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Research paper

An environmental life cycle assessment (LCA) of the optimisation of decentralised wastewater treatment systems (DEWATS) in the eThekwini Municipality, South Africa

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Sanitation in South Africa faces numerous challenges and new technologies are needed to cater for the country's growing population. One such technology, showing potential in other developing countries, is DEWATS (decentralized wastewater treatment systems). This research investigated the environmental performance and optimisation potential of DEWATS in the local context by employing life cycle assessment (LCA) methodology to 3 possible scenarios. These were defined as (i) a 'typical' flush water system, (ii) a reduced flush water system and (iii) a reduced flush water system with urine separation and struvite production to replace a commercial fertiliser. LCAs were performed and the construction and operation of all three systems were modelled. The SimaPro LCA software was employed and 18 different environmental impacts were evaluated by following the ReCiPe midpoint method. This resulted in an environmental profile for each system enabling comparisons. The water consumed for sanitation is the highest single contributor to environmental burdens in all three systems and reducing the amount of toilet flush water not only saves a scarce resource but also decreased most other environmental burdens. The best overall environmental performance was achieved by the system with reduced flush water and the separation and processing of urine to a fertiliser. The use of rainwater for flushing toilets can lead to further improvements for all three systems. When comparing the burdens of the operation of DEWATS with those of their construction, these decrease with the reduction in water consumption, focusing further potential improvements on the materials used in construction. Therefore, this study shows how LCA can be used for local optimisation of DEWATS and guiding further improvements for these systems.

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INTRODUCTION

South Africa, like many developing nations, experiences significant challenges in water and sanitation (DWS, 2025). Access to sanitation is defined as households having a connection to municipal sewers, a septic tank, a ventilated improved pit latrine, or a chemical toilet (DWS, 2025) Overall, such access increased from 68.9% in 2011 to 80.7% in 2022 (Stats SA, 2024). In particular, provinces with large rural communities (like Limpopo and KwaZulu-Natal) have reduced access to sewer networks, with only 32.1% and 55.5% of households connected (Stats SA, 2024). Sanitation access below the national average is also observed in peri-urban areas that are beyond the waterborne service boundaries of local municipalities (DWS, 2025). This backlog has historical roots in Apartheid-era service disparities. More recently, rapid population growth, unregulated urbanisation, and the persistence of informal settlements have further exacerbated sanitation problems (Sutherland et al., 2014 and DWS, 2025).

Local municipalities are experiencing significant challenges in delivering and maintaining sanitation (DWS, 2025). These are wide ranging and include ageing infrastructure contributing to inadequate performance, and the limited adoption of advanced treatment technologies (DWS, 2025). One of the technologies proved locally to have potential to provide sanitation in households not connected to sewers is DEWATS (decentralized wastewater treatment systems) (Arumugam et al., 2023). DEWATS is described as a low operation and maintenance wastewater treatment technology using biological and physical processes (such as anaerobic baffled reactors and/or constructed wetlands) and has minimal to zero energy requirements (Arumugam et al., 2023). Venture et al. (2024) have comprehensively reviewed DEWATS and Fereira et al. (2021) and Varma et al. (2022) undertook local reviews (i.e. for Brazil and India) where DEWATS is seen as a technology that can contribute to solving the sanitation problems of developing countries.

In the eThekwini Municipality (KwaZulu-Natal Province) DEWATS is employed in a pilot plant, which has been serving 84 low-income households since 2014 (Arumugam et al., 2023). Based on this performance and the lessons learned, the municipality decided to use DEWATS in the provision of sanitation in a low-cost housing project called Banana City, which started in 2020 but was delayed due to the Covid-19 pandemic. In addition to typical DEWATS processes (i.e. anaerobic baffled reactor and constructed wetlands), other interventions included the use of low-flush toilets and urine separation at source. This research aimed to use an environmental life cycle assessment (LCA) to evaluate the environmental impacts of DEWATS, both planned and partially implemented, as well as those linked to introducing low-flush toilets and urine separation at Banana City. The initiative also envisioned producing urine-derived fertiliser as a replacement for commercial fertiliser (termed avoided product).

LCAs have been used extensively for water systems, including wastewater treatment (see Loubet, 2014 and Rashid et al., 2023 for reviews) and can assess different options, as well as compare the environmental burdens of the entire life cycle of defined water processes, systems, and/or plants.

LCA evaluates every life cycle phase, from the production of raw materials through manufacture/assembly, distribution, and transportation, maintenance, reuse, and repair, to end-of-life disposal (Howe et al., 2017). In South Africa, LCAs have been applied in the past to various water systems (see Buckley et al., 2011 and Harding et al., 2021 for reviews) including potable water as well as the treatment and recycling of wastewater. More recently LCAs have been employed for the assessment of rainwater harvesting (Maharaj and Friedrich, 2024) and pre-treatment for desalination (Draper et al., 2024). However, none of these local studies investigated DEWATS, and at an international level only a few studies are employing LCA for DEWATS, mainly in comparative research (e.g. Risch et al., 2021 for Europe and Singh et al., 2019 for India). Therefore, this investigation aimed to fill this research gap by evaluating the environmental performance and optimisation potential of DEWATS in the South African context.

CASE STUDY

Banana City, located within the eThekwini Municipality (see Fig. 1), was originally an informal settlement with limited access to water and sanitation. The current development aims to formalise 420 subsidised low-cost housing plots, across a 10 ha area as shown in Fig. 2. During construction, informal residents are temporarily relocated and will be allocated formal housing upon project completion. As the site falls within the waterborne edge, the eThekwini Municipality intends to supply potable water using existing infrastructure. For the provision of sanitation, 2 DEWATS plants were planned (shown in yellow in Fig. 2) at the lowest topographic points of the development. This placement uses gravity for wastewater transport, minimising the need for pumping and energy. DEWATS 01 has an area of approximately 3 700 m^2 and DEWATS 02 approximately 3 600 m^2. The design for the DEWATS plants at Banana City was based on the experience gathered and ongoing research conducted locally at the Newlands Mashu DEWATS pilot plant (see Arumugam et al., 2023) and was undertaken by BORDA (Bremen Overseas Research and Development Association).

The two Banana City DEWATS were designed to treat domestic wastewater that is collected from toilet systems, bathrooms and kitchens. The baseline data presented in Table 1 were considered for the design and were used for the calculation of the initial inputs for the LCAs for this research.

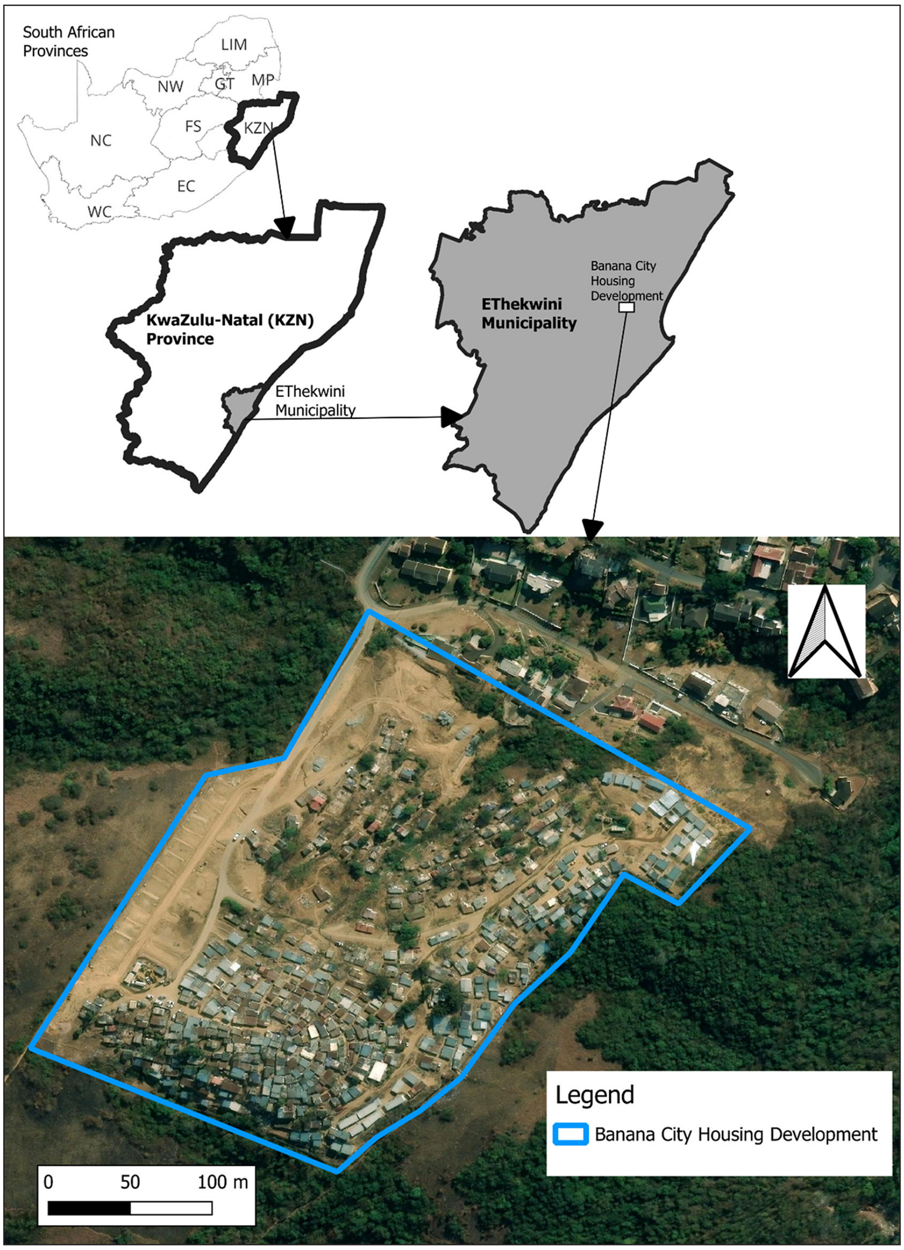

Figure 1. Location of Banana City

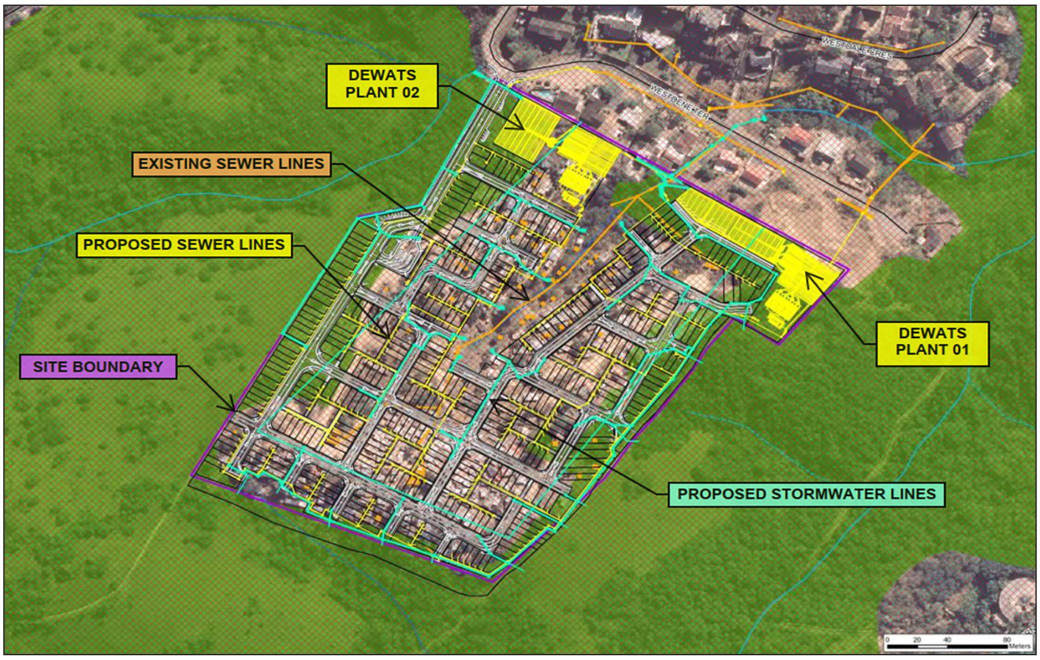

Figure 2. Banana City planned sanitation (adapted from Nelson Allopi & Associates and BORDA, 2018)

Table 1. Baseline data used to design the DEWATS plants at Banana City (Source: Nelson Allopi & Associates and BORDA, 2018)

Banana City: drainage areas			**DEWATS 01**	**DEWATS 02**
Source	**Unit**	**Rate**		
Houses/plot	No.		232	191
No. of people per household (to increase to 8)	No.	5		
People currently served	No.		1 160	995
Extension reserve (considering 8 people per household)	%	60	696	573
Total no. of people served in the future	No.		1 856	1 592
Water consumption	m^3/day	0.1	185.6	159.2
Wastewater generation (accounting for non-return water)	%	85	157.8	135.3
Rain and stormwater ingression	%	15	27.8	23.9
Design base wastewater flow	m^3/day		185.6	159.2

Table 1 shows that 85% of the potable water consumed results in wastewater, with a 15% household-level water loss (e.g. car washing and plant watering). The wastewater system design also incorporates a 15% surface water intrusion. The above values were derived from local research (Nelson Allopi & Associates and BORDA, 2018).

The DEWATS treatment processes/units are screening (to remove detritus), settling chambers for primary sedimentation and flotation, anaerobic baffled reactors (ABRs) and anaerobic filters (AFs) for secondary treatment, and finally the constructed vertical-flow wetlands (VFCW) for tertiary treatment (see Figs 3 and 4). The effluent from both DEWATS plants will be discharged to the existing watercourse; more details on the individual components of the process units are presented in Maharaj (2023).

In Fig. 3, urine-diverting, innovative flush toilets developed by Envirosan Sanitation Solutions (EPS, 2020) are shown. They separate urine and reduce flush water usage from 8 L to 2 L per flush, and were especially designed for rural and peri-urban areas in developing countries (EPS, 2020). Extensive local testing was undertaken (EPS, 2020). Detailed specifications of these toilets are provided by EPS (2020) and Maharaj (2023). The diversion of urine enables nutrient recycling and valorisation, offering multiple environmental and resource management benefits (Sena and Hicks, 2018).

Several urine valorisation methods were investigated, namely, struvite precipitation, nutrification, distillation, and electrolysis. After evaluation, struvite precipitation was identified as the most feasible method for the local context. Therefore, a urine treatment facility was designed to produce struvite (also known as magnesium ammonium phosphate hexahydrate) by precipitation (see Fig. 5) and was incorporated into the project. It will be located adjacent to the DEWATS plants in Banana City.

METHODOLOGY

This study followed an LCA methodology in line with the International Organisation for Standardisation (ISO) 14040 series of standard (ISO, 2006) and its defined four main stages: goal and scope definition, inventory analysis, impact assessment and interpretation.

Goal and scope of the study

The aim of this research was to investigate the environmental impacts associated with DEWATS in the local context and to identify opportunities for improvement. Therefore, the study's target audience are scientists and engineers involved in the development, design and implementation of local sanitation, as well as water authorities at different government levels. The study investigated three DEWATS sanitation scenarios/systems as presented in Fig. 6.

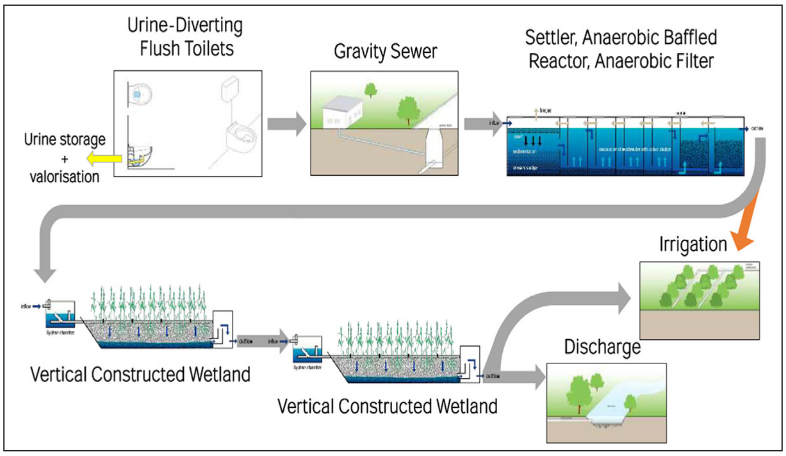

Figure 3. Banana City DEWATS (Nelson Allopi & Associates and BORDA, 2018)

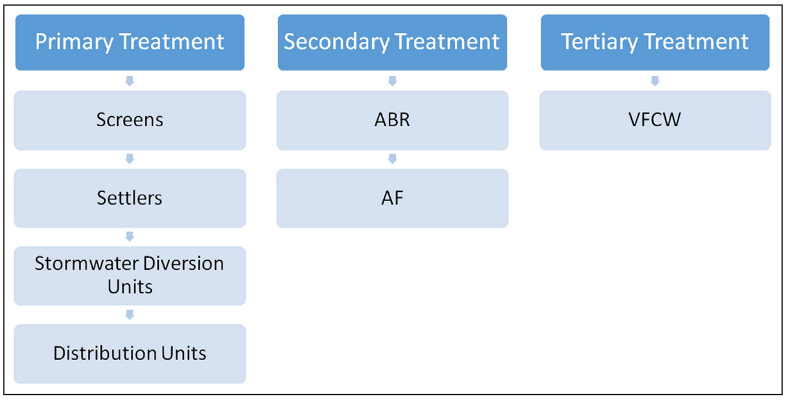

Figure 4. Banana City DEWATS modules (Adapted from Nelson Allopi & Associates, 2018)

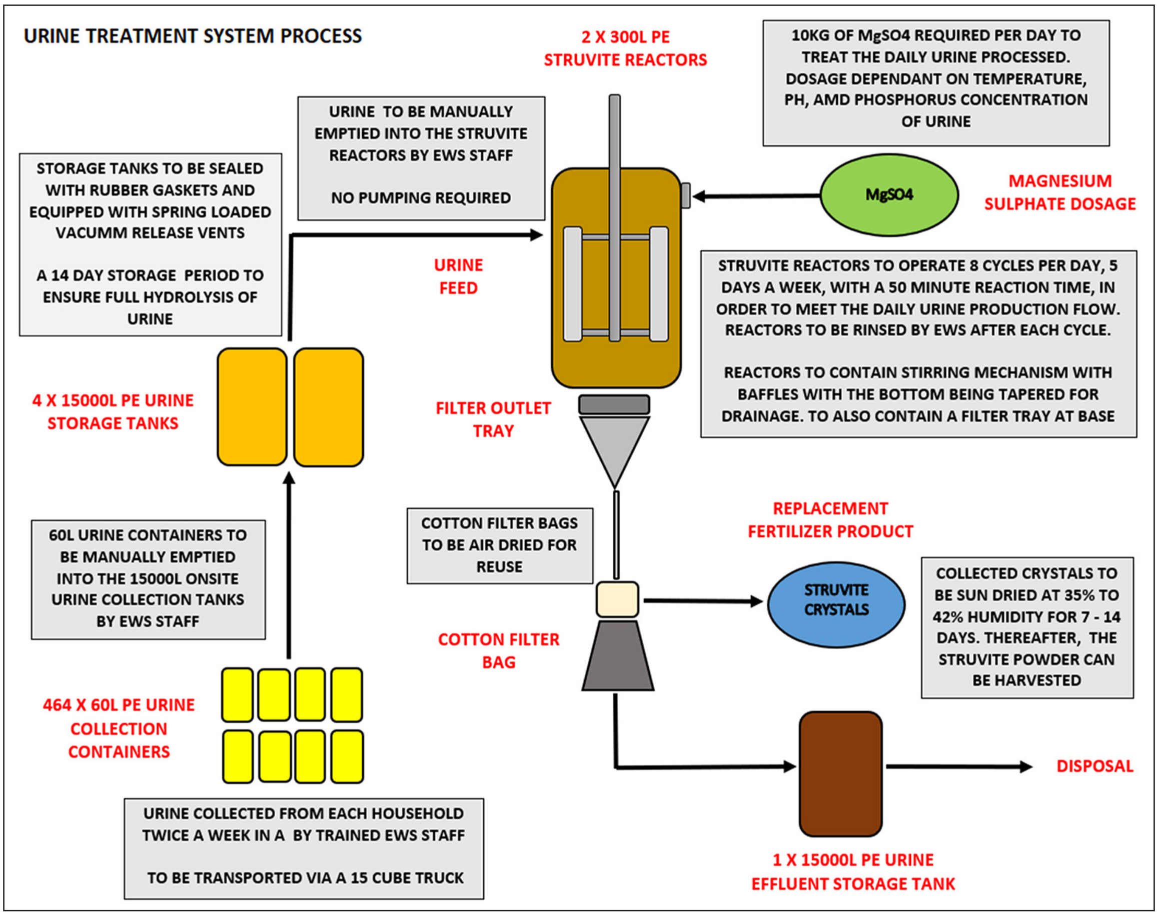

Figure 5. Urine treatment facility for struvite production

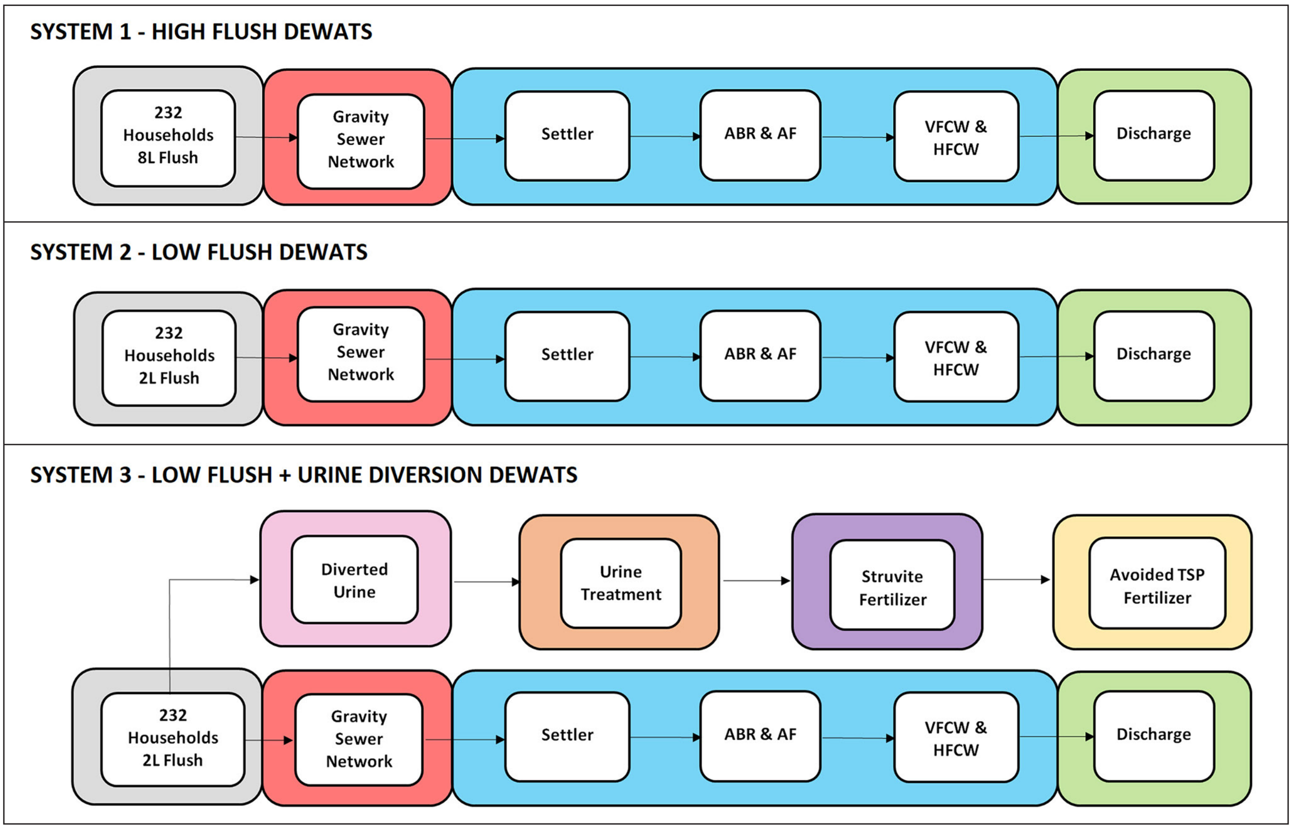

Figure 6. Overview of the three systems defined and investigated

System 1 represents the high-flush DEWATS with a conventional 8 L flush toilet used in all 232 households within the DEWATS 01 area. This system represents the 'typical' South African situation, based on the initial eThekwini Municipality implementation at the Newlands Mashu DEWATS.

System 2 represents the planned Banana City sanitation, using the 2 L low-flush toilets throughout the households within the DEWATS 01 area. This system reflects the situation at the low-cost housing development.

System 3 represents an optimisation of the Banana City DEWATS, which integrates the 2 L low-flush toilets with urine diversion throughout the households within the DEWATS 01 area. It aims to represent a future DEWATS and it includes the production of struvite and subsequent replacement of a commercial fertiliser (i.e. triple-superphosphate (TSP) which is the avoided product).

To enable comparison between the three different systems, a consistent functional unit was defined, namely the provision of sanitation services for the 232 low-income households of the Banana City DEWATS 01 area (see Fig. 2) over a period of 1 year. Since the quality of the wastewater treated in all systems is considered the same and the final effluent conforms to the same output standard, a volumetric functional unit is suitable for this study. Only the DEWATS 01 design was chosen because of the modular nature of both plants and their similarity in terms of processes used, area serviced, topography of catchments and number of households. The selection of this functional unit enabled a baseline reference to which all inputs and outputs were related.

This study followed a simplified LCA approach (called cradle-to-gate), as only the construction and operation life stages were included; the decommissioning stage was left out as its contribution is considered negligible. This is in line with numerous other LCA studies investigating water systems (Loubet et al., 2014; Rashid et al, 2023) and DEWATS in particular (Singh et al., 2019; Risch et al., 2021). To determine the inputs and outputs from the construction and operation stages for the three systems the design of the DEWATS 01 Plant by BORDA was sourced (i.e., System 2 in this study) and similar designs have been developed for Systems 1 and 3. Table 2 summarises the design parameters for all the systems investigated.

Data collection and inventory analysis

A process flow diagram was created for each system with the relevant processes, flows, and materials. These were used to develop inventory spreadsheets, with all material and energy inputs and outputs for each unit process for each system, for construction and operation. Based on the design data, it was possible to perform calculations and quantify inputs for the materials used (e.g. in construction – concrete, bricks, cast-iron manholes, sand and gravel, reinforcing steel, etc.). A similar approach was followed for the operational data which were gathered from various sources (mainly BORDA and the eThekwini Municipality). More details are presented in Maharaj (2023).

In a next step the construction and operational data were scaled to the functional unit and diagrams for each system were produced, as shown in Figs 7, 8 and 9. These figures show the processes included for the LCA of each system and, therefore, individual boundaries of systems. Based on these boundaries (i.e. processes included) each system had an inventory list, which was then inputted for the LCA of that system into the SimaPro software.

The inventory lists for Systems 1, 2 and 3 (scaled for the same functional unit) were used as foreground data, which were then linked and scaled to each of the corresponding process background data from the Ecoinvent database (version v3) contained within SimaPro. For example, the quantity per strength of concrete was totalled from the design of the DEWATS plant (foreground process) and linked with the associated processes (i.e. concrete production linked to cement, aggregate, sand and water production as well as the associated energy needed for the materials and the mixing). The concrete and cement production are background processes, in this case, and the database contains

Table 2. Design data for Systems 1, 2 and 3

Item	Unit	DEWATS 01			
		System 1	System 2	System 3	Reference
System description					
System details	-	Typical DEWATS	Current DEWATS	Optimized DEWATS	Assumption
System example	-	Newlands Mashu DEWATS	Current Banana City DEWATS	Future eThekwini DEWATS	Assumption
System type		High flush	Low flush	Low flush + Urine diversion	Assumption
Replaced/avoided product	-	-	-	Struvite fertilizer	Assumption
Wastewater generation					
No. of households	No.	232	232	232	BORDA
No. of people per household	No.	8	8	8	BORDA
People served	No.	1 856	1 856	1 856	BORDA
Water consumption per person	L/day	140[a]	120[b]	120[b]	Assumption
Total volume wastewater base flow	m^3/day	254[c]	218[c]	215[c]	Calculation
Flush water					
Volume of flush water	L/flush	8	2	2	Assumption
No. of flushes	No.	3	3	3	Assumption
Flush water produced per person	L/day	24	6	6	Calculation
Total volume flush water	m^3/day	45	12	12	Calculation
Urine diversion					
Faeces produced per person	kg/day	0.25	0.25	0.25	Assumption
Urine produced per person	L/day	1.4	1.4	1.4	Assumption
Total volume urine collected + 10% flush water per household	L/day	-	-	16	Calculation
Total urine collected	m^3/day	-	-	3.7	Calculation
Urine-derived fertilizer replacement					
Struvite to replace TSP fertilizer quantity	kg/yr	-	-	9 500	Assumption

a: Calculated high flush scenario water consumption per person per day – see Maharaj (2023)
b: Assumed minimum water consumption per person per day for rural and peri-urban areas in developing countries – see Maharaj (2023), Nelson Allopi & Associates and BORDA (2018)
c: Calculated wastewater flows based on varying water consumption – see Maharaj (2023)

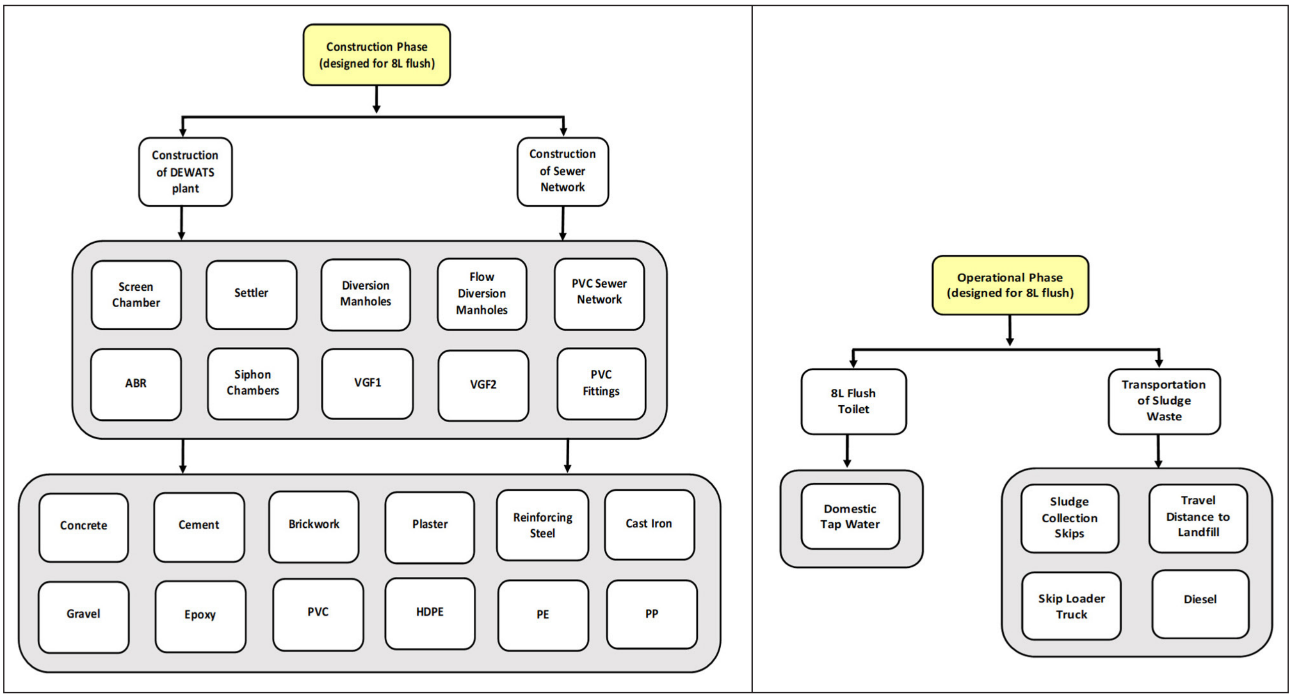

Figure 7. Construction and operation for System 1

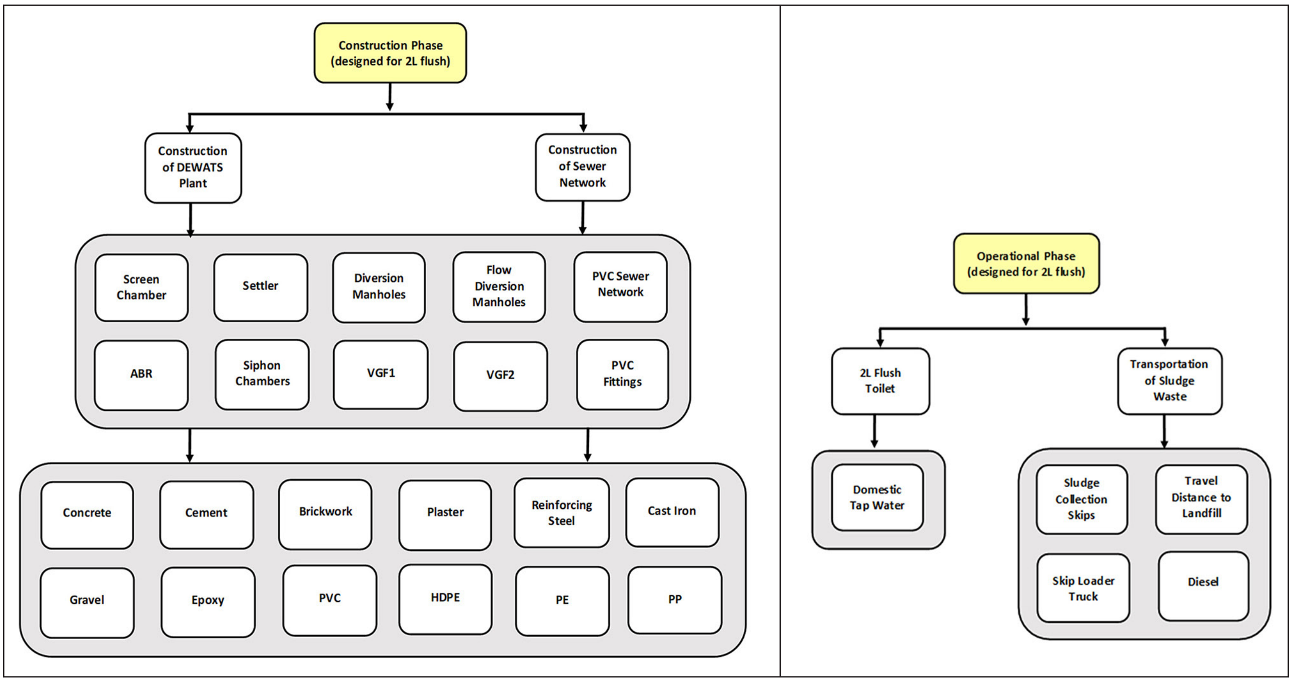

Figure 8. Construction and operation for System 2

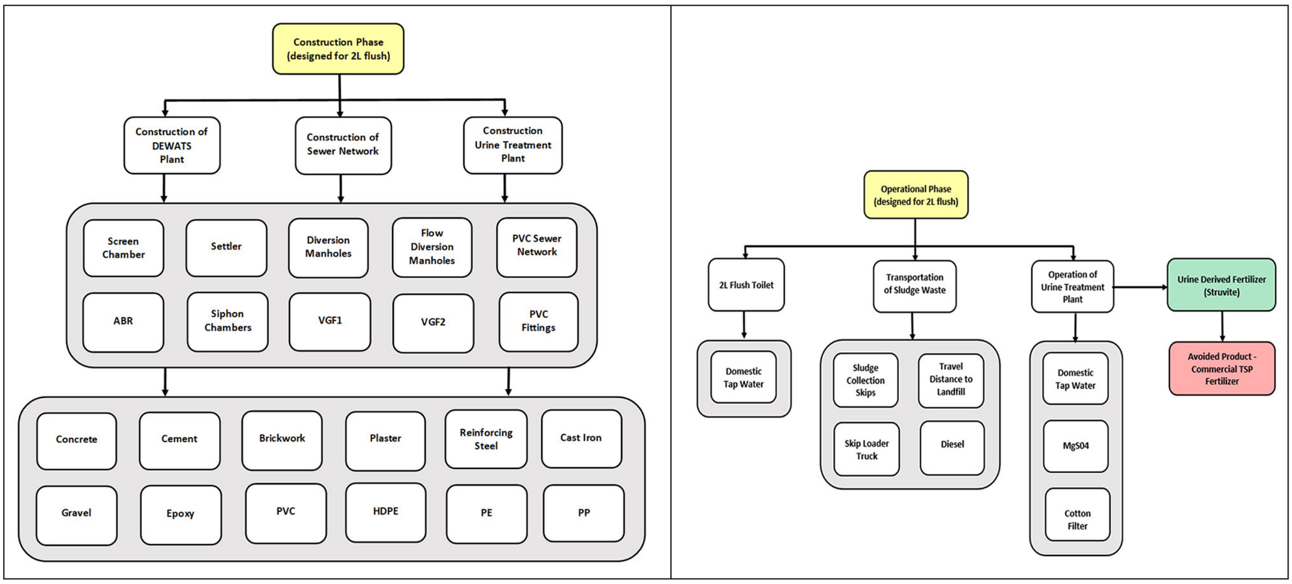

Figure 9. Construction and operation for System 3

all the inputs and outputs linked to their production. This database includes hundreds of inventory data sets available for different sectors and is one of the most extensive LCA database available (Moreno-Ruiz et al., 2020). Ecoinvent also contains South African processes (e.g. electricity production by Eskom) and these have been preferred. When South African data were not available, international data were used, while trying to best match South African conditions. The SimaPro tool, including the Ecoinvent database, is updated at least once a year, enabling the most current data for modelling. It also conforms with the ISO 14040 standard on how to perform an LCA, hence enabling comparison.

LCA impact assessment and the use of SimaPro software

The SimaPro software (PhD version 9.5.0.0) was employed for undertaking individual LCAs for each of the three systems. The inventory inputs and outputs of each system were summarised and their contribution/burdens towards different environmental impact categories were assigned and quantified. The first step in this typical LCA methodology is the classification (i.e. assigning input and output inventory data to pre-defined environmental impacts to which they contribute), and 18 environmental impacts were considered. The second step is the characterisation, which entails the calculation of scores for each environmental impact. Scientifically derived characterisation factors are used for each impact category, allowing the calculation of a single score per impact (Huijbregts et al., 2016). All the scores for all the impacts make up the environmental profile of that system. The characterisation for this study used the ReCiPe, hierarchic (H) midpoint characterisation factors (Huijbregts et al., 2016). This is one of the methodological pathways available in SimaPro and was considered the most appropriate due to relatively low uncertainty of results (PreSustainability, 2016) and wide use in other water-related LCA studies.

Normalisation is the next step and in the standardised LCA methodology it is optional (ISO, 2006), as it transforms an environmental score for an impact category by dividing it by a reference value, resulting in a dimensionless indicator. Pizzol et al. (2017) showed that normalisation is used in LCA studies mainly as a 'plausibility check' to see if the order of magnitude of the results is valid. However, additional uncertainties can be introduced through normalisation due to the choice of the reference values (i.e. normalisation factors). For this study the ReCiPe 2016 normalisation factors were used and all the impact categories linked to toxicity were excluded, due to uncertainty and incompleteness of methodological factors. For this study normalisation was also employed as a plausibility check to increase the confidence in the results from the characterisation.

Interpretation is the last step in an LCA and is mandatory in the standardised LCA methodology (ISO, 2006). In addition to environmental profiles and the order of magnitude of impacts for each system, as part of this study's interpretation, comparative analyses were performed, as well as sensitivity analyses of critical modelling parameters. An improvement analysis which led to recommendations was also undertaken.

RESULTS AND DISCUSSION

Comparative LCA scores for the three systems and the order of magnitude of impacts

Table 3 provides a tabulated summary of the environmental profiles for Systems 1, 2 and 3 for all the environmental impact categories included. The largest environmental burdens are shown by System 1, followed by System 2. System 3 had the lowest overall environmental scores across most of the impact categories. The reductions associated with System 2 and 3 can be traced back to the incorporation of low-flush toilets and urine diversion, as well as utilising urine-derived struvite as a direct replacement/avoided product for a commercial fertiliser (TSP). The negative scores for System 3 represent net environmental savings as opposed to the burdens, which in the LCA methodology are positive.

Table 4 shows the order of magnitude for all three investigated systems for all 18 impact categories. For more details on magnitude calculations see Maharaj (2023).

Table 3. Environmental scores for Systems 1, 2 and 3

Impact category	Unit	System 1 total score	System 2 total score	System 3 total score
Global warming	kg CO_2 eq	2.74×10^4	1.51×10^4	1.00×10^4
Stratospheric ozone depletion	kg CFC11 eq	1.37×10^{-2}	7.50×10^{-3}	6.61×10^{-3}
Ionising radiation	kBq C0-60 eq	1.02×10^3	5.61×10^2	4.00×10^2
Ozone formation, human health	kg NOx eq	8.46×10^1	4.47×10^1	2.76×10^1
Fine particulate matter formation	kg PM2.5 eq	4.86×10^1	2.43×10^1	1.10×10^0
Ozone formation, terrestrial ecosystems	kg NOx eq	8.63×10^1	4.59×10^1	2.86×10^1
Terrestrial acidification	kg $S0_2$ eq	1.33×10^2	6.28×10^1	-4.00×10^0
Freshwater eutrophication	kg P eq	1.05×10^1	4.71×10^0	-3.90×10^0
Marine eutrophication	kg N eq	8.34×10^{-1}	4.23×10^{-1}	1.23×10^0
Terrestrial ecotoxicity	kg 1.4-DCB	5.85×10^4	3.96×10^4	-2.60×10^3
Freshwater ecotoxicity	kg 1.4-DCB	8.44×10^2	4.60×10^2	-6.68×10^2
Marine ecotoxicity	kg 1.4-DCB	1.16×10^3	6.38×10^2	-8.34×10^2
Human carcinogenic toxicity	kg 1.4-DCB	7.14×10^3	4.36×10^3	3.86×10^3
Human non-carcinogenic toxicity	kg 1.4-DCB	2.16×10^4	1.08×10^4	-9.13×10^3
Land use	m^2a crop eq	1.01×10^3	5.94×10^2	7.10×10^3
Mineral resource scarcity	kg Cu eq	2.53×10^2	1.63×10^2	-2.63×10^2
Fossil resource scarcity	kg oil eq	1.02×10^4	6.90×10^3	5.29×10^3
Water consumption	m^3	1.66×10^4	4.21×10^3	3.89×10^3

Table 4. Difference between System 1, 2 and 3 environmental scores

Impact category	Unit	System 2 over System 1	System 3 over System 2	System 3 over System 1	KEY
Global warming	kg CO_2 eq	1.81	1.51	2.73	Increased contributions
Stratospheric ozone depletion	kg CFC11 eq	1.83	1.13	2.08	
Ionising radiation	kBq C0-60 eq	1.81	1.40	2.54	Decreased contributions
Ozone formation, human health	kg NOx eq	1.89	1.62	3.07	
Fine particulate matter formation	kg PM2.5 eq	2.00	22.09	44.18	
Ozone formation, terrestrial ecosystems	kg NOx eq	1.88	1.60	3.02	
Terrestrial acidification	kg SO_2 eq	2.12	16.70*	34.35*	
Freshwater eutrophication	kg P eq	2.22	2.21*	3.68*	
Marine eutrophication	kg N eq	1.97	0.34	0.68	
Terrestrial ecotoxicity	kg 1.4-DCB	1.48	16.23*	23.50*	
Freshwater ecotoxicity	kg 1.4-DCB	1.83	1.69*	2.26*	
Marine ecotoxicity	kg 1.4-DCB	1.82	1.76*	2.39*	
Human carcinogenic toxicity	kg 1.4-DCB	1.64	1.13	1.85	
Human non-carcinogenic toxicity	kg 1.4-DCB	2.00	2.18*	3.37*	
Land use	m^2a crop eq	1.70	0.08	0.14	
Mineral resource scarcity	kg Cu eq	1.55	1.62*	1.96*	
Fossil resource scarcity	kg oil eq	1.48	1.30	1.93	
Water consumption	m^3	3.94	1.08	4.26	

* Order of magnitude for impact categories that contained negative scores (from the avoided product) due to the avoided product in System 3 were calculated without the negative signs. This approach was adopted to highlight the factor differences between systems based on absolute values.

The scores for System 1 were found to be almost twice as large in relation to System 2 for almost all impacts. The largest improvement was seen in 'water consumption', where the score for System 2 over System 1 was larger by a factor of 3.94. These results clearly indicate the importance of flush water and its associated environmental impacts, and sets the tone for the further optimisation for this input.

When assessing the improvement of System 3 over System 2, a similar trend was found. Most impact categories showed further reductions in environmental scores with the impact categories of 'fine particulate matter formation' (a factor change of 22.09), 'terrestrial acidification' (a factor change of 16.70), and 'terrestrial ecotoxicity' (a factor change of 16.23), showing the highest differences in magnitude. However, two impact categories were found to have increased environmental burdens, namely, 'marine eutrophication' (factor change of 0.34) which is linked to cotton production for filtration bags used for struvite, and 'land use' (a factor change of 0.08) which is linked to the area required for the cotton production. The additional space required for the planned urine treatment facility does not significantly contribute to the overall environmental scores for System 3 as it is not a greenfield project and is within Banana City.

Most of the impact categories for System 3 showed a significant reduction in environmental burdens when compared to System 1, by factors of more than 2, with the most significant reductions coming from the impact categories of 'fine particulate matter formation' (factor change of 44.18), 'terrestrial acidification' (factor change of 34.35), and 'terrestrial ecotoxicity' (factor change of 23.50). However, the only two impact categories with an increased contribution were 'marine eutrophication' (factor change of 0.68), and 'land use' (factor change of 0.14), which are again linked to the cotton filters used in struvite production.

Results for the individual systems

Figure 10 illustrates the contributions to environmental scores for System 1. The majority of burdens have a relatively similar contribution split between construction and operation, with a variance of only 10% of the halfway mark. The importance of flush water was noted for the 'water consumption' impact category and the importance of materials for 'mineral resources'. Besides 'water consumption', the construction of this DEWATS accounts for the largest contributions across the majority of the impact categories. Transportation and the construction of the sewer network were found to be insignificant for most of the impact categories.

Figure 10. System 1: (a) percentage contributions of construction and operation; (b) percentage breakdown of all inputs for the construction and operation

Figure 11 illustrates the results for System 2. Most of the impact categories show relatively higher scores from construction as compared to operation. The ‘water consumption’ score is an exception and illustrates the significance of potable water even in a low-flush system, emphasising the local importance of water as a resource. As less water is used in this system, the construction of the DEWATS and the materials used carry higher environmental burdens. The contribution of transportation is also increased in this system.

Figure 12 shows the results for System 3 and the construction contributions are also relatively higher compared to operation, with the exception of ‘water consumption’. Significant positive contributions associated with the incorporation of the struvite fertiliser (shown as TSP replacement/avoided product) are seen for all of the 18 impact categories (indicated by the negative percentage contributions (i.e. savings)). These reduced burdens of the replacement/avoided product outweigh the construction and operational burdens for System 3 for most of the impact categories and have a direct positive impact on the overall environmental profile.

For the construction of System 3, materials used for the DEWATS plant featured prominently, overshadowing those for the struvite plant and the associated sewer network. In terms of the operational inputs, transportation was the largest contributor across most of the impact categories, followed by domestic flush water. This stems from the optimisation of System 3, where the reduction in domestic flush water resulted in the transportation percentage burdens increasing. The additional transportation of the collected urine from the households to the struvite plant also contributed to this increase.

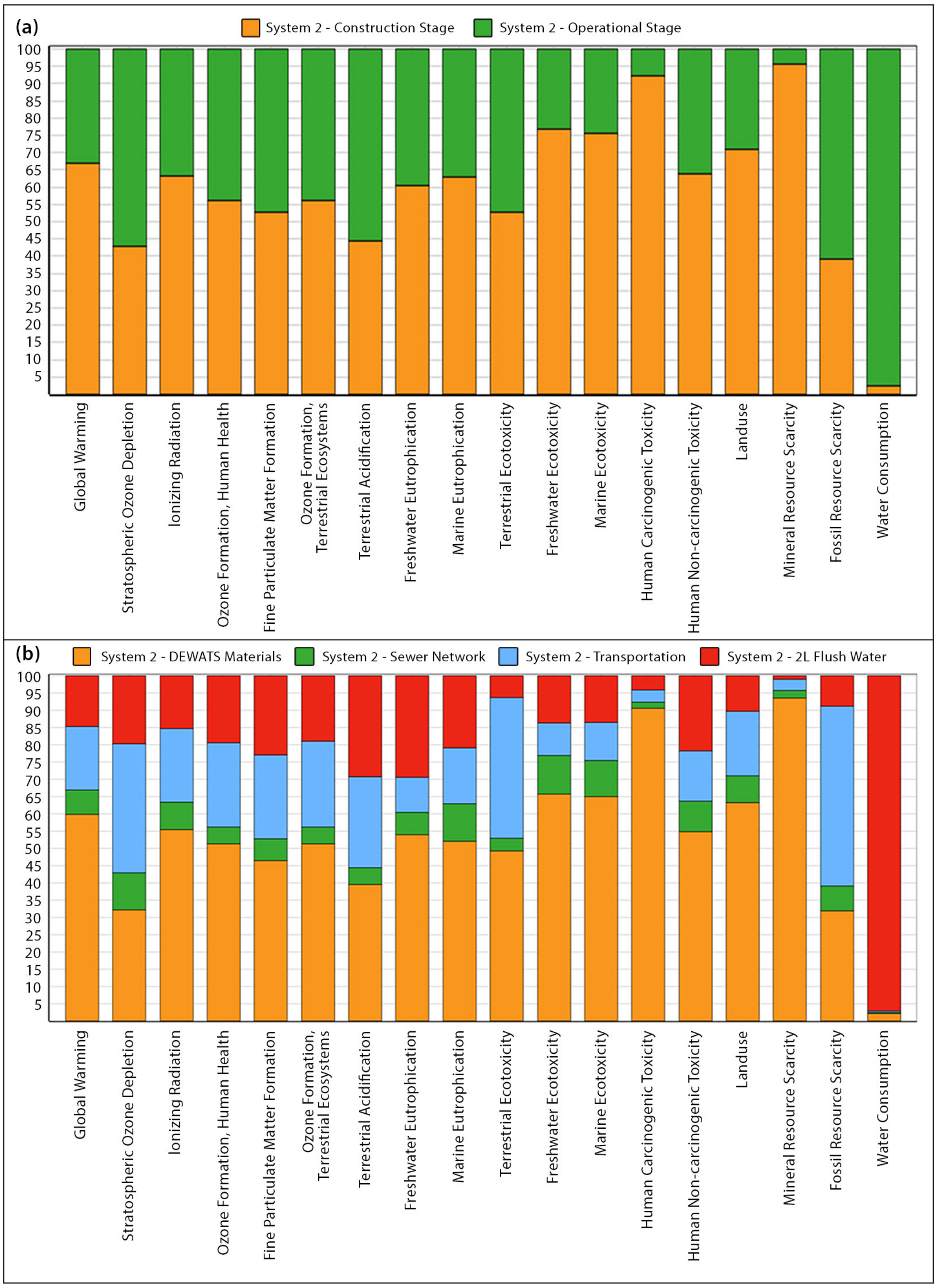

Figure 11. System 2: (a) percentage contribution of construction and operation, (b) percentage breakdown of all inputs for the construction and operation

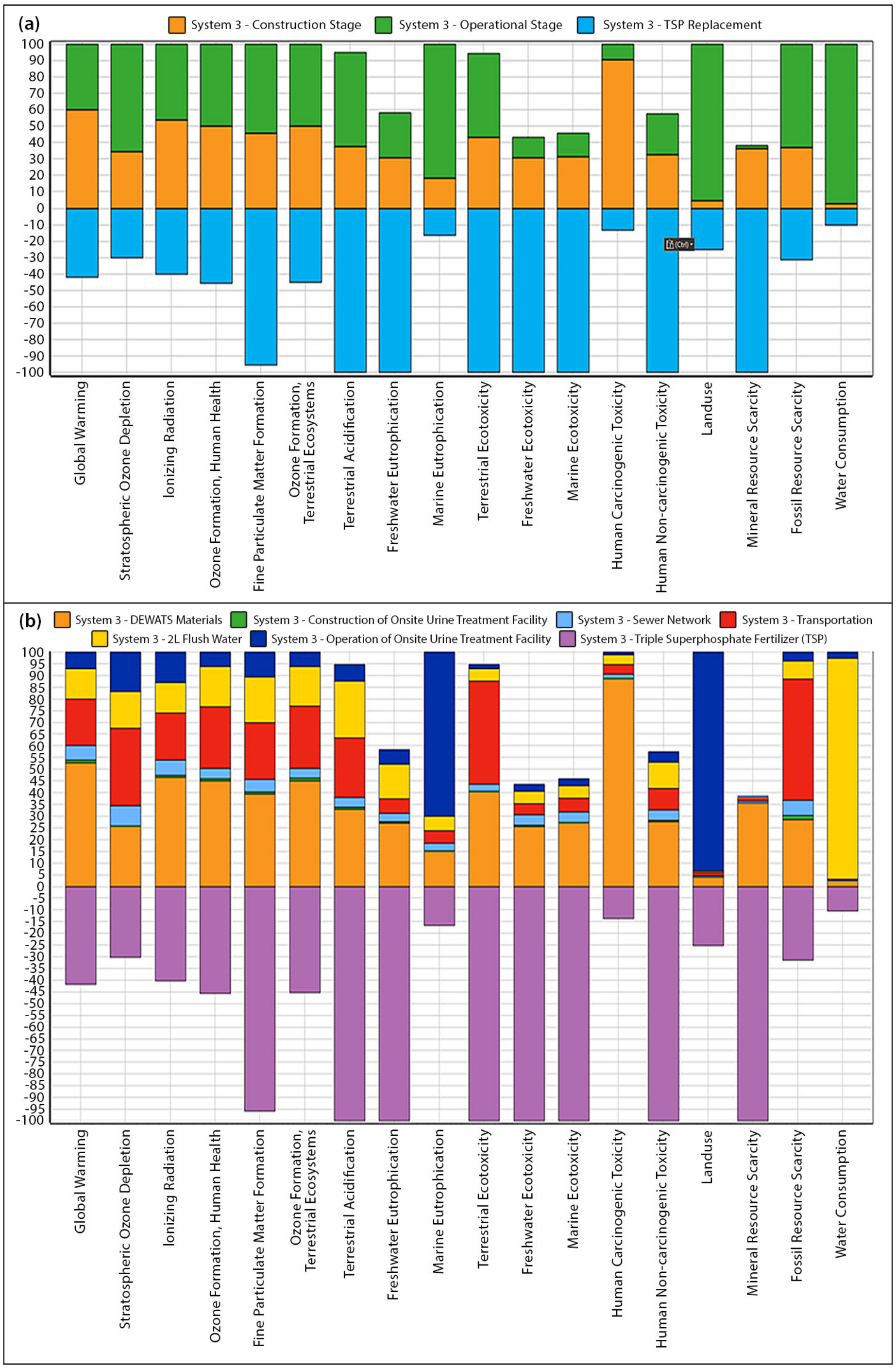

Figure 12. System 3: (a) percentage contribution of construction and operation, (b) percentage breakdown of all inputs for the construction and operation

The struvite plant was found to cause only small burdens for most of the impact categories, with two outliers, namely, 'marine eutrophication' and 'land use'. Both these burdens are traced back to the production of cotton filter bags, as discussed previously (see Fig. 5). Therefore, two possible alternate filtration materials were investigated, aiming at lowering environmental scores for these impact categories, but without increasing the scores for other impact categories. Overall, the results for System 3 show that locally optimised systems are possible, resulting in significant environmental savings and a win-win scenario.

Normalisation results

Normalised results are presented in Fig. 13 and confirmed the significant reduction in environmental burdens seen when improving from System 1 to 2 and 2 to 3. The most significant impact category for all three systems after normalisation was 'water consumption', confirming the characterisation results. When System 1 was optimised through low-flush and struvite production, a reduction of more than 80% occurred for water consumption after normalisation. To a much lesser extent, the impact categories of 'freshwater eutrophication', 'freshwater ecotoxicity', and 'marine ecotoxicity', also showed decreasing burdens. These impact categories can be traced back to the construction materials of the DEWATS. In particular, for the impact category of 'freshwater eutrophication', the potential for improvement due to the replacement/avoidance of a commercial fertiliser has to be highlighted. Therefore, such fertiliser replacement should be investigated for other local sanitation systems.

'Water consumption' was analysed in more detail and Table 5 summarises the relative contribution of flush water to each of

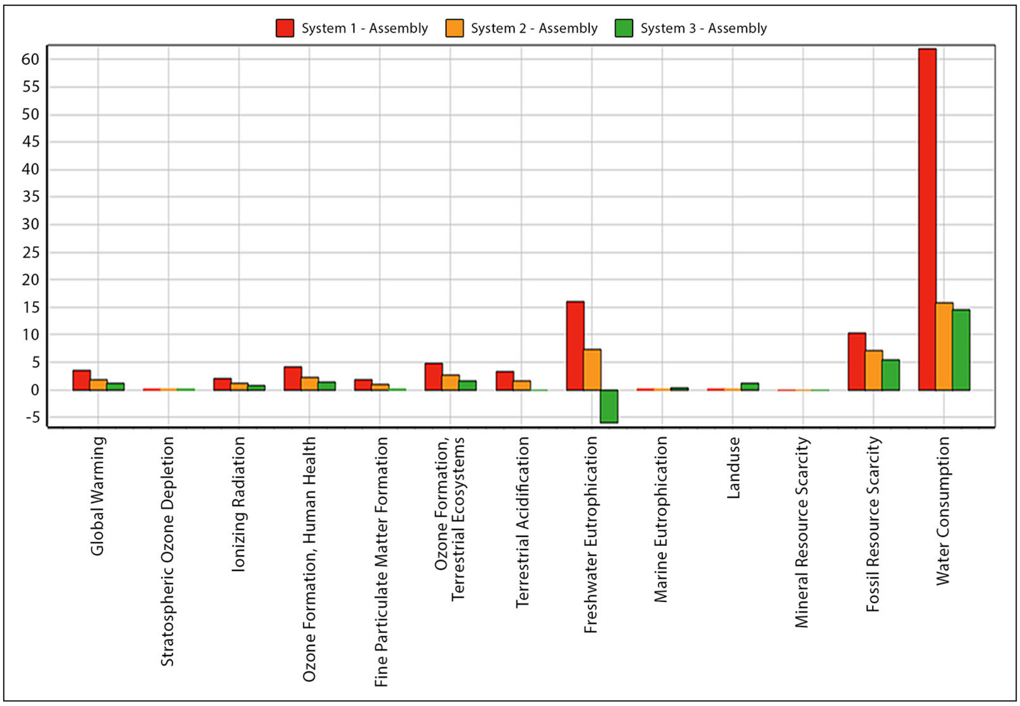

Figure 13. Normalised impacts for Systems 1, 2, and 3

Table 5. Percentage contribution of toilet flush water to environmental scores

Impact category	Unit	Contribution (%) of flush water in each system		
		System 1	System 2	System 3
Global warming	kg CO_2 eq	32.4%	14.6%	12.9%
Stratospheric ozone depletion	kg CFC11 eq	43.1%	19.7%	15.6%
Ionising radiation	kBq C0-60 eq	33.9%	15.3%	12.8%
Ozone formation, human health	kg NOx eq	41.1%	19.3%	17.1%
Fine particulate matter formation	kg PM2.5 eq	46.3%	22.9%	19.4%
Ozone formation, terrestrial ecosystems	kg NOx eq	40.5%	19.0%	16.7%
Terrestrial acidification	kg SO_2 eq	55.2%	29.3%	24.4%
Freshwater eutrophication	kg P eq	53.0%	29.4%	14.8%
Marine eutrophication	kg N eq	42.4%	20.9%	6.0%
Terrestrial ecotoxicity	kg 1.4-DCB	17.0%	6.3%	5.1%
Freshwater ecotoxicity	kg 1.4-DCB	29.9%	13.7%	5.4%
Marine ecotoxicity	kg 1.4-DCB	29.6%	15.5%	5.6%
Human carcinogenic toxicity	kg 1.4-DCB	10.1%	4.1%	4.0%
Human non-carcinogenic toxicity	kg 1.4-DCB	43.4%	21.8%	11.0%
Land use	m^2a crop eq	24.3%	10.3%	0.6%
Mineral resource scarcity	kg Cu eq	2.8%	1.1%	0.4%
Fossil resource scarcity	kg oil eq	23.7%	8.8%	7.8%
Water consumption	m^3	98.9%	97.0%	94.2%

the systems modelled. For System 1 this high contribution was expected. However, 'water consumption' still featured prominently in Systems 2 and 3; hence further improvements for all systems were investigated by using rainwater to flush toilets.

Normalisation results also confirm that once a typical high-flush DEWATS is optimised, the specific environmental contributions are now centred around other inputs besides potable water. As the contribution of flush water decreases, the relative share of environmental burdens of the other inputs increase (i.e. materials and transportation in this case). In this regard, DEWATS seem to be different when compared to other wastewater treatment systems that use energy for operation (see Buckley et al., 2011; Loubet et al., 2014).

Improvement analyses

Two interventions aimed at increasing the environmental performance of the DEWATS investigated were prioritised based on the LCA results presented in the previous sections. These included the incorporation of rainwater harvesting to be used for toilet flushing for all three systems and the replacement of cotton in struvite production for System 3, with filtration bags made of other materials.

Gravity-fed rainwater harvesting was investigated, based on its potential to significantly reduce toilet flush water in Banana City. The analysis considered roof size, household installation requirements, and average monthly rainfall to estimate potential water savings for Systems 1, 2, and 3. Figure 14 illustrates these results and shows that the overall potential savings for System 1 are higher compared to Systems 2 and 3. During the rainy seasons of October to March in the eThekwini Municipality, a higher overall water saving was possible. In the drier months of June to August, only a lower overall water saving was achievable. Without storage included, for System 1, the average expected flush water savings is around 2 620 litres per household per month, whilst for System 2 and System 3 the expected average saving is 1 125 litres per household per month. Theoretically, this means that System 1 could supply less than half of its required flush water from the rainwater that can be harvested, whilst System 2 and System 3 would be able to completely function on rainwater. Even though these preliminary results show potential for significant improvement, further investigations are needed for better modelling at household level and for the inclusion of rainwater storage. The construction materials for the rainwater harvesting systems (like extra pipes and storage tanks), as well as its operation (e.g. filters) need to be included in a detailed LCA.

The scores for System 3 showed that the cotton filtration bags for the production of struvite caused higher environmental burdens for the impact categories of 'marine eutrophication' and 'land use'. Hence, alternate materials were investigated, namely polyester and polypropylene, which can be used for low-temperature filtration as in the struvite process (Filmedia, 2023). Table 6 shows the results obtained after the LCAs were re-run using these alternate materials. It is evident that all impact categories showed slightly improved scores with the use of these materials; however, the differences were minimal. Therefore, the environmental improvement possible was considered to be small.

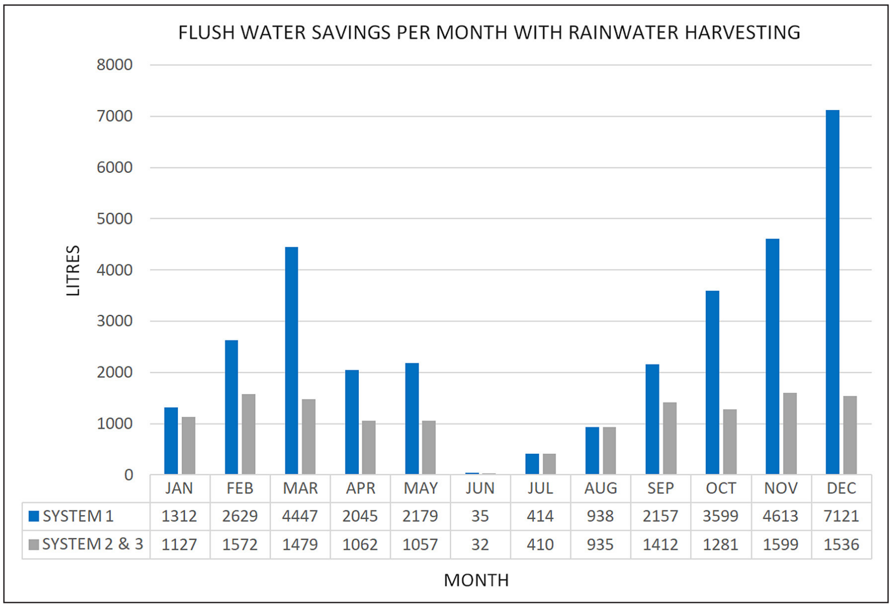

Figure 14. Flush water savings possible by rainwater harvesting

Table 6. Improvement analysis for substituting cotton in filter bags with polyester and polypropylene

Impact category	Unit	Reference scenario	Improvement analysis	
		System 3 scores (cotton)	System 3 scores (polyester)	System 3 scores (polypropylene)
Global warming	kg CO_2 eq	1.00×10^{4}	9.90×10^{3}	9.85×10^{3}
Stratospheric ozone depletion	kg CFC11 eq	6.61×10^{-3}	5.79×10^{-3}	5.40×10^{-3}
Ionising radiation	kBq C0-60 eq	4.00×10^{2}	3.94×10^{2}	3.91×10^{2}
Ozone formation, human health	kg NOx eq	2.76×10^{1}	2.73×10^{1}	2.71×10^{1}
Fine particulate matter formation	kg PM2.5 eq	1.10×10^{0}	8.46×10^{-1}	7.59×10^{-1}
Ozone formation, terrestrial ecosystems	kg NOx eq	2.86×10^{1}	2.83×10^{1}	2.81×10^{1}
Terrestrial acidification	kg SO_2 eq	-4.00×10^{0}	-5.31×10^{0}	-5.50×10^{0}
Freshwater eutrophication	kg P eq	-3.90×10^{0}	-4.00×10^{0}	-4.02×10^{0}
Marine eutrophication	kg N eq	1.23×10^{0}	2.36×10^{-1}	2.29×10^{-1}
Terrestrial ecotoxicity	kg 1.4-DCB	-2.60×10^{3}	-2.63×10^{3}	-2.81×10^{3}
Freshwater ecotoxicity	kg 1.4-DCB	-6.68×10^{2}	-6.73×10^{2}	-6.76×10^{2}
Marine ecotoxicity	kg 1.4-DCB	-8.34×10^{2}	-8.42×10^{2}	-8.45×10^{2}
Human carcinogenic toxicity	kg 1.4-DCB	3.86×10^{3}	3.86×10^{3}	3.85×10^{3}
Human non-carcinogenic toxicity	kg 1.4-DCB	-9.13×10^{3}	-9.27×10^{3}	-9.33×10^{3}
Land use	m^2a crop eq	7.10×10^{3}	-1.74×10^{3}	-1.75×10^{3}
Mineral resource scarcity	kg Cu eq	-2.63×10^{2}	-2.63×10^{2}	-2.63×10^{2}
Fossil resource scarcity	kg oil eq	5.29×10^{3}	5.28×10^{3}	5.28×10^{3}
Water consumption	m^3	3.89×10^{3}	3.79×10^{3}	3.78×10^{3}

Sensitivity analyses for important parameters

An important assumption in the calculation of environmental scores was the number of people per household. A value of 8 people per household was assumed, which is aligned with the future expected population growth of Banana City. Since the used value (year 2023) was 5 people per household, a sensitivity analysis was undertaken. Scores in Table 7 show an overall higher environmental burden associated with 8 people per household as compared to 5 people, for all impact categories. Overall, it was found that System 1 is more sensitive to the change in the number of people as compared to System 3, and different impact categories had different variations, with 'water consumption', 'terrestrial acidification' and 'freshwater eutrophication' showing marked changes with the variation in the number of people per household, for all three systems. These are impact categories linked to water management and there is a direct proportionality between scores in System 1 and System 2. However, for System 3, these percentages change to show a much larger variation for these impact categories. Hence, these impact categories are very sensitive to the change of this parameter. As the number of people in the households of the Banana City development increases, the (over-)conservative design associated with a lower flush (but a higher number of people) is acceptable, and the variation of this parameter presents the lowest sensitivity for all categories of this scenario. This sensitivity has implications for the environmental profiles for the three systems, as 'water consumption' was identified as a major input, carrying sizable environmental burdens. Therefore, rainwater harvesting for improvement becomes more important to save potable water, to increase the independence of individual households, and to further reduce uncertainties linked to local population increase.

For System 3 an important parameter was the replacement ratio of struvite to TSP. In this study a 1:1 replacement ratio was assumed based on work by Erdal et al. (2024) which showed that struvite can perform equally or better than commercial fertiliser, including TSP, due to its slow soil release and multi-nutrient content. However, two other lower performance replacement rates were tested. A TSP replacement ratio of 1.67:1 (meaning that 1 kg struvite is replacing only 0.60 kg of TSP) was used based on the findings by Brye et al. (2022) for a low concentration of urine in the wastewater effluent. In the case of Banana City, this is only possible if rainwater mixes with the urine by accident, since the separated urine is contained in a closed system in order to maintain a high concentration, as this is important in struvite production. The low concentration thus represents a worst-case scenario. An intermediary struvite to TSP replacement ratio of 1.25:1 (meaning that 1 kg of struvite is replacing 0.80 kg of TSP) was also used (Brye et al., 2022).

The results are presented in Table 8 and show that when 1 kg of struvite replaced only 0.60 or 0.80 kg of TSP, most impact categories (15 out of 18) have increased scores, and this can be attributed directly to the reduced quantity of avoided TSP fertiliser product. Therefore, the environmental contributions for all impact categories increase as the replacement ratio decreases, indicating that the assumed ratio is a significant parameter for System 3. This is aligned with other literature findings that show that the success of urine diversion and struvite production is directly related to the amount of conventional fertiliser use that it offsets (Sena and Hicks, 2018). Considering the particular details for Banana City, the replacement ratio of 1:1 is the most representative. However, dilution of the urine during collection and transport to the struvite plant should be prevented, as dilution will increase the inefficiency of System 3 leading to reduced performance.

CONCLUSION

This is the first local study employing LCAs for quantifying the environmental burdens of DEWATS and investigating possible optimisation scenarios for these low-energy sanitation systems. The main results show that the amount of flush water used is the highest contributor to environmental burdens for all three systems investigated. Hence, the reduction of the amounts of potable water for flushing toilets showed decreased environmental burdens for the majority of the 18 environmental impact categories investigated. Thus, the number of people per

Table 7. Sensitivity to the number of people per household for Systems 1, 2 and 3 (percentage change relative to an 8-person household)

Impact category	Unit	System 1 score (8 people)	System 1 score (5 people)	System 1 change	System 2 score (8 people)	System 2 score (5 people)	System 2 change	System 3 score (8 people)	System 3 score (5 people)	System 3 change
Global warming	kg CO_2 eq	2.74×10^{4}	2.41×10^{4}	**12.04%**	1.51×10^{4}	1.43×10^{4}	**5.42%**	1.00×10^{4}	9.17×10^{3}	**8.30%**
Stratospheric ozone depletion	kg CFC11 eq	1.37×10^{-2}	1.15×10^{-2}	**16.18%**	7.50×10^{-3}	6.95×10^{-3}	**7.33%**	6.61×10^{-3}	6.06×10^{-3}	**8.32%**
Ionising radiation	kBq C0-60 eq	1.02×10^{3}	8.86×10^{2}	**12.71%**	5.61×10^{2}	5.29×10^{2}	**5.70%**	4.00×10^{2}	3.67×10^{2}	**8.25%**
Ozone formation, human health	kg NOx eq	8.46×10^{1}	7.15×10^{1}	**15.48%**	4.47×10^{1}	4.14×10^{1}	**7.38%**	2.76×10^{1}	2.44×10^{1}	**11.59%**
Fine particulate matter formation	kg PM2.5 eq	4.86×10^{1}	4.01×10^{1}	**17.49%**	2.43×10^{1}	2.25×10^{1}	**7.41%**	1.10×10^{0}	-9.34×10^{-1}	**184.91%**
Ozone formation, terrestrial ecosystems	kg NOx eq	8.63×10^{1}	7.32×10^{1}	**15.18%**	4.59×10^{1}	4.27×10^{1}	**6.97%**	2.86×10^{1}	2.54×10^{1}	**11.19%**
Terrestrial acidification	kg SO_2 eq	1.33×10^{2}	1.06×10^{2}	**20.54%**	6.28×10^{1}	5.59×10^{1}	**10.99%**	-4.00×10^{0}	-1.09×10^{1}	**172.50%**
Freshwater eutrophication	kg P eq	1.05×10^{1}	8.37×10^{0}	**19.90%**	4.71×10^{0}	4.20×10^{0}	**10.83%**	-3.90×10^{0}	-4.41×10^{0}	**13.08%**
Marine eutrophication	kg N eq	8.34×10^{-1}	7.02×10^{-1}	**15.83%**	4.23×10^{-1}	3.90×10^{-1}	**7.80%**	1.23×10^{0}	1.19×10^{0}	**3.09%**
Terrestrial ecotoxicity	kg 1.4-DCB	5.85×10^{4}	5.48×10^{4}	**6.32%**	3.96×10^{4}	3.86×10^{4}	**2.53%**	-2.60×10^{3}	-3.52×10^{3}	**35.38%**
Freshwater ecotoxicity	kg 1.4-DCB	8.44×10^{2}	7.49×10^{2}	**11.26%**	4.60×10^{2}	4.36×10^{2}	**5.22%**	-6.68×10^{2}	-6.88×10^{2}	**2.99%**
Marine ecotoxicity	kg 1.4-DCB	1.16×10^{3}	1.03×10^{3}	**11.28%**	6.38×10^{2}	6.06×10^{2}	**5.02%**	-8.34×10^{2}	-8.67×10^{2}	**3.96%**
Human carcinogenic toxicity	kg 1.4-DCB	7.14×10^{3}	6.87×10^{3}	**3.81%**	4.36×10^{3}	4.29×10^{3}	**1.65%**	3.86×10^{3}	3.79×10^{3}	**1.76%**
Human non-carcinogenic toxicity	kg 1.4-DCB	2.16×10^{4}	1.81×10^{4}	**16.20%**	1.08×10^{4}	9.90×10^{3}	**8.16%**	-9.13×10^{3}	-9.98×10^{3}	**9.31%**
Land use	m^2a crop eq	1.01×10^{3}	9.19×10^{2}	**9.10%**	5.94×10^{2}	5.71×10^{2}	**3.87%**	7.10×10^{3}	7.07×10^{3}	**0.38%**
Mineral resource scarcity	kg Cu eq	2.53×10^{2}	2.50×10^{2}	**1.26%**	1.63×10^{2}	1.62×10^{2}	**0.57%**	-2.63×10^{2}	-2.64×10^{2}	**0.45%**
Fossil resource scarcity	kg oil eq	1.02×10^{4}	9.29×10^{3}	**8.92%**	6.90×10^{3}	6.67×10^{3}	**3.33%**	5.29×10^{3}	5.06×10^{3}	**4.35%**
Water consumption	m^3	1.66×10^{4}	1.04×10^{4}	**37.22%**	4.21×10^{3}	2.68×10^{3}	**36.30%**	3.89×10^{3}	2.36×10^{3}	**39.33%**

Table 8. Sensitivity analysis for the replacement ratio of struvite to TSP for System 3

Impact category	Unit	Reference scenario	Sensitivity analysis 1		Sensitivity analysis 2	
		System 3 score 1:1 ratio (1 kg struvite = 1 kg tsp)	System 3 score 1.25:1 ratio (1 kg struvite = 0.80 kg tsp)	% change*	System 3 score 1.67:1 ratio (1 kg struvite = 0.60 kg tsp)	% change*
Global warming	kg CO_2 eq	1.00×10^{4}	1.14×10^{4}	13.55%	1.29×10^{4}	28.49%
Stratospheric ozone depletion	kg CFC11 eq	6.61×10^{-3}	7.19×10^{-3}	8.77%	7.77×10^{-3}	17.55%
Ionising radiation	kBq C0-60 e	4.00×10^{2}	4.54×10^{2}	13.50%	5.08×10^{2}	27.00%
Ozone formation, human health	kg NOx eq	2.76×10^{1}	3.23×10^{1}	17.03%	3.70×10^{1}	34.06%
Fine particulate matter formation	kg pm2.5 eq	1.10×10^{0}	6.72×10^{0}	510.91%	1.23×10^{1}	1 018.18%
Ozone formation, terrestrial ecosystems	kg NOx eq	2.86×10^{1}	3.34×10^{1}	16.78%	3.81×10^{1}	33.22%
Terrestrial acidification	kg SO_2 eq	-4.00×10^{0}	1.11×10^{1}	377.50%	2.61×10^{1}	752.50%
Freshwater eutrophication	kg P eq	-3.90×10^{0}	-2.02×10^{0}	48.21%	-1.48×10^{-1}	96.21%
Marine eutrophication	kg N eq	1.23×10^{0}	1.27×10^{0}	3.42%	1.32×10^{0}	7.49%
Terrestrial ecotoxicity	kg 1.4-DCB	-2.60×10^{3}	7.08×10^{3}	372.31%	1.68×10^{4}	746.15%
Freshwater ecotoxicity	kg 1.4-DCB	-6.68×10^{2}	-4.29×10^{2}	35.78%	-1.93×10^{2}	71.11%
Marine ecotoxicity	kg 1.4-DCB	-8.34×10^{2}	-5.27×10^{2}	36.81%	-2.18×10^{2}	73.86%
Human carcinogenic toxicity	kg 1.4-DCB	3.86×10^{3}	3.98×10^{3}	3.16%	4.10×10^{3}	6.27%
Human non-carcinogenic toxicity	kg 1.4-DCB	-9.13×10^{3}	-4.83×10^{3}	47.10%	-5.55×10^{2}	93.92%
Land use	m^2a crop eq	7.10×10^{3}	7.58×10^{3}	6.81%	8.06×10^{3}	13.57%
Mineral resource scarcity	kg Cu eq	-2.63×10^{2}	-1.77×10^{2}	32.66%	-9.18×10^{1}	65.07%
Fossil resource scarcity	kg oil eq	5.29×10^{3}	5.77×10^{3}	9.07%	6.26×10^{3}	18.34%
Water consumption	m^3	3.89×10^{3}	3.98×10^{3}	2.31%	4.07×10^{3}	4.63%

*The % change refers to the change in relation to the reference scenario (1:1 ratio)

household is an important parameter in the amount of wastewater generated and this was confirmed by the sensitivity analysis. Hence, investigations into the harvesting of rainwater should be performed, not only to decrease environmental burdens and conserve a precious resource, but also to increase the resilience of DEWATS to social factors. The simplified rainwater harvesting calculations included in this research showed potential for further improving the performance of South African DEWATS; however, this depends on the average rainfall and might not be valid in low-rainfall areas within the country.

The use of low-flush interventions, urine diversion and its on-site treatment, as well as the utilisation of urine-derived fertiliser (struvite) as a replacement/avoided product for a commercial fertiliser, holds great potential to improve the current environmental performance of DEWATS in and around the eThekwini Municipality, as well as elsewhere in South Africa, and in other developing countries. These interventions should also be investigated for implementation in higher energy DEWATS and for conventional wastewater treatment plants.

Another important conclusion from this research is that, unlike in LCAs for high-energy sanitation systems, the DEWATS investigated showed increasing environmental burdens from construction and transport, alongside the decrease in the amount of flush water used in operation. Exploring alternate and more sustainable options for future low-energy DEWATS materials should be undertaken. This includes alternate and recycled materials, not only for the process units constructed for the primary, secondary and tertiary DEWATS treatment but also for those involved in the separation of urine and for struvite production. Understanding the optimum replacement ratio of struvite to TSP and other fertilisers, especially in a local context, can also improve the quality of such LCAs as it would lead to better understanding of the exact amount of avoided product that can be offset when conducting similar studies in South Africa.

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