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Formation and control of disinfection byproducts and toxicity during reclaimed water chlorination: A review

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ABSTRACT

Chlorination is essential to the safety of reclaimed water; however, this process leads to concern regarding the formation of disinfection byproducts (DBPs) and toxicity. This study reviewed the formation and control strategies for DBPs and toxicity in reclaimed water during chlorination. Both regulated and emerging DBPs have been frequently detected in reclaimed water during chlorination at a higher level than those in drinking water, indicating they pose a greater risk to humans. Luminescent bacteria and *Daphnia magna* acute toxicity, anti-estrogenic activity and cytotoxicity generally increased after chlorination because of the formation of DBPs. Genotoxicity by *umu*-test and estrogenic activity were decreased after chlorination because of destruction of toxic chemicals. During chlorination, water quality significantly impacted changes in toxicity. Ammonium tended to attenuate toxicity changes by reacting with chlorine to form chloramine, while bromide tended to aggravate toxicity changes by forming hypobromous acid. During pretreatment by ozonation and coagulation, disinfection byproduct formation potential (DBPFP) and toxicity formation potential (TFP) occasionally increase, which is accompanied by DOC removal; thus, the decrease of DOC was limited to indicate the decrease of DBPFP and TFP. It is more important to eliminate the key fraction of precursors such as hydrophobic acid and hydrophilic neutrals. During chlorination, toxicities can increase with the increasing chlorine dose and contact time. To control the excessive toxicity formation, a relatively low

Abbreviations: AEAFP, anti-estrogenic activity formation potential; ATP, adenosine triphosphate; BAC, biological activated carbon; BCAA, bromochloroacetic acid; BCAN, bromochloroacetonitrile; BDCAA, bromodichloroacetic acid; BDCAcAm, bromodichloroacetamide; BDCM, bromodichloromethane; DBAA, dibromoacetic acid; DBAcAm, dibromoacetamide; DBAN, dibromoacetonitrile; DBCAcAm, dibromochloroacetamide; DBCM, dibromochloromethane; DBPFP, disinfection byproduct formation potential; DBPs, disinfection byproducts; DCAA, dichloroacetic acid; DCAcAm, dichloroacetamide; DCP, dichloropropanone; DCAN, dichloroacetonitrile; DOM, dissolved organic matter; EDCs, endocrine disrupting chemicals; FP, formation potential; HAAs, haloacetic acids; MBAA, bromoacetic acid; MBAN, bromoacetonitrile; MCAA, chloroacetic acid; MIAA, Iodoacetic acid; MTT, 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide; NDMA, N-nitrosodimethylamine; RO, reverse osmosis; TBAcAm, tribromoacetamide; TBAN, tribromoacetonitrile; TBM, bromoform; TCA, chlorohydrate; TCAA, trichloroacetic acid; TCAcAm, trichloroacetamide; TCP, trichloropropanone; TCM, chloroform; TFP, toxicity formation potential; THMs, Trihalomethanes; TOBr, total organic bromine; TOCl, total organic chlorine; TOX, total organic halogen

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chlorine dose and short contact time were required. Quenching chlorine residual with reductive reagents also effectively abated the formation of toxic compounds.

Contents

Introduction

The multiple pressures of climate change, population growth, urbanization and industrialization have led to declining availability of fresh water resources (Bagatin et al., 2014; Sun et al., Q6 2016). According to the WRG (2009), the world is likely to be confronted with a 40% water deficit if current trends continue. Accordingly, reclaimed water has become an essential alternative water resource to address the ever-increasing demand for water resources worldwide (Tortajada and Nam Ong, 2016; Fatta-Kassinos et al., 2016) and is now extensively used for industry, agriculture, landscaping, and even potable reuse (Asano et al., 2007). Given its stable quantity, developed wastewater treatment technologies, and economic and social benefits, reclaimed water is likely to play a critical role in future water resources.

Because it contains a variety of pathogens, reclaimed water needs to be disinfected to minimize the health risk it poses to humans (Li et al., 2013). Despite the development of many alternative disinfectants, including chloramines, chlorine dioxide, ozone, and UV, disinfection with chlorine is still the technology most extensively utilized to ensure the safety of reclaimed water (USEPA, 2004). In addition to being applied at the end of treatment to inactivate pathogens, chlorination is widely used to provide residual chlorine in distribution systems to control the regrowth of microorganisms, as well as to destroy biofilms during backflushing of biological activated carbon and reverse osmosis system.

Although it inactivates pathogens, the extensive use of chlorination has led to concern regarding the formation of disinfection byproducts (DBPs) (Chu et al., 2016a). During chlorination, chlorine reacts with precursors, primarily dissolved organic matter (DOM), to form various DBPs (Richardson, 2011). Most identified individual DBPs and the mixture of DBPs (such as the total organic halogen; TOX) have been shown to be cytotoxic, genotoxic and carcinogenic (Richardson et al., 2007). Given the potential ecological and health risks that might be posed by DBPs, researchers have focused on the precursors, formation, speciation, toxicity, and identification of DBPs for years (Chu et al., 2016b, 2016c; Krasner et al., 2006; Plewa et al., 2004a; Wu et al., 2016). DBPs in drinking water have been studied and reviewed in detail because of their potential for direct contact and ingestion by humans; however, it is harder to study DBPs in chlorinated reclaimed water because of the diversity and complexity of water quality and precursors. The concentration, reactivity, and composition of DOM, which are precursors of DBPs, in reclaimed water are significantly different from those in drinking water (Chang et al., 2001; Hu et al., 2016; Hudson et al., 2007), which inevitably leads to the formation of different DBPs in varying concentrations and subsequent harmful effects (Sirivedhin and Gray, 2005). Q7 However, the formation of DBPs in chlorinated reclaimed water needs to be further explored.

Toxicity studies have been conducted to understand the risk posed by chlorinated water, but because most of these have investigated individual DBPs, our understanding is limited regarding real-world mixtures of DBPs in chlorinated water. Thus, many investigators have evaluated comprehensive bio-toxicity (Bayo et al., 2009; Patterson et al., 1995; Rice et al., 2008; Watson et al., 2012; Yang et al., 2014). For years, different bioassay methods with subject organisms of different levels have been developed to evaluate toxicity (Jeong

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