Journal of Cleaner Production 67 (2014) 45–57

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Comparison of black water source-separation and conventional sanitation systems using life cycle assessment

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ARTICLE INFO

Article history:
Received 10 June 2013
Received in revised form
26 November 2013
Accepted 6 December 2013
Available online 21 December 2013

Keywords:
Black water
Source-separation system
Wastewater management
Digestate management
Environmental impacts
Life cycle assessment

ABSTRACT

The municipal sanitation system based on black water source-separation (BWS) is often advanced as a viable environmental alternative to conventional systems (CONV). However, current studies have not led to any formal conclusions on the environmental advantage of such a system. The objective of this study is to compare the environmental performances of BWS and CONV in terms of environmental damage using the life cycle assessment method. The functional unit is to ensure wastewater and kitchen refuse collection and treatment and by-product (digestate/sludge and biogas) recycling for one inhabitant for one year. The results show that BWS generates higher impact scores than CONV: 100%, 89%, 24% and 25% more for the human health, ecosystem quality, climate change and resources indicators, respectively, when metal emission impacts from fertilizers are excluded. If metal emission impacts were accounted for the conclusions are reversed for human health and ecosystem quality. The exclusion of metal emission impacts from fertilizers for the interpretation of the results is based on acknowledged overestimation and high degree of uncertainty of (eco)toxicity impacts by existing assessment methods. However, even with such exclusion, the impact scores of both systems for the ecosystem quality indicator are still not significantly different because of the large contribution of metal emissions from the background data, which still remained in the inventory. Depending on the grid mix and organic fertilizer transport distance assumptions, the study conclusions may be inverted for the climate change and resources indicators, since BWS may obtain lower impact scores than CONV. The main contributors to BWS impact scores are ammonia emissions from applied digestate and digestate management (transport, storage and spreading). Suggestions for significant enhancements are required for BWS to attain better environmental performances than CONV.

1. Introduction and objective

Municipal wastewater sanitation aims to remove pollutants in order to comply with wastewater regulations. To achieve this, treatment processes requiring significant amounts of materials, chemicals and energy for their construction and operation are implemented. These processes do not generally target the reuse of wastewater constituents.

Many researchers advocate a paradigm shift in order to improve the overall performances of sanitation systems: wastewater content (water, organic matter and nutrients) should not be considered as pollutants but rather as resources that should be recycled (Larsen, 2011; Otterpohl, 2002; Zeeman et al., 2008). Various approaches that integrate this new paradigm have been proposed as alternatives to the conventional sanitation system (CONV). One of these approaches is the black water source-separation system (BWS), which consists of the separation of black water (urine, faeces and flush water) from grey water (bathroom, kitchen and laundry water) in the wastewater collection. Among many handling options, black water can be treated with organic kitchen refuse in an anaerobic digester producing biogas and a digestate that is reused, with or without further treatment, on farmland as a substitute for synthetic fertilizers. Grey water can be treated by a constructed wetland or a more conventional treatment (aeration and chemical precipitation) according to the discharge or reuse pathway. Such a BWS has been implemented in the 200-inhabitant

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http://dx.doi.org/10.1016/j.jclepro.2013.12.012

Flintenbreite real estate project in Lübeck, Germany (Otterpohl, 2002). Project promoters cited the low energy and material intensity of the infrastructure, the reduction in tap water demand and the agronomical benefits of the digestate to demonstrate the advantages of the new approach.

A life cycle assessment (LCA) aiming to assess the environmental advantages and drawbacks of various sanitation approaches demonstrated that a BWS with a constructed wetland for grey water treatment yielded fewer potential impacts than CONV for primary energy, climate change, human toxicity, terrestrial and aquatic ecotoxicity and greater impacts for aquatic eutrophication and acidification (Remy, 2010). However, the authors also pointed out that the extended scope used in the study, which included kitchen refuse in the reference flows, favored the BWS over CONV because of energy considerations (Remy and Jekel, 2012). Indeed, taking kitchen refuse into consideration leads to less energy consumption by BWS since the kitchen refuse is converted into biogas during anaerobic digestion (with black water), while CONV involves treatment by composting with no energy recovery. Concurrently, a material and energy flow analysis by Meinzinger (2010) showed that a BWS with a membrane bioreactor for grey water treatment had a higher primary energy demand than CONV, even considering the anaerobic digestion of kitchen refuse for BWS and their composting for CONV. However, the analysis also found that BWS lead to lower tap water consumption and higher nutrients recycling potential towards farmland. A substance-flow analysis conducted by Hellstrom et al. (2008) concluded that BWS with a conventional treatment for the grey water and a reverse osmosis treatment for the digestate obtains higher nutrient recovery (total amount of N/P/K), lower eutrophication potential, lower global warming potential, but higher acidification potential than CONV which treats organic waste by incineration. Another substance-flow analysis showed similar results, but found a higher primary energy consumption for BWS with conventional treatment of grey water and no digestate treatment compared to CONV including composting of organic waste and sludge (Tidåker et al., 2006).

These results showed that both BWS and CONV have specific advantages and disadvantages but do not enable sanitation sector decision-makers (designers, service providers and government authorities) to reach any formal conclusions on the environmental advantage of either system. Indeed, depending on the impact indicators considered, one system may appear to be better than the other but the relative significance of these impact indicators when compared to each other is not given. It is then difficult for the stakeholders to make decisions when trade-offs exist between different impact categories (e.g. accepting a higher eutrophication level in order to reduce climate change or acidification impacts).

The objective of this study is to compare the environmental performances of BWS and CONV in terms of damages (endpoint level) in order to be able to mediate the trade-offs and facilitate decision-making when designing and assessing the systems.

2. Methods

The study is conducted using the life cycle assessment (LCA) method, as defined by ISO 14040 and 14044 (2006).

2.1. Goals and scope

The goals of the study are to 1) assess the environmental performances of BWS and CONV over their entire life cycles; 2) conduct a contribution analysis of each system process; and 3) test the robustness of the results through an uncertainty analysis and a sensitivity analysis. The study is aimed at designers (engineers, urban planners, etc.), service providers and government authorities involved in sanitation. The study results are therefore presented at the damage level, which allows using a lower number of more relevant environmental indicators (human health, ecosystem quality, climate change and resources impacts) than the problem level (usually around 15 different indicators such as eutrophication, toxicity, etc.) and as such makes decision-making easier.

The functional unit is "to ensure wastewater and kitchen refuse collection and treatment and by-product (digestate/sludge and biogas) recycling for one inhabitant for one year". Digestate and sludge are recycled on farmland as organic fertilizers. The biogas from the anaerobic digestion of effluent or sludge is used in a boiler to produce hot water. Hence, the functions provided by the by-products, which are considered useful products that have positive economic value, are included in the system boundaries following the system expansion method (ISO 14044, 2006). To establish the functional equivalence between the systems, processes (synthetic fertilizers and hot water) are then added to the system that does not perform by-product recycling to the same level as the other.

The scope of the study includes all of the foreground and background processes pertaining to the collection, treatment and recycling of reference and intermediate flows and those related to the added processes (Fig. 1). Resources and emissions life cycle inventory data (extraction, production, manufacturing and operation) were compiled for each system process. The dismantling phase is excluded, along with the mass and energy flows considered similar for both systems (e.g. toilet, washing device, kitchen refuse collection and transport, etc.).

This study is based on a hypothetical model in which the existing systems (CONV) and the new system (BWS) are scaled for a new 50 000-inhabitant settlement and operated over a 50-year period. The settlement is located in the Montreal area (province of Quebec, Canada). Population density is set at 50 inhabitants per hectare. The amounts and composition of the reference flows used in this study represent the Canadian context (Table 1), although the composition is comparable to those of other industrialized nations. Both systems discharge effluent with similar contaminant concentrations, in compliance with Canadian performance standards (CCME, 2009). Other residual domestic flows (rainwater, garden refuse, etc.), and business and industry effluents are not considered, since they are managed independently without any effect on the studied systems.

2.2. Description of the systems

The technological configuration of BWS is mainly based on the Flintenbreite sanitation system in Lübeck, Germany (Otterpohl, 2002), and the configuration of CONV represents a generic system, which includes a wastewater treatment plant (WWTP) with extended nutrients removal (Remy, 2010). Both systems are designed to best fit Quebec (Canada) context.

BWS consists of separate collection routes for black water, grey water and kitchen refuse (Fig. 1). From a one-liter per flush vacuum toilet, black water is forwarded to the treatment building by a vacuum system and low-pressure pump. Kitchen refuse is transported by truck and dumped into a shredder in the treatment building. Black water and shredded kitchen refuse go into a pre-treatment, which includes a grinder and a pasteurizer and then through an anaerobic digester. Biogas is first scrubbed and then burnt in a boiler producing hot water. The hot water is used to heat the pre-treatment and treatment equipment, and the remaining hot water is used by nearby businesses. Digestate from the anaerobic digester is sent and stored on farmland without dewatering in order to preserve a maximum amount of nutrients. This digestate management approach is also justified since dewatering could only be carried out with the implementation of an additional process