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Assessment of environmental impacts and operational costs of the implementation of an innovative source-separated urine treatment

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ABSTRACT

Innovative treatment technologies and management methods are necessary to valorise the constituents of wastewater, in particular nutrients from urine (highly concentrated and can have significant impacts related to artificial fertilizer production). The FP7 project, ValuefromUrine, proposed a new two-step process (called VFU) based on struvite precipitation and microbial electrolysis cell (MEC) to recover ammonia, which is further transformed into ammonium sulphate. The environmental and economic impacts of its prospective implementation in the Netherlands were evaluated based on life cycle assessment (LCA) methodology and operational costs. In order to tackle the lack of stable data from the pilot plant and the complex effects on wastewater treatment plant (WWTP), process simulation was coupled with LCA and costs assessment using the Python programming language. Additionally, particular attention was given to the propagation and analysis of inputs uncertainties. Five scenarios of VFU implementation were compared to the conventional treatment of 1 m^3 of wastewater. Inventory data were obtained from SUMO software for the WWTP operation. LCA was based on Brightway2 software (using ecoinvent database and ReCiPe method). The results, based on 500 iterations sampled from inputs distributions (foreground parameters, ecoinvent background data and market prices), showed a significant advantage of VFU technology, both at a small and decentralized scale and at a large and centralized scale (95% confidence intervals not including zero values). The benefits mainly concern the production of fertilizers, the decreased efforts at the WWTP, the water savings from toilets flushing, as well as the lower infrastructure volumes if the WWTP is redesigned (in case of significant reduction of nutrients load in wastewater). The modelling approach, which could be applied to other case studies, improves the representativeness and the interpretation of results (e.g. complex relationships, global sensitivity analysis) but requires additional efforts (computing and engineering knowledge, longer calculation time). Finally, the sustainability assessment should be refined in the future with the development of the technology at larger scale to update these preliminary conclusions before its commercialization.

1. Introduction

In the context of circular economy and energy constraints, the treatment of source-separated urine seems very promising to efficiently recover nutrients in the form of fertilizers due to the very high nutrient content of urine (Ishii and Boyer, 2015). Numerous technologies were developed since the 1990s to face this challenge (e.g. Kirchmann and Pettersson, 1995; Koster and Koomen, 1988). In the frame of the project ValuefromUrine (2012–2016), funded by the European 7th Framework Programme and coordinated by Wetsus (www.valuefromurine.eu), an innovative two-step process (Fig. 1) was developed to recover nutrients from urine into valuable products (Zamora et al., 2017). First, struvite crystals are generated from precipitation with magnesium – Mg salt (eliminating phosphorous – P). Then, a microbial electrolysis cell (MEC) aims at recovering nitrogen – N by transforming ammonium contained in

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urine into volatile ammonia, as a result of electron transport between the two electrodes of the cell through bacteria catalysis. The volatilized ammonia is recovered as ammonium sulphate via transmembrane chemisorption with sulfuric acid. This new recovery technique aims at mitigating chemical and energy demand compared to common ammonia stripping. The technology, hereafter called VFU (Value From Urine), was installed and tested at the pilot scale to pre-treat male urine from an office building (collected from water-free urinals) in Leeuwarden (the Netherlands).

New processes should comply with sustainability principles where generated benefits compensate implementation costs. The life cycle assessment (LCA) methodology (ruled by ISO 14040/44, 2006) was used by several authors to compare the environmental performances of urine separation systems with conventional wastewater systems. Tillman et al. (1998), Maurer et al. (2003), Benetto et al. (2009) and Spångberg et al. (2014) focused on the direct urine application after storage. Other studies included urine treatment technologies: oxidation (Remy, 2010), struvite precipitation (Ishii and Boyer, 2015; Bisinella de Faria et al., 2015), as well as ion-exchange treatment (Landry and Boyer, 2016). All these studies showed potential benefits of urine separation systems, thanks to flushing water savings, lower efforts at the waste water treatment plant (WWTP) and mineral fertilizer substitution, but with some trade-offs between impact categories. The economic impacts are evidently important. To that respect, the conclusions from the few available studies (Landry and Boyer, 2016; Ishii and Boyer, 2015; Berndtsson, 2006) diverge.

For both environmental and economic assessments, scholars underlined issues related to data quality and uncertainty, limiting the validity of the conclusions. In particular, the consequences of urine separation in the WWTP were modelled with quite basic assumptions, either using the ecoinvent database tool (Doka, 2009) or empirical ratios for energy/chemicals consumption. In a few LCA studies of wastewater treatment (Foley et al., 2010; Flores-Alsina et al., 2010; Corominas et al., 2012, 2013), simulation tools (BioWin, IWA Benchmark Simulation Model or WEST®) were used to compute the life cycle inventory (LCI) of the processes, in steady state or dynamic conditions. This approach was followed by Bisinella de Faria et al. (2015) to better represent the effects of urine source-separation by coupling dynamic modelling (BioWin model) and LCA (Python interface embedded in Umberto® software).

This study aims at assessing the environmental consequences following the prospective market penetration of the VFU technology within a sewage network in the Netherlands, taken as test bed case for the project. To this end, the coupling approach of Bisinella de Faria et al. (2015) was adapted to investigate the consequences on wastewater treatment and extended by integrating operational cost calculations and characterising and analysing result uncertainties. The specific objectives of the study are: i) to couple process-based simulation with LCA and operational cost calculations, ii) compare the sustainability performances of different scenarios for VFU implementation and iii) discuss the interests and limitations of the modelling framework and results.

2. Material and methods

2.1. Goal and scope of the study

The study focuses on the consequences of the implementation of the VFU technology within a sewage network of 50,000 population equivalents (PE) in the Netherlands, which represents a common network size (EEA, 2016). A consequential LCA approach was therefore adopted to identify the possible direct and indirect changes induced by urine source separation, following the market-based perspective of Weidema (2003). VFU-based scenarios were founded on common strategies for urban wastewater management, specifying objectives of urine separation, and were further compared with conventional centralized wastewater treatment (*Reference* scenario, i.e. a business as usual situation). *SVFU* scenario corresponds to the decentralized pre-treatment of urine (as done for the pilot plant). Several VFU units would be installed in sufficiently large buildings (e.g. office buildings, concert halls) to pre-treat 10% of urine volume from the WWTP inflow. The second implementation option, called *LVFU*, would be to install a larger VFU unit as pre-treatment in the centralized WWTP. In that case, the urine collected at buildings would be transported by trucks to the plant, which would pre-treat 50% of urine inflow. While 10% urine separation (*SVFU* scenario) was predicted to have no influence on the WWTP design, the *LVFU* scenario could modify it due to the significant decrease of nutrients load. Three scenarios were therefore added in the comparison analysis (see section 2.3.3. for detailed description of the processes): i) simple redesign without post-denitrification and adapted tank volumes (*LVFU-SR* scenario); ii) adjunction of primary sedimentation tank (*LVFU-PST* scenario); and iii) adjunction of enhanced primary clarification with anaerobic digestion of the sludge (*LVFU-EPC-AD* scenario).

The functional unit chosen was the treatment of 1 m^3 of wastewater, of which 10% and 50% of urine volume was treated separately by VFU technology for *SVU* scenario and *LVFU-based* scenarios, respectively. While all the scenarios are compared based on the same inflows (volume and quality of wastewater and urine streams generated by 50,000 PE in the Netherlands), the

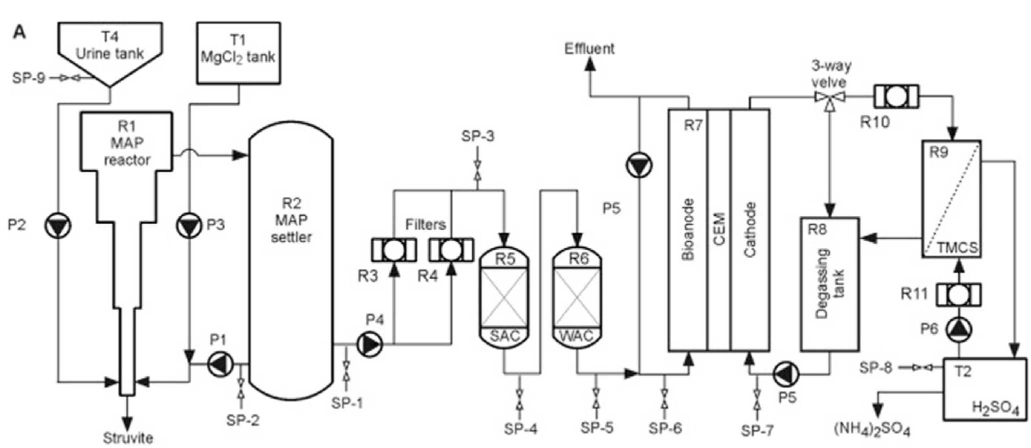

Fig. 1. Flow scheme diagram of the VFU pilot system (from Zamora et al., 2017).