study of the efficacy of plant-scale PAC combined with enhanced coagulation for DBP minimisation from the humic-rich surface waters of South Western Australia. South Western Australia has been undergoing long-term drought since the 1970s and waters of more marginal quality have become important drinking water sources. This study investigated the efficiency of NOM removal, the changes in the disinfection behaviour of the treated water, and the variations in distribution system water quality, as a result of the addition of PAC treatment at the WTP. The efficiency of NOM removal before and after the use of PAC at the WTP was evaluated by comparison of the characteristics of NOM in the treated waters. The disinfection behaviour of waters treated with and without PAC was studied through bench-scale evaluation of the DBP formation potential of the treated waters. The variations in distribution system water quality were assessed by analyses of selected water quality parameters in samples collected at selected sampling sites, before and after the application of PAC treatment at the WTP. To our knowledge, there has only been one other published report on the plant-scale application of PAC combined with enhanced coagulation to improve the removal of NOM (Carrière et al., 2009). This is the first comprehensive assessment of the impact of plant-scale application of PAC combined with enhanced coagulation on the removal of NOM and the formation potential of DBPs from an Australian source water.

2. Materials and methods

2.1. Sample collection

Two sampling events were carried out, before and after the application of PAC treatment at the WTP treating water from the SW reservoir. At each sampling event, raw and treated (after filtration and prior to disinfection) water samples, and samples from distribution system sampling points were collected. Disinfectant residual in the samples from the distribution system was quenched with either sodium sulphite or ascorbic acid solution.

2.2. Chemicals and reagents

All chemicals, reagents, and organic solvents used in this study were of analytical grade purity (AR grade ⩾99% pure) or better, and were used without further purification.

2.3. Water quality analysis

Water samples were filtered through a 0.45 μm glass membrane filter prior to DOC and UV_{254} measurements. The UV_{254} absorbance of the water samples was determined using a HP 8452A Diode Array Spectrophotometer with a 5 cm quartz cell.