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Evaluation of new alternatives in wastewater treatment plants based on dynamic modelling and life cycle assessment (DM-LCA)

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ABSTRACT

With a view to quantifying the energy and environmental advantages of Urine Source-Separation (USS) combined with different treatment processes, five wastewater treatment plant (WWTP) scenarios were compared to a reference scenario using Dynamic Modelling (DM) and Life Cycle Assessment (LCA), and an integrated DM-LCA framework was thus developed. Dynamic simulations were carried out in BioWin® in order to obtain a realistic evaluation of the dynamic behaviour and performance of plants under perturbation. LCA calculations were performed within Umberto® using the Ecoinvent database. A Python™ interface was used to integrate and convert simulation data and to introduce them into Umberto® to achieve a complete LCA evaluation comprising foreground and background processes. Comparisons between steady-state and dynamic simulations revealed the importance of considering dynamic aspects such as nutrient and flow peaks. The results of the evaluation highlighted the potential of the USS scenario for nutrient recovery whereas the Enhanced Primary Clarification (EPC) scenario gave increased biogas production and also notably decreased aeration consumption, leading to a positive energy balance. Both USS and EPC scenarios also showed increased stability of plant operation, with smaller daily averages of total nitrogen and phosphorus. In this context, USS and EPC results demonstrated that the coupled USS + EPC scenario and its combinations with agricultural spreading of N-rich effluent and nitritation/anaerobic deammonification could present an energy-positive balance with respectively 27% and 33% lower energy requirements and an increase in biogas production of 23%, compared to the reference scenario. The coupled scenarios also presented lesser environmental impacts (reduction of 31% and 39% in total endpoint impacts) along with effluent quality well within the specified limits. The marked environmental performance (reduction of global warming) when nitrogen is used in agriculture shows the importance of future research on sustainable solutions for nitrogen recovery. The contribution analysis of midpoint impacts also showed hotspots that it will be important to optimize further, such as plant infrastructure and direct N_2O emissions.

1. Introduction

Nowadays, Wastewater Treatment Plants (WWTPs) are facing ever stricter regulations with respect to the environment and human health, and are also beginning to be considered as sources of material and/or energy, obtained by recovering nutrients such as nitrogen (N) and phosphorus (P), and through biogas production.

The collection of separate wastewater flows (e.g. urine, faeces, kitchen and bathroom wastewater) at their source could allow the recovery of nutrients thanks to the distinct composition of these flows. In this sense, there is a particular interest in urine, which represents less than 1% of the total volume and only 14% of total organic carbon (TOC) but 88% of total Kjehldahl nitrogen (TKN) and 57% of total phosphorus (Larsen and Gujer, 1996).

Urine can be treated with magnesium in order to form struvite ($MgNH_4PO_4$. $6H_2O$), a slow-release fertilizer (Maurer et al., 2006). In addition to the possibilities of recovery, urine separation can decrease the energy consumption in WWTPs through a reduction in the needs for N-removal besides the decrease in consumption of

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chemicals used for P-elimination. Another important feature of urine separation is the avoidance of ammonia peaks, which increases operating stability and allows plant size to be reduced (Rauch et al., 2003).

Additionally, if less organic matter is needed for denitrification, more organic matter can be dedicated to anaerobic digestion, which helps to turn the energy balance of WWTPs into a net positive energy (production of surplus of energy). Accordingly, Flores-Alsina et al. (2014) proposed the enhancement of total suspended solids (TSS) removal in the primary clarifier, which led to a higher chemical oxygen demand (COD) for the digestion and consequently more biogas production.

The negative feature of WWTPs is the generation of various (direct) forms of pollution through gas emissions, and effluent and sludge discharge into the environment. Moreover, the utilization of energy and chemicals by the plant is responsible for indirect environmental burdens due to the production of these utilities. The environmental performance of different WWTP configurations can be evaluated by the Life Cycle Assessment (LCA) method (ISO 14040/44, 2006). While the Life Cycle Inventory (LCI) of background processes can be obtained from databases, the foreground process inventory is usually obtained by data collection at the plant. An alternative to data collection is modelling and simulation – a very useful tool when predictive results or ecodesign proposals are sought (Méry et al., 2013).

Numerous LCA applications have been published for different WWTP configurations and a state of the art has been drawn up by Corominas et al. (2013a). Yoshida et al. (2013) have published an LCA review of sewage sludge management and the environmental performance of WWTPs with nutrient recovery. However, the studies reviewed, mostly based on site data collection for LCI, cannot be used for outlining general trends or for process optimization, because of the great number of parameters, possible scenarios and treatment objectives.

Foley et al. (2010) used steady state simulation results obtained with Biowin® for a systematic evaluation of the life cycle inventories of ten scenarios in 6 WWTP configurations. The results showed that the quantity of infrastructure materials needed and the consumption of chemicals increased when lower N and P concentrations were imposed in the effluent, as did energy consumption and GHG emissions in N-limiting effluent scenarios. Flores-Alsina et al. (2014) used dynamic simulation applied to an extended version of BSM2 (Benchmark Simulation Model N°2) to calculate the greenhouse gases (GHGs) emitted on site and the amounts of energy and chemicals produced, with the aim of evaluating control/operating strategies. These authors also showed the importance of considering both water and sludge lines when analysing GHG emissions and pointed out the considerable environmental impact of N_2O emission.

Rémy (2010) analysed eight impact categories when comparing alternative systems using pilot projects and literature data. The study showed that separation systems presented important benefits, although eutrophication and acidification were more increased by agricultural disposal of liquid fertilizers. The study also highlighted the importance of optimizing alternative treatment systems. Tillman et al. (1998) studied the impact of possible source separation systems in two regions in Sweden compared to existing conventional treatment systems. Their results showed that the urine separation scenario presented the lowest environmental impact (e.g. nitrogen emissions to surface water were reduced). Björklund et al. (2000) studied several treatment options and concluded that nutrient recycling could reduce the net impact, even though nutrient spreading could raise the acidification impact. They also highlighted the importance of ancillary systems for the environmental analysis.

To the best of our knowledge, none of these studies proposed an effective integration of process dynamic modelling and complete LCA. Such integration requires adapted modelling and evaluation tools, able to capture the influence of process parameters and dynamics in the impact calculation results. In this sense, some elaboration complexities and limitations involved are related to the fact that, as WWTPs are constantly subjected to flow and load perturbations, dynamic aspects should be taken into account in the aim of achieving relative robustness in operational conditions in any situation, ensuring stability and the correct operation of the plant. Also, as LCA is traditionally a non-dynamic methodology, an interface between dynamic modelling results and inventory flows in LCA is required, together with the conversion of specific inventory items (in order to obtain compatible units for inventory flows).

Lastly, considering the whole WWTP system means taking account not only of the benefits and drawbacks of coupled water and sludge lines but also of all background processes such as disposal of by-products, consumption of energy and chemicals, and transport.

Until now, the benefit of alternative wastewater management with urine separation has been estimated by a few studies with emphasis on the agricultural utilization of urine. However, a urine separation scenario has never been evaluated through whole plant modelling coupled with urine treatment (such as struvite precipitation and nitritation/deammonification with *Anammoxidans* bacteria) by a DM-LCA analysis.

So, the goal of the present study is to obtain reliable, predictive LCA results (mutually interconnected with the process parameters and dynamics) for reference and alternative scenarios in WWTPs. The alternative scenarios consider urine source-separation followed by urine treatment, and enhanced precipitation in the primary clarifier. This study also aims to identify possible benefits and drawbacks of alternative systems so that they can be further optimized as conventional systems have already been. To achieve this, a DM-LCA framework was developed for the predictive evaluation of global performances, coupling dynamic simulation results and environmental evaluation.

2. Materials and methods

2.1. The integrated DM-LCA methodology

As mentioned above, the integration of the dynamic modelling approach and LCA tools is a prerequisite when trying to analyse the total environmental footprint of a WWTP system.

The DM-LCA approach developed here used three different platforms, interconnected as shown in Fig. 1. WWTP scenarios were simulated with BioWin® v4.0.0.976, a Windows-based wastewater treatment process simulator that includes biological, chemical, and physical processes (Envirosim, 2014). The interface between WWTP dynamic modelling and LCA calculations were performed through Python™ scripts.

To achieve the study objectives, model parameters were fixed initially and dynamic influent data was provided to the simulator (Fig. 1 data flow 1). Dynamic simulations were also designed to reach effluent quality limits (e.g. 10 g m^{-3} of total N, 1 g m^{-3} of total P, 35 g m^{-3} of total suspended solids, 100 g m^{-3} of total COD and 4 g m^{-3} of ammonium ion). As a result of the dynamic simulation, process inventories (Fig. 1 data flow 2) were generated with their own inputs and outputs. After the dynamic simulations, Python™ scripts (Fig. 1 data flow 3) integrated the results over the simulation time. All parameter values and examples of calculations can be found in the Supplementary Information document (SI, Section 1).

The results were then converted to an Umberto®-compatible input file for foreground and background processes. Python™