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# Life cycle assessment as development and decision support tool for wastewater resource recovery technology

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ABSTRACT

Life cycle assessment (LCA) has been increasingly used in the field of wastewater treatment where the focus has been to identify environmental trade-offs of current technologies. In a novel approach, we use LCA to support early stage research and development of a biochemical system for wastewater resource recovery. The freshwater and nutrient content of wastewater are recognized as potential valuable resources that can be recovered for beneficial reuse. Both recovery and reuse are intended to address existing environmental concerns, for example, water scarcity and use of non-renewable phosphorus. However, the resource recovery may come at the cost of unintended environmental impacts. One promising recovery system, referred to as TRENS, consists of an enhanced biological phosphorus removal and recovery system (EBP2R) connected to a photobioreactor. Based on a simulation of a full-scale nutrient and water recovery system in its potential operating environment, we assess the potential environmental impacts of such a system using the EASETECH model. In the simulation, recovered water and nutrients are used in scenarios of agricultural irrigation-fertilization and aquifer recharge. In these scenarios, TRENS reduces global warming up to 15% and marine eutrophication impacts up to 9% compared to conventional treatment. This is due to the recovery and reuse of nutrient resources, primarily nitrogen. The key environmental concerns obtained through the LCA are linked to increased human toxicity impacts from the chosen end use of wastewater recovery products. The toxicity impacts are from both heavy metals release associated with land application of recovered nutrients and production of $AlCl_3$, which is required for advanced wastewater treatment prior to aquifer recharge. Perturbation analysis of the LCA pinpointed nutrient substitution and heavy metals content of algae biofertilizer as critical areas for further research if the performance of nutrient recovery systems such as TRENS is to be better characterized. Our study provides valuable feedback to the TRENS developers and identifies the importance of system expansion to include impacts outside the immediate nutrient recovery system itself. The study also show for the first time the successful evaluation of urban-to-agricultural water systems in EASETECH.

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## 1. Introduction

Sustainability in the urban water cycle is increasingly at the forefront of discussions on new treatment technologies due changes in climate, population, and regulation (Guest et al., 2009). Wastewater resource recovery and reuse is one area where technology is responding to the need for pollution prevention and resource efficiency. Wastewater (also referred to as used water – Verstraete et al., 2009) technology development has traditionally been compliance-driven, designed to meet safety and discharge regulations. During conventional treatment, nutrients – notably nitrogen and phosphorus – are biologically and physical–chemically converted and removed from the water. Increasingly, the freshwater and nutrient content of wastewater are recognized as resources that can be recovered to address existing environmental concerns (e.g. water scarcity, use of non-renewable phosphorus) (Guest et al., 2009). However, resource recovery may come at the cost of increased treatment intensity and there is a need to assess

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treatment systems from a holistic systems perspective so that the quest for sustainability in the water cycle does not overshadow other environmental concerns (Mo and Zhang, 2013; Batstone et al., 2014).

TRENS is a wastewater resources recovery technology currently under development (Valverde-Pérez et al., 2015b), which combines an enhanced biological phosphorous removal and recovery (EBP2R) system (Valverde-Pérez et al., 2015) with a downstream photobioreactor (PBR) to cultivate green microalgae under optimal growth conditions. The system recovers both water and nutrient resources from wastewater, with the nutrients being taken up and encapsulated by the algal biomass. This water and algae suspension can then be used together (for combined irrigation and fertilization, otherwise referred to as fertigation) or individually if the algae are harvested through solid–liquid separation. The coupled system is a completely biological process that is less chemical and energy intensive than conventional physical–chemical phosphorus removal processes – e.g. struvite precipitation, ultrafiltration (Valverde-Pérez et al., 2015), thereby reducing the water and energy demand of traditional algae cultivation (Clarens et al., 2010).

In recent years, Life Cycle Assessment (LCA) has been used in environmental assessment of urban water systems (Loubet et al., 2014), including wastewater specific studies (Corominas et al., 2013; Zang et al., 2015). Moreover, LCA has been used in understanding environmental trade-offs in optimizing specific treatment technologies such as ozonation (Rodríguez et al., 2012). Recent wastewater related LCA studies for technology development include coupled wastewater treatment for microalgae biofuel production (Rothermel et al., 2013) and nutrient removal and recovery from anaerobic digestion supernatant (Rodriguez-Garcia et al., 2014). Both of these studies report the need to expand the system boundaries to include the wastewater treatment plant (WWTP) when evaluating wastewater technologies and emphasize the need to consider options at a plant level rather than at a unit process level. One of the challenges of LCA is delineating the system boundary since they vary widely, with some studies limited to the WWTP and others encompassing the entire urban water system (Corominas et al., 2013; Zang et al., 2015). The environmental performance of WWTPs is largely dependent on effluent discharge and sludge application on land (Hospido et al., 2004, 2012; Foley et al., 2010), although plant performance can be affected by influent composition, plant size, and local climate (Lorenzo-Toja et al., 2015). Furthermore, the sludge and solids stream of wastewater treatment accumulates beneficial and problematic compounds (e.g. phosphorus and heavy metals) that need to be included in LCA (Yoshida et al., 2013). Therefore, any environmental assessment of a novel wastewater technology needs to include life cycle boundaries that encompass the end use of water and nutrients.

This is the first study related to LCA-supported technology development that accounts not only for the WWTP, but also the larger system, which includes the urban-rural water connection and end-use of recovered water and nutrients. This broader system boundary is particularly necessary in view of the development objectives of TRENS, which is to provide an efficient resource recovery technology. An LCA carried out in the early development phase of TRENS provides a diagnostic opportunity: a chance to identify environmental impacts that may be roadblocks to developing and marketing a sustainability-focused technology. Moreover, the LCA results become documentation for sustainability that can iteratively follow TRENS throughout its development, optimization, and ultimately implementation.

The study objectives are (1) to demonstrate the use of LCA in the early research and development phase of a new wastewater process by quantifying its environmental performance using accepted impact categories; (2) to provide a first assessment of the environmental impacts of the TRENS system and (3) to use LCA results to provide feedback for additional research by identifying further areas of interest and data needs. The TRENS performance is assessed in three scenarios based on the Lynetten WWTP in Copenhagen. The scenarios were chosen to ensure an evaluation that captures the necessary infrastructure additions, operational changes, and reuse options.

## 2. Materials and methods

### 2.1. Framing a context for water and nutrient recovery

Copenhagen and its surrounding municipalities are supplied entirely by groundwater. HOFOR, the local water utility, supplies approximately 50 million $m^3$ annually to 1 million residents in the area. A high percentage of Danish households (>85%) are connected to the sewers, meaning a large portion of the distributed water resource can be recaptured (Hochstrat et al., 2005). The Lynetten WWTP serves a catchment area of 76 $km^2$ of the central and North–East sections of Copenhagen (Flores-Alsina et al., 2014) and treated 59.3 million $m^3$ in 2012 (Lynettefællesskabet I/S). In the existing Lynetten WWTP, the effluent is discharged and mixed into the sea water of Øresund. Through the treatment process, nitrogen resources in the wastewater are converted to free nitrogen gas and lost to the atmosphere, while phosphorus is lost to the sludge and subsequently incinerated. In the WWTP, excess phosphorus that is not taken up in the biologically process is removed through chemical precipitation using iron (III) chloride ($FeCl_3$).

The groundwater resource surrounding Copenhagen is overexploited due to abstraction for drinking water. Henriksen et al. (2008) reported an estimated deficit of 77 million $m^3$/year for the Northern-Zealand area, which encompasses Copenhagen. However, the refinement in spatial resolution can change results of water stress evaluations by 10–53% (Hybel et al., 2015). In this context, wastewater reuse presents a valid opportunity to ameliorate the local groundwater resource deficit related to the Northern-Zealand area. In particular, there is an opportunity to collect water from the high-use urban area and return it to the rural groundwater abstraction areas.

Regulatory standards of treated wastewater reuse for irrigation or aquifer recharge are not specifically addressed by existing European Union (EU) policies, although there is an on-going effort to identify appropriate policies and encourage reuse (EC, 2012). Treated wastewater is most commonly reused for non-potable purposes such as irrigation of non-food crops or crops requiring further processing (Bixio et al., 2006). This restricted use is due partly to the public's perceived risks from wastewater and partly to the lack of formal regulatory frameworks (Bixio et al., 2005; Chen et al., 2012). The implications of water quality, and therefore treatment needs, for scenario design is presented in Section 2.3.

### 2.2. TRENS process addition to existing WWTP

The TRENS system was included in this study as a side-stream process, where a portion of the influent wastewater at the Lynetten WWTP was diverted, while the remainder passed through existing conventional treatment (Fig. 1). The new side-stream system was designed to treat 10% of WWTP influent flow, which is approximately 5.9 million $m^3$/yr or 16,247 $m^3$/d. This flow rate is in excess of the reported local agricultural demands for irrigation water (2.1 and 0.93 million $m^3$/yr for Zealand and the Capital Region, respectively, covering 2561 $km^2$ in total). However, it is possible that irrigation values are underestimated since the total is based on self-reported water use from only 22% of the farms

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