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Life Cycle Assessment as Decision Support Tool For Development Of Resource Recovery Technology

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Summary of key findings

In a novel approach, we use life cycle assessment (LCA) to support early stage research and development of a biochemical system for wastewater resource recovery (TRENS system, (12). To this end, we combined the use of conventional activated sludge models (ASM-2d, (8); ASM-A, (12)) with environmental assessment models (EASETECH, (2)). The chosen scenario in the LCA study considers TRENS as a side-stream process implemented in a full-scale wastewater treatment plant (WWTP) in Copenhagen, Denmark. TRENS reduces global warming up to 15% and marine eutrophication impacts up to 9% compared to conventional treatment. This is due to the TRENS system's lower greenhouse gas emissions, as well as nutrient recovery. The key environmental concerns obtained through the LCA are linked to increased human toxicity impacts from the chosen end use of TRENS products. The toxicity impacts are from heavy metals release associated with land application of recovered wastewater nutrients. Our study provided valuable feedback to the TRENS developers and identified the importance of system expansion to include impacts outside the immediate biological system of TRENS itself.

Background and relevance

LCA is increasingly used in the wastewater field. At the same time, there is growing recognition that wastewater resources can be reused to address existing environmental concerns (e.g. water scarcity). One promising resource recovery process, referred to as TRENS (Wágner et al., 2015), consists of an enhanced biological phosphorous removal and recovery (EBP2R) system (11) coupled to a photobioreactor (PBR) to cultivate green microalgae. TRENS recovers both water and nutrient resources, with the nutrients being taken up and encapsulated by algal biomass. The water and algae suspension can be used together (for combined irrigation and fertilization, referred to as fertigation) or individually if the algae are harvested through solid-liquid separation. TRENS is a biological process that is less chemical and energy intensive than conventional physical-chemical phosphorus removal processes (e.g. struvite precipitation), thereby reducing the water and energy demand of traditional algae cultivation (1).

We use LCA as a development tool to identify bottlenecks of the TRENS process from an environmental perspective, so TRENS developers can improve process design and focus ongoing research. The study objectives are to i) demonstrate the use of LCA in the early research phase of a new technology, ii) provide a first assessment of the environmental impacts of the TRENS system and iii) use LCA results to provide feedback for additional research by identifying areas of interest and data needs.

In order to assess TRENS performance, this study uses the Lynetten WWTP in Copenhagen as a basis for comparison. TRENS is included as a side-stream process, where 10% (approximately, 16000 m3/d) of the influent wastewater is diverted, while the remainder passes through existing conventional treatment. The end use considered for the recovered resources is fertigation.

The LCA is performed using EASETECH (DTU, Denmark) software that allows heterogeneous materials handling and flow tracking at the substance level essential for evaluating environmental technologies (2). The study boundary starts from the WWTP influent, and extends to cover the WWTP itself, the TRENS process, transportation of the treated water in a pressurized pipeline, and fertigation. Construction and operating phases are included in the scope of analysis. In the operating phase, direct emissions (e.g. gas and effluent) and indirect emissions (e.g. from chemical production) are included. The functional unit is 1 m3 of influent wastewater with the same composition as reported by Lynettefællesskabet I/S (9). Life cycling inventory data is collected from operating reports for existing processes, databases, and modeling studies using activated sludge models (ASM-2d, (8); ASM-A, (12)). Background inventory data is obtained through the Ecoinvent LCA database (6). This study uses the life cycle impact assessment method recommended by the International Reference Life Cycle Data System (3,4). Further details of the applied methodology can be found in Fang et al. (5).

Results and discussion

For the existing Lynetten WWTP, the two impact categories of ecotoxicity (ETox) and marine eutrophication (ME) are the highest at 3.1 and 1.0 milli-person equivalents (mPE), respectively. This is primarily due to the discharge of treated effluent to the sea. Nitrate in the effluent contribute most to the ME category, while the heavy metals in the effluent (mainly zinc and copper) contribute to the ETox category. Global warming at 7.8×10-2 mPE (GWP) is the third highest category. The largest contributor to this impact is energy consumption during WWTP operation (67%), followed by emissions of N2O during treatment (18%), emissions during incineration (11%), and methane leaks during biogas collection at the anaerobic digester (4%). All impact categories except one are within the same order of magnitude as an LCA study of Copenhagen WWTP Avedøre (13). The results suggest that the status quo model provides a reasonable representation of a large, centralized WWTP consistent with literature values of other wastewater LCA studies.
Following TRENS implementation, changes from the baseline are on the order of 0 to 0.20 mPE per m3. The small changes are partly due to design of the side-stream system. Since only 10% of the influent water passes through TRENS, the impacts are dominated by 90% of the flow passing through the WWTP. The dominating effect of the mainstream processes is also reported in Rodriguez-Garcia et al. (10), where they found that side-stream process impacts were negligible, particularly in the categories of GWP and AC. However, it is important to present the side-stream as part of the WWTP so that impacts can be viewed in context of the whole system.
In the fertigation scenario, the same main WWTP processes contribute to the impacts. However, the use-on-land process now plays a large part in the toxicity impacts, emphasizing the need for system expansion beyond the resource recovery technology itself. The largest changes occur in the ME, ETox, and human toxicity cancer- (HTc) and non-cancer (HTnc) categories. Overall, the reduced impacts result from two main processes: (1) reduced flow through WWTP secondary treatment leading to less N2O emissions, and (2) offset mineral fertilizer production. Increases in environmental impacts were mainly due to four processes: i) land application of algal suspension, ii) TRENS system energy use, iii) pipeline energy use, and iv) emissions from increased biogas combustion. The largest change from the baseline (+0.19 mPE, +290%) is in HTnc category, result of heavy metals application to soil from the treated effluent. The other toxicity categories (ETox and HTc) are similarly affected by the heavy metals. There is a decrease in ME from the baseline (-9.2e-2 mPE, -9%), which is due to the avoided discharge nitrate to the sea. GWP impacts are reduced by 15% (1.2e-2 mPE) due to lower emissions of N2O from the WWTP, since the diverted water does not undergo nitrogen removal, the main source of N2O. For TRENS developers the interest would be to characterize emissions from the PBR, as there are studies suggesting N2O is generated during algae cultivation (7).
The study evaluated the relative importance of construction and operation phases of the system. Several impacts categories (TE, ME, POF, ETox, HTc, and RD) that are dominated by the operating phase for the WWTP, are instead dominated by the construction phase for TRENS and the pipeline. The differences are due to higher use of plastic materials in PBR and pipeline construction, suggesting that alternative technologies may be more sustainable (e.g. open ponds). The results illustrate the variability of life cycle phase contributions to environmental impacts.

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