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Comparison of development scenarios of a black water source-separation sanitation system using life cycle assessment and environmental life cycle costing

Charles Thibodeau*, Frédéric Monette, Mathias Glaus

STEPPE—Experimental Station in Environmental Pilot Processes, École de technologie supérieure, Construction Engineering Department, 1100 Notre-Dame West Street, Montreal, Quebec, Canada H3C 1K3

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ABSTRACT

The objective of the study is to compare different development scenarios of a black water source-separation sanitation system (BWS) that could be environmentally and economically more viable than a conventional system (CONV). Scenarios performance is evaluated using life cycle assessment and environmental life cycle costing. System boundaries include the processes related to the collection and treatment of wastewater and organic kitchen refuse collection and the recycling of by-product (digestate/sludge and biogas) produced in the treatment step. The BWS scenario that entails a vacuum toilet flow-volume reduction to 0.5 L/flush results in significantly higher performances than the ones of CONV for the climate change and resources indicators, while involving a significantly lower performance with regards to human health and a comparable cost. The BWS scenario based on digestate mass reduction with reverse osmosis and acidification prior to its transport to farmland achieves comparable performances to the ones of CONV for all indicators. The BWS scenario with digestate treatment by means of phosphorus precipitation (struvite) and nitritation–anammox reactors gives performances that are comparable to the ones of CONV for all indicators, with the exception of climate change, for which this scenario has a significantly lower performance if the electricity is produced by hydropower. When single-pathway scenarios are combined, the multi-pathway scenarios thus created can produce results that are significantly superior to the CONV result for the climate change, resources and human health indicators although the cost remains comparable.

1. Introduction and objective

During the past decades, municipal wastewater sanitation system development has focused mainly on increasing the level of treatment of various pollutants in order to meet increasingly restrictive wastewater discharge standards. This end-of-pipe approach, even though it resolves acute hygiene and aquatic environment-related problems, does not act preventatively to control the generated wastewater at the source and does not foster resource recycling (Otterpohl, 2002). Wastewater sanitation systems thus usually involve using large quantities of potable water for collection, necessitate complex treatment processes since the different streams of residential wastewater are mixed, and have a limited potential with respect to recycling wastewater constituents.

As alternatives to conventional systems (CONV), many approaches based on the source-separation of the residential wastewater streams, the integration of water, wastewater and (organic) waste systems and resources recycling have been introduced (Wilderer, 2001). One of these approaches is the source-separation of black water (urine, faeces and flush water) and grey water (bathroom, kitchen and laundry water) in the collection of wastewater (Otterpohl et al., 1999). The black water source-separation system (BWS) can be found in various technical system configurations in a few small-scale demonstration and proposed projects (Augustin et al., 2013; Otterpohl, 2002; Peter-Frohlich et al., 2007; Zeeman et al., 2008). In many system configurations, the black water is collected by a vacuum system (1 L/flush) and then treated in an anaerobic digester together with organic kitchen refuse. The grey water is collected by gravity and treated either in a constructed wetland, a membrane bioreactor (allowing water reuse) or in a conventional activated sludge process. Among

* Corresponding author. Tel.: +1 514 396 8800x7499.
E-mail address: charles.thibodeau.1@ens.etsmtl.ca (C. Thibodeau).

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many digestate handling approaches, the digestate is often directly recycled (without dewatering) as agricultural fertilizer in order to recover most of the nutrients.

With the aim of comparing the economic and environmental performance of such source-sanitation systems, different assessment frameworks are available. With regards to environmental performance assessment, two types of framework are mostly used: (1) specific resource and emission flows analysis (e.g. energy use, nutrient recovery, water use, exergy, etc.) (Balkema et al., 2002) and (2) life cycle assessment (LCA) (Corominas et al., 2013). While the specific resource and emission flows analysis provides useful information regarding the system's environmental performance, the LCA method aims at assessing the potential environmental impacts of a product system (goods and services) from cradle to grave (the entire value chain) (Hellweg and Milà i Canals, 2014). Related to wastewater treatment, LCA has been applied in more than 40 studies in international peer-reviewed journals (Corominas et al., 2013). Among the several economic assessment frameworks available, life cycling costing (LCC) is a method commonly used to capture all relevant costs related to a product or service over its life cycle (U.S. General Services Administration, 2012). In the literature, some LCC studies have been applied to wastewater treatment systems (e.g. Rebitzer et al., 2003; Lim et al., 2009; Glick and Guggemos, 2013). Ultimately, the combination of LCA and LCC in a common framework enables enhancing the relevance and the completeness of the decision-making process and showing the relation between additional cost and the environmental impact avoided over the entire system lifecycle (Jolliet et al., 2010; Schmidt, 2003). Such an LCC that is meant to be combined with an LCA is generally referred to as an “environmental LCC”, where the LCC expresses the cost with the same functional unit, system boundaries and actor perspective as the LCA (Hunkeler et al., 2008b).

Some studies have aimed at comparing the environmental and economic performance of BWS that includes the direct recycling of digestate with CONV. From the European demonstration project for the separate discharge and treatment of urine, faeces and grey water (Peter-Frohlich et al., 2007), an LCA and an LCC comparing various source-separation systems with CONV were performed. The LCA showed notably that BWS uses less primary energy, has fewer potential impacts on climate change but more on acidification than CONV (Remy, 2010); the LCC conclusion is that BWS costs 3.9% more than CONV (Oldenburg, 2007). An LCA and an environmental LCC conducted under Canadian conditions showed that BWS posts higher environmental impact scores than CONV regarding climate change, human health, ecosystem quality and resources indicators (Thibodeau et al., 2014), and additional costs (+33% to +118%) according to implementation scales (Thibodeau et al., 2011). Conducting a substance-flow analysis, Tidåker et al. (2006) showed that BWS yielded a lower global warming potential and higher nutrient recovery in agricultural use, but found higher primary energy consumption and acidification compared to CONV. From the previous studies, three key factors (processes) have been identified as influencing the environmental and economic performance of BWS that includes the direct recycling of digestate: (1) the flush volume of the vacuum system (Thibodeau et al., 2011); (2) the digestate transport distance to farmland; and (3) the digestate application method (Remy, 2010; Thibodeau et al., 2014; Tidåker et al., 2006).

Concurrently, a few studies were performed on BWS that includes digestate mass reduction prior to agriculture recycling as an alternative to the direct digestate recycling approach. Using a specific resource flow analysis framework, Zeeman et al. (2008) showed the benefits of BWS with recovery/removal of digestate nutrients, which considerably limits the mass of fertilizer to be applied on farmland. Implemented in a new housing estate in Sneek in the Netherlands, this BWS entails energy savings, phosphorus recycling in the form of struvite for agriculture, and potential reusable water as compared to CONV. With a substance-flow analysis, Hellstrom et al. (2008) showed that a BWS that reduces the digestate mass by means of reverse osmosis (concentrate to be reused in agriculture) results in lower global warming potential, higher nutrient recovery and lower eutrophication potential, but higher acidification potential than CONV. Based on her previous work (Tidåker et al., 2006), Tidåker (2007) suggested assessing the environmental performance of a source-separation system based on irrigation of the energy crop by dilute sewage products (e.g. black water). To our knowledge, no life cycle study was undertaken on such a black water irrigation system.

The previous studies presented the environmental or the economic performance of BWS based on direct recycling or BWS digestate mass reduction as compared with CONV. Except for the LCC from Oldenburg (2007) and the LCA from Remy (2010) that assessed one common BWS scenario within the same system boundaries, no other studies use both LCC and LCA to compare BWS and CONV. Moreover, none compare the two digestate handling approaches. Hence, from a system developer point of view, evidence is lacking as to which BWS configuration—with particular focus on the digestate handling approach—would be the most promising one to develop further in order to minimize both the environmental impact and cost. With regards to the BWS based on direct recycling of digestate, key processes have been identified, but the levels of efficiency they must achieve in order that BWS performance equals that of CONV for environmental and economic indicators have not been determined. These levels would allow setting critical targets in the development of BWS based on direct recycling of digestate. Moreover, the environmental and economic performance of various BWS based on digestate mass reduction must be assessed since few performance results are provided in the literature. A global comparison of BWS development scenarios based on direct recycling of digestate and digestate mass reduction could then be performed to identify the most promising development scenarios. It would also be appropriate to assess some scenario combinations that can likely occur through an integrated development of BWS.

This study aims to compare single and combined BWS development scenarios based on direct recycling of digestate (key process improvement) and digestate mass reduction in order to determine which ones have the lowest potential environmental impact scores and cost compared to those of CONV.

2. Methods

The life cycle assessment (ISO 14040, 2006; ISO 14044, 2006) is used to assess the environmental performance of sanitation systems under analysis. To assess their economic performance, the environmental life cycle costing method is used (Hunkeler et al., 2008a; Swarr et al., 2011).

2.1. Goals and scope

The main goal of this study is to identify the BWS single-pathway and multi-pathway development scenarios that most minimize the environmental impact scores and cost compared to those of CONV. In order to achieve this, four secondary goals are being pursued: (1) evaluate BWS development pathways based on direct recycling of digestate and determine the efficiency levels of key processes that enable BWS to equal the performance of CONV; (2) evaluate BWS development pathways based on digestate mass reduction; (3) compare single-pathway scenarios, i.e. those that