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Conceptual environmental impact assessment of a novel self-sustained sanitation system incorporating a quantitative microbial risk assessment approach

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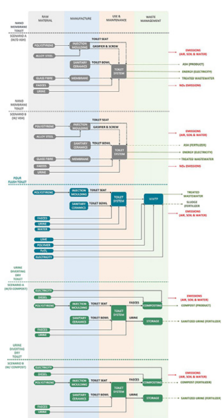
HIGHLIGHTS

- Detailed LCA study is conducted for novel toilet system, Nano Membrane Toilet (NMT).
- Pour Flush Toilet (PFT), Urine Diverting Dry Toilet (UDDT) and the NMT are assessed.
- LCA study has been coupled with QMRA analysis for Human Health Impact Category.
- Under traditional LCA, the UDDT demonstrates a better environmental performance.
- Incorporating QMRA the NMT system performs better against the human health impact.

GRAPHICAL ABSTRACT



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ABSTRACT

In many developing countries, including South Africa, water scarcity has resulted in poor sanitation practices. The majority of the sanitation infrastructures in those regions fail to meet basic hygienic standards. This along with the lack of proper sewage/wastewater infrastructure creates significant environmental and public health concerns. A self-sustained, waterless "Nano Membrane Toilet" (NMT) design was proposed as a result of the "Reinvent the Toilet Challenge" funded by the Bill and Melinda Gates Foundation. A "cradle-to-grave" life cycle assessment (LCA) approach was adopted to study the use of NMT in comparison with conventional pour flush toilet (PFT) and urine-diverting dry toilet (UDDT). All three scenarios were applied in the context of South Africa. In addition, a Quantitative Microbial Risk Assessment (QMRA) was used to reflect the impact of the pathogen risk on human health. LCA study showed that UDDT had the best environmental performance, followed by NMT and PFT systems for all impact categories investigated including human health, resource and ecosystem. This was mainly due to the environmental credits associated with the use of urine and compost as fertilizers. However, with the incorporation of the pathogen impact into the human health impact category, the NMT had a significant better performance than the PFT and UDDT systems, which exhibited an impact category value 4E + 04 and 4E + 03 times higher,

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respectively. Sensitivity analysis identified that the use of ash as fertilizer, electricity generation and the reduction of NOx emissions were the key areas that influenced significantly the environmental performance of the NMT system.

1. Introduction

Provision of sanitation facilities which meet the international baseline standards (UNICEF and WHO, 2017), constitutes a major problem in developing world. In particular, in sub-Saharan African countries only 28% of the population were reported to have access to at least a basic sanitation service in 2015 (UNICEF and WHO, 2017). This situation is compounded by the lack of proper sewerage and the poor operation and maintenance of the domestic faecal sludge management facilities (Wang et al., 2014). Existing sanitation practices in the majority of developing countries rely mainly on on-site waste treatment approaches (African Water Facility, 2014; Nyenje et al., 2010; Wang et al., 2014), including flush and waterless latrines connected to pit or septic tanks as a basic treatment of the waste (Huuhtanen and Laukkanen, 2009; Kjellén et al., 2011). Depending on the deployment, the waste can be a sludge with mixed urine and faeces, or source separated urine and faeces. In the case of faecal sludge, on-site treatment involves mainly solid-liquid separation by sedimentation in the septic tank and the subsequent filtration of the effluent into the ground (Brikké and Bredero, 2003; Orner and Mihelcic, 2018; Tilley et al., 2014). The remaining solids are degraded under anaerobic conditions for a period of 6 months to 10 years to produce a nutrient-rich humus (Schönning et al., 2005). Source separation of urine can be achieved by waterless systems through a specific user interface design. In this case, urine is sanitized in a storage tank and faeces are composted in a dehydration vault for a minimum period of 6 months (Tilley et al., 2014). Based on the scientific literature, after the treatment period both products can be used as organic fertilizers in local fields, provided that proper sanitization is attained (Andersson, 2015; Karak and Bhattacharyya, 2011; Kirchmann and Pettersson, 1995; Petersens and Beck-friis, 2012). However, although the social acceptability of their use in agriculture varies considerably among the developing countries (Moilwa, 2007; Mugivhisa, 2015), in this environmental study the given products have been considered scientifically acceptable, similarly to other relevant LCA studies (Kulak et al., 2017; Remy and Jekel, 2008; Flores et al., 2009).

Although, these conventional sanitation methods have been established in developing countries for many years, in practice they often fail to meet the design standards and operation requirements recommended by WHO. As a result, they pose significant human health risks and environmental concerns. To exemplify, a sanitation sustainability survey conducted in South Africa showed that 28% of the examined toilet systems was inadequately functional, while negligence of proper maintenance and operation of the pits was generally observed (Dwaf, 2012). According to another study that examined the challenges linked to the provision of a sustainable sanitation in Kigali city in Rwanda, odour and insect issues accounted for the second and fourth most common problems faced during the use of existing sanitation systems (Tsinda et al., 2013), and the difficulty in cleaning the toilet facility was perceived as the third major concern. In addition, there has been evidence that improper design and use of the pit latrines, due to both human and environmental factors, can facilitate the transmission of pathogens to the groundwater (Graham and Polizzotto, 2013; Nyenje et al., 2013; Pickering et al., 2012; Stenström et al., 2011). As the importance of a safely managed sanitation system has been highly emphasized as a prerequisite of social and economic welfare (UNICEF and WHO, 2017), such indications need to be taken into earnest consideration and measures to improve existing sanitation, waste and wastewater management infrastructures in developing countries need to be deployed.

A novel approach towards the provision of a sustainable sanitation in the developing countries has been proposed by Cranfield University in the context of the Bill & Melinda Gates Foundation's "Reinvent the Toilet Challenge" (Hanak et al., 2016; Onabanjo et al., 2017, 2016a, 2016b). The design and operating principle of the waterless Nano Membrane Toilet (NMT), is to incorporate into a single system the on-site combustion of human faeces and the purification of urine by membrane separation. The system benefits from the safe in-situ waste management which generates clean water and energy as valuable by-products, with the latter being recovered for meeting household power needs. The NMT technology is in its early stage of development and its efficacy at an end-user level has not yet been fully assessed. However, proceeding at this stage, with an *ex-ante* environmental appraisal of the system life cycle is likely to yield critical insights into its relative performance compared to established technologies and, in turn, into the potential areas of further optimization.

The majority of the life cycle assessment studies on sanitation technologies reported in literature explore primarily the environmental performance of the waste and wastewater treatment techniques employed in different toilet systems, excluding the life cycle of the latter systems (Flores et al., 2009; Friedrich et al., 2009; Remy and Jekel, 2007; Roux et al., 2011; Thibodeau et al., 2014). More precisely, Benetto et al. have carried out a comparative life cycle assessment (LCA) study of the EcoSan (Ecological Sanitation) concept, and the conventional wastewater treatment facilities for the case of Luxembourg (Benetto et al., 2009). Results have demonstrated an outperformance of the EcoSan system over small-scale conventional plants. Remy and Jerel, (Remy and Jekel, 2008) have evaluated the environmental impact of source separation sanitation systems and conventional sanitation systems, i.e. connected to sewage treatment plant, in the context of an urban settlement in Germany. Based on their research findings, certain source separation methods manifest a better profile over the conventional wastewater treatment for selected impact categories. Only a few studies have assessed the environmental impact of different toilet systems -flush, composting, pit latrine and source-separating toilets-, either on a standalone basis (Kohler Co, 2014) or along with the involved waste and/or wastewater activities (Anand and Apul, 2011; Devkota et al., 2013; Gao et al., 2015; Kulak et al., 2017). Although the aforementioned studies provide important views on the environmental performance and relative competitiveness of existing sanitation alternatives, a new approach to the life cycle assessment of such systems is proposed by incorporating the health risks linked to pathogen exposure. To elaborate, the results of the quantitative microbial risk analysis (QMRA), widely employed in the appraisal of drinking water quality and the respective health risks (Fuhrimann et al., 2016; Petterson and Ashbolt, 2016; WHO, 2016), have been coupled with the LCA results in order to incorporate the pathogen risk into the environmental impact of wastewater management systems on human health (Dong et al., 2017; Harder et al., 2016, 2015, 2014; Kobayashi et al., 2015). Such holistic approach has not been yet applied in the environmental assessment of the contemporary sanitation systems. This knowledge gap is likely to be filled by the present research work which aims at providing a comprehensive environmental assessment of the Nano Membrane Toilet (NMT) against the established on-site unsewered sanitation technologies in the context of South Africa, with the view to identifying areas of potential improvement of the NMT system which is still in the development phase. The conventional technologies selected for this study are the pour flush and the urine-diverting-dry toilet systems. In order to evaluate the given technologies on a fair basis, the conventional ones have been considered to be