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Innovative membrane filtration system for micropollutant removal from drinking water – prospective environmental LCA and its integration in business decisions

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ABSTRACT

Micropollutants in freshwater, e.g., pharmaceuticals such as contraceptives, are a source of increased concern for human health and wildlife. Even after excretion, some of these compounds are pharmaceutically active in aquatic environment and they are found to cause endocrine disruption in both human and wildlife populations. In this study we analyzed a membrane system, coated with enzymes, which removes endocrine disrupting chemicals or micropollutants from surface water used for drinking. In order to help a membrane manufacturer in product development, we conducted a cradle-to-grave life cycle assessment. Water purification with two membrane systems, based on membrane coating covalent binding versus adsorption, were analyzed and compared with granulated activated carbon made from coal and wood. It was found that the membrane with covalent binding can have much lower environmental impacts than activated carbon made from coal. A sensitivity analysis showed that operational electricity use, the source of electricity and membrane coating frequency influence the results significantly. Scenario analysis indicates that a membrane system with covalent binding which uses operational electricity lower than 0.2 kWh per m^3 of filtered water and with monthly enzyme coating frequency can perform better than conventional activated carbon systems irrespective of the electricity source. These findings can be used to guide the optimization of the membrane parameters. This study provided an understanding of the membrane modification for micropollutant removal and its impacts on environment. Finally, we describe how environmental sustainability can be integrated into business decisions, such as process and material selection and design optimization, with the help of life cycle assessment.

1. Introduction

Progress in science and technology had led to numerous products to address human needs such as pharmaceuticals (e.g., pain killers, contraceptives, anti-depressants, cancer drugs, hormone therapies, and veterinary medicine to promote growth of cattle and antibiotics) and personal care products (PCPs) (e.g., skin creams, antibacterial soaps, shampoos, sun screens, perfumes, and musks) which are used daily and end up in wastewater. The consumption of these products by humans and animals can lead to increase of pharmaceutically active chemicals (PAC) in the aquatic environment from the urine and faeces (Velicu and Suri, 2009). Wise et al. (2011) estimated that 40% of all oral contraceptives consumed reach sewage streams in the form of available synthetic estrogen (17 alpha-ethinyl estradiol, EE2). Khanal et al. (2006) reported that 90% of the estrogen load in the environment comes from animal manure originating from natural steroidal hormones used for herd health programs (Fisher and Scott, 2008). Numerous studies have reported that these can act as endocrine disrupting chemicals (EDC). For instance, Fisher and Borland (2003) reported that 30 tonnes/year of EDCs are released into the natural environment around Sydney. These have been detected in wastewater influents and effluents due to persistence and inefficient removal by current water purification systems. Consequently EDCs end up in surface water which is used for drinking (Caldwell et al., 2010; Touraud et al., 2011). Kidd et al. (2007) conducted a 7 year experiment to understand the effect of estrogens on wild fish populations and found that chronic exposure of fathead minnows to low concentrations of EE2 led to feminization (intersex) of male fish and

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altered oogenesis, i.e., creation of egg cells, in females causing a near extinction of this fish from a lake.

The Endocrine Society published the following position statement: “Evidence for adverse reproductive outcomes (infertility, cancers, malformations) from exposure to EDCs is strong, and there is mounting evidence for effects on … thyroid, neuroendocrine, obesity and metabolism, and insulin and glucose homeostasis” (Diamanti-Kandarakis et al., 2009). While, according to Wise et al. (2011) and Caldwell et al. (2010), risks to human health from EE2 at the present concentration levels in drinking water appears to be minimal, Touraud et al. (2011) state that there is no consensus among scientific community about these risks. An EU-funded research programme concluded that “The contribution of drinking water to the exposure of humans toward EE2 seems to be very low. However, since EE2 is one of the most potent synthetic estrogenic compounds unintentional exposure of the population, especially developing embryos or pre-pubertal boys and girls, should strictly be avoided” (Wenzel et al., 2003).

Human exposure to EDCs could occur via two potential pathways: consumption of water or consumption of fish which have accumulated PACs through bioaccumulation (Caldwell et al., 2010; Khanal et al., 2006). Both pathways indicate the urgent need for removing pharmaceuticals and EDCs from surface water which is used for human consumption.

Kim et al. (2007) conducted full and pilot scale experiments to understand the efficacy of different water treatment technologies in removing pharmaceuticals and EDCs from surface water and wastewater. They found that conventional drinking water treatment such as coagulation and sand filtration and conventional wastewater treatment (WWT), e.g., activated sludge, are inefficient for removal of these compounds. Instead, they suggested Granulated Activated Carbon (GAC) and Microfiltration (MF) with Reverse Osmosis (RO) or Nanofiltration (NF) due to their high removal rate. Koh et al. (2008) also mentioned these technologies for the removal of EDCs at wastewater treatment plants. Filby et al. (2010) found that there are likely benefits of applying GAC and ClO_2 for wastewater treatment with an efficiency of removal ranging between 70 and 100% for total estrogenicity and 53–100% for individual steroid estrogens. Chong et al. (2012) assessed advanced oxidation technologies that remove EDCs after conventional wastewater treatment. Most research deals with EDCs' removal by means of conventional water treatment methods, while practically no research has been published on the development of membrane technologies for micropollutant (such as hormones and other endocrine disrupting chemicals) removal from surface water used for drinking purpose. The latter is the topic of this paper.

In an EU-funded project (Surfuncell, 2012) research has been conducted to modify the surface of a water treatment membrane to ensure safe micropollutant or EDCs removal capability. In this study, we have chosen a hollow fiber nanofiltration membrane due to its high ratio of surface area to volume and due to the avoidance of extensive pre-treatment as required for spiral wound nanofiltration membranes. Cellulose triacetate, referred to as cellulose acetate (CA) throughout this study, has been chosen as membrane material not only due to the interest of the producer to move toward renewable resources but also due to the focus of the Surfuncell project which aims to combine the use of cellulose with new technologies to offer novel solutions. The main research question addressed by this paper is whether the new micropollutant removing membrane system can be environmentally preferable compared to a GAC system and how an eco-friendly configuration of a modified membrane process would look like? We chose the Life Cycle Assessment (LCA) approach due to its systemic nature of analysis. Covering the entire value chain and all relevant impact categories, LCA does not allow shifting the burden from one process step to the other and neither from one impact category to the other. For detailed understanding we refer readers to ISO-14040 (2006) and 14044 (2006) and the European Commission's International Reference Life Cycle Data System (ILCD, 2010).

Hallstedt et al. (2010) have presented an approach for sustainability integration in decision systems for product development. This is a top-down approach focusing on business goals, plans, incentives, decision tools etc. In addition, there is a need for guiding various business functions at the operational level, ensuring successful integration of sustainability in core business. We address this role of LCA in the discussion section.

2. Methods and materials

2.1. *Goal and scope of LCA*

The purpose of this prospective LCA is to determine the environmental impacts of a nanofiltration membrane system coated with enzyme for removal of micropollutants from surface water for drinking water. We compare with the conventional Granulated Activated Carbon (GAC) water treatment to identify improvement opportunities with regard to environmental performance. This study is not a comparative assertion but a comparison which supports decisions in product development, helping to identify a new product configuration and associated processes with low environmental impacts (ILCD, 2010; pp. 140). According to Kim et al. (2007) GAC is commonly applied to remove micropollutants present in surface water. In this study, the conventional GAC system uses activated carbon made from coal and wood.

2.1.1. *Functional unit and technology status*

The functional unit (FU) of this study is the supply of one cubic meter of drinking water with minimized content of micropollutants. The important quality parameters of conventional drinking water filtration systems are pH, alkalinity, hardness, total organic carbon (TOC) and dissolved organic carbon (DOC). In order to ensure comparable water quality regardless of the treatment, we choose carbon usage rate[1] of GAC adsorption that compares with the quality of water treated with a nanofiltration membrane system (Bonton et al., 2011). Micropollutant removal by membrane was proven at laboratory scale (proof of principle), which shows almost complete removal of Bisphenol-A. Performance tests at pilot plant level (i.e. proof of concept) are under preparation. This indicates that the micropollutant removal performance of nanofiltration membrane system could be higher than GAC adsorption reported by Kim et al. (2007).

2.1.2. *Impact categories and methods*

Main environmental indicators studied are Non-Renewable Energy Use (NREU); based on the Cumulative Energy Demand (CED) method and climate change according to the IPCC 2007 GWP 100a method (Hischier et al., 2010). Other impact categories are covered using the ReCiPe (v1.05, July 2010), midpoint impact assessment method with hierarchist perspective and European normalization factors (Goedkoop et al., 2009). For modeling the life cycles, we used SimaPro v7.3.0, with ecoinvent v2.2 database for background data.

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[1] The carbon usage rate (CUR) determines the rate at which carbon will be exhausted and how often carbon must be replaced/regenerated.

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