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Review

Novel technologies for reverse osmosis concentrate treatment: A review

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ABSTRACT

Global water shortages due to droughts and population growth have created increasing interest in water reuse and recycling and, concomitantly, development of effective water treatment processes. Pressured membrane processes, in particular reverse osmosis, have been adopted in water treatment industries and utilities despite the relatively high operational cost and energy consumption. However, emerging contaminants are present in reverse osmosis concentrate in higher concentrations than in the feed water, and have created challenges for treatment of the concentrate. Further, standards and guidelines for assessment and treatment of newly identified contaminants are currently lacking. Research is needed regarding the treatment and disposal of emerging contaminants of concern in reverse osmosis concentrate, in order to develop cost-effective methods for minimizing potential impacts on public health and the environment. This paper reviews treatment options for concentrate from membrane processes. Barriers to emerging treatment options are discussed and novel treatment processes are evaluated based on a literature review.

1. Introduction

Membrane processes including reverse osmosis (RO) have been widely adopted for water treatment and reuse. The global market for RO continues to grow and is predicted to reach $8.1 billion by 2018 (Cumming, 2014) as RO is increasingly deployed in water treatment plants, quickly replacing conventional softening processes that use lime and soda ash. In particular, RO uses pressured membranes for treatment and desalination of brackish water, producing high-quality water. However, as with other membrane processes (i.e., nanofiltration, ultrafiltration, microfiltration), the challenge of RO is management of the concentrate generated from the filtration processes. Untreated or improperly managed concentrate can result in adverse environmental effects, due to high salinity, nutrients (phosphorus, nitrogen), organic contaminants including emerging contaminants, and trace amounts of inorganics.

Cost-effective treatment and management strategies for concentrate are still in their infancy. While review articles have focused on traditional RO treatment methods or recent advances in RO technology (Pérez-González et al., 2012; Malaeb and Ayoub, 2011; Fujioka et al., 2012), there are few studies addressing the characteristics of contaminants or treatment options for minimizing or removing contaminants of concern. Yet contaminants in concentrate can impact ecosystems and water quality in areas where the concentrate is discharged. Given that the characteristics of emerging organic contaminants significantly affect the efficiency of water treatment methods, and given the potent toxicity and persistence of such contaminants, innovative and cost-effective treatment technologies are needed.

This review aims to provide (i) an overview of emerging contaminants, (ii) strategies for minimizing and treating concentrate from RO processes with the use of integrated water treatment processes, (iii) description of treatment technologies specifically targeting emerging contaminants of concern in concentrate, (iv) proposals for treatment options based on literature reviewed, and (v) discussion of future research needs.

2. Emerging contaminants in concentrate

The most significant drawbacks of using pressurized membrane systems for water treatment are membrane fouling and concentrate management. While there has been intensive research on

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membrane fouling, little information is available concerning the treatment of concentrates, a long-standing problem.

Methods of treatment and volume reduction of concentrate must be based on the characteristics of the concentrate as well as the operational and design characteristics of membrane systems. The composition of raw water, operating parameters of the membrane process, and overall system elements (i.e., pre-treatment, cleaning chemicals used) can influence both quality and quantity of the concentrate generated. Development of effective treatment methods for the concentrate entails evaluating significant parameters, such as volume generated, concentration, characteristics of the feed water, and operational conditions, and using well-verified analytical methods to detect trace amounts of contaminants, including emerging contaminants.

Emerging contaminants can be classified as persistent organic contaminants (e.g., pesticides), endocrine-disrupting chemicals (EDCs) (e.g., estrogens), pharmaceuticals and personal care products (e.g., drugs, sunscreens, cosmetics), and nanomaterials (e.g., nano-scale titania). Contaminants that are listed as "emerging" include industrials, pharmaceuticals, detergents, personal care products, disinfectants, and life-style compounds (i.e., caffeine, nicotine) (Meffe and De Bustamante, 2014). Recently, the U.S. EPA has described the newly identified emerging contaminants perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA). RO with other treatment processes (i.e., activated carbon) has been effective in reducing contaminant levels (e.g., perfluorochemicals, PFCs) to the drinking water quality standard (below 0.2 μg/L) (U.S. EPA, 2012). However, contaminants in the concentrate produced from RO have been difficult to destroy to undetectable trace levels, and recent studies show that wastes containing emerging contaminants such as PFOS and PFOA from RO concentrate still require incineration (Hartten, 2014; MDH, 2014; Vectis et al., 2009).

Emerging contaminants detected in the environment typically originate from hospitals, pharmaceutical manufacturing plants, agricultural practices, and wastewater treatment facilities (Daughton and Ternes, 1999; Halling-Sorensen et al., 1998; Kasprzyk-Hordern et al., 2008; Kummerer, 2009; Lapworth et al., 2012; López-Serna et al., 2013; Postigo et al., 2010). Reuse of municipal wastewater has been a particular concern due to N-nitrosodimethylamine (NDMA), a potently carcinogenic water disinfection byproduct formed in high concentrations (Mitch et al., 2003).

2.1. Characteristics of emerging contaminants

2.1.1. Environmental persistence

Residue of emerging contaminants including bisphenol A (BPA), PPCPs, and PFCs, can be found in most environmental media (Murray et al., 2010; Arukwe et al., 2012). The most persistent emerging organic contaminants detected in sediments and sludge are reported to be, in order of persistence, polycyclic aromatic hydrocarbons (PAHs) > polychlorinated naphthalenes > polychlorinated dibenzo-*p*-dioxin/polychlorinated dibenzofuran (PCDDs/Fs) > polychlorinated biphenyl (PCBs) > polybrominated diphenylether (PBDEs) (Eljarrat and Barceló, 2003). Compounds with high sorption affinity, log $K_{ow} > 4$ (Pan et al., 2009), remain persistent in environmental media, and are consequently difficult to remove. For instance, carbamazepine has been identified as one of the most persistent environmental contaminants (Löffler et al., 2005; Williams et al., 2009; Martínez-Hernández et al., 2014). Among emerging organic contaminants, most pesticides are persistent and often comprise the highest concentration detected in water, followed by industrial contaminants and pharmaceuticals (Meffe and De Bustamante, 2014). Hydrophilic and highly water-soluble chemicals may persist in both surface and ground water.

2.1.2. Human and ecosystem effects

Persistent emerging contaminants, detected in municipal wastewater, surface water, and drinking water, are usually toxic to humans and do impact ecosystems. Some emerging organic contaminants are hydrophobic, bioaccumulative, semi-volatile and toxic, including pesticides, polychlorinated biphenyls, and polychlorinated naphthalenes (Eljarrat and Barceló, 2003). Potential risks for humans and ecosystems are defined using acceptable daily intake (ADI) and the reference dose (RfD) (Dorne et al., 2007).

Contaminants in the industrials category include bisphenols, alkylphenols, perfluorates, antioxidants, phthalates, PBDEs, and examples of PPCPs comprised of synthetic hormones and polycyclic musks (Murray et al., 2010). Among the emerging organic contaminants, the most frequently detected environmentally, and posing risks to human health, include industrials (PFOA, PFOS), pesticides (diazinon), and PPCPs (E1) (Schriks et al., 2010). Among the emerging contaminants, PBDEs have a potential to adversely affect human endocrine systems and bioaccumulate (Hooper and McDonald, 2000; Meerts et al., 2001; Rahman et al., 2001), while relatively limited information is available on the toxicity of PFOS and PFOA (Hekster et al., 2003). Lack of analytical methods for detecting trace amounts of such contaminants in the environment is a major limitation (Stewart et al., 2014).

Among pharmaceuticals, amoxicillin is one of the top priorities for treatment. Amoxicillin in medical wastewater not only exhibits significant ecotoxicity (Escher et al., 2011), but is also detected in high concentrations, and is linked to the formation of antibiotic-resistant species. As previously noted, another commonly used emerging organic contaminant is carbamazepine. When residue contaminated with carbamazepine is metabolized by organisms, their growth and characteristics are adversely affected due to oxidative stress on critical organs (Nassef et al., 2010). Similarly, carbamazepine likely presents high risks to humans due to its impact on human embryonic cells (Murray et al., 2010; Pomati et al., 2006).

Table 1 summarizes relevant properties of emerging contaminants of concern in concentrate by use category (industrials, pharmaceuticals, pesticides, and disinfection byproducts). According to hazard indexes, some endocrine-disrupting chemicals such as sulfamethoxazole and caffeine have been reported to constitute the majority of the total hazard quotient (Yan et al., 2014).

Due to lack of data, it has been difficult to evaluate or predict adverse effects of emerging contaminants at concentrations detected in the environment. Table 1 lists a group of emerging contaminants defined as persistent based on toxicity and octanol–water coefficient (log K_{ow}), which together provide basic data for risk assessment and development of treatment strategies. For quantifying the risks to humans and ecosystems, some of the ADI values (mg kg^{-1} day^{-1}) are 1.5×10^{-3} (PFOA), 1.5×10^{-4} (PFOS), 5.0×10^{-2} (BPA), 1.3×10^{-5} (estrone, E1) and 9.0×10^{-5} (diazinon) (Fromme et al., 2009; Kolpin et al., 2002, 2004; Loos et al., 2009; Schriks et al., 2010; Snyder et al., 2008; Teuschler et al., 1999; U.S. EPA, 2010).

2.2. Factors affecting concentrations of emerging contaminants in concentrate

Environmental conditions (i.e., temperature, pH, and ionic strength) can affect the levels of emerging contaminants present in concentrates. For instance, among N-nitrosamines (disinfection byproduct), feed solution temperature significantly influenced the rejection of NDMA, and a 10-fold increase of ionic strength resulted