Science of the Total Environment 837 (2022) 155777

Contents lists available at ScienceDirect

Science of the Total Environment

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

Resource-oriented sanitation: Identifying appropriate technologies and environmental gains by coupling Santiago software and life cycle assessment in a Brazilian case study

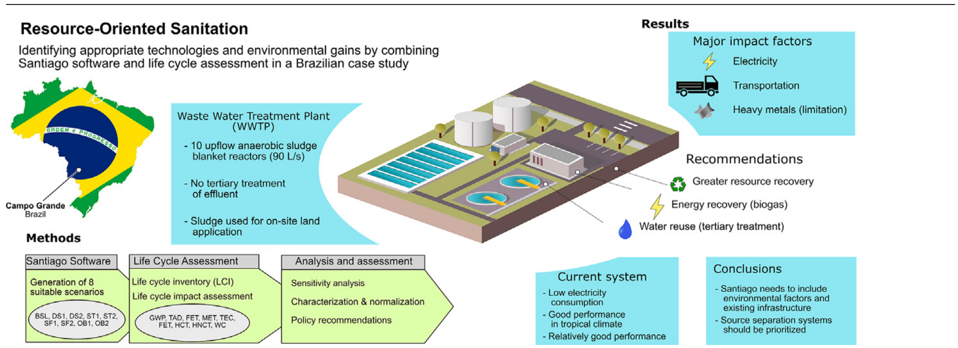
Priscila de Morais Lima [a,*], Thais Andrade de Sampaio Lopes [b], Luciano Matos Queiroz [c], Jennifer Rae McConville [a]

[a] Department of Energy and Technology, Swedish University of Agricultural Sciences (SLU), Almas Allé 8, 750 07 Uppsala, Sweden
[b] Federal Institute of Education, Science and Technology Baiano (IF Baiano), Itapetinga, Bahia, Brazil
[c] Environmental Department, Polytechnic School, Federal University of Bahia, Brazil

HIGHLIGHTS

- Coupling Santiago and LCA to identify sanitation scenarios for west central Brazil.
- UASB reactors had high CO_2 emissions and resource recovery should be prioritized.
- Urine and feces separation with soil application performed best in most categories.
- Electricity and transport play major roles in wastewater management.
- Improvements are needed in Santiago to include environmental aspects.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Paola Verlicchi

Keywords:
Wastewater treatment plant (WWTP)
Decision-making
Environmental burden
Nutrient recovery

ABSTRACT

Implementation of resource recovery technologies is becoming increasingly important, as humans are exhausting the world's natural resources. Recovering nutrients and water from wastewater treatment systems will play an important role in changing the current trends towards a circular economy. However, guidance is still needed to determine the most appropriate way to do this. In this study two decision-support tools, sanitation planning software (Santiago) and life cycle assessment (LCA), were applied to identify appropriate technologies and their environmental impacts. As a case study, current and alternative scenarios for a wastewater treatment plant (WWTP) in Campo Grande, west-central Brazil, were used. Among 12 scenarios provided by Santiago for efficient nutrient recovery, eight were selected for further assessment. The current WWTP system (UASB reactors) resulted in the highest negative impacts in two of nine assessment categories (freshwater and marine eutrophication), due to nutrient discharge to water. A source separation scenario with urine stored in a urine bank and co-composting of feces showed best overall performance. Electricity consumption played a crucial role for impacts in several categories, while water consumption was not significantly affected by choice of toilet. One Santiago scenario matched the most appropriate scenario with the best environmental performance, but the other seven scenarios were not as beneficial, indicating a need for some adjustments in the software. These results highlight the importance of performing LCA to compare alternative scenarios, even when using a tool designed to identify locally appropriate technologies. The results also indicate that the current wastewater treatment system has reasonable environmental performance, but could be improved if measures were taken to recover energy and reuse water.

* Corresponding author.
E-mail address: pri.lima.91@gmail.com (P.M. Lima).

http://dx.doi.org/10.1016/j.scitotenv.2022.155777
Received 30 September 2021; Received in revised form 4 May 2022; Accepted 4 May 2022
Available online 8 May 2022

1. Introduction

Despite being one of the largest economies in the world, Brazil still has far to go in providing sanitation services, especially wastewater collection, transport, and treatment, for its population. According to the Brazilian Water Agency (ANA and de Á., 2017), 27% of the population does not have wastewater collection or treatment and 2400 tons of organic matter are dumped into the environment each year. As a result, it is estimated that more than 110,000 km of Brazilian rivers are contaminated and unsuitable for public water supply.

The Federal Sanitation Law, revised in 2020 with the aim of reversing this serious environmental degradation, established the goal that 93% of households in Brazilian urban areas must be served with appropriate wastewater collection, transport, and treatment by 2033. Considering the territorial scale of Brazil (8.5 million km^2), its deep social inequalities, and its population of more than 220 million people, this will be a huge challenge. However, it is also an excellent opportunity to pursue initiatives on resource-oriented sanitation systems. Considering global demand for water, food, and energy, it is no longer acceptable to apply wastewater treatment only to remove pollutants in order to meet environmental standards. The impacts caused by wastewater treatment affect local and global sustainability (Muga and Mihelcic, 2008), and therefore wastewater treatment should be viewed as a resource recovery system and alternative source of water, energy, and fertilizers for agriculture (McCarty et al., 2011).

However, to convert opportunity into reality, it is essential to choose technical systems suited to the Brazilian reality and aimed at recovering resources. Implementation of new technologies such as advanced treatments to recover water, energy and nutrients in sanitation services and efficient water management can be challenging to developing countries (UN, 2018). Since decision-makers have to consider multiple aspects and may lack knowledge on performance of new innovations, financial resources, and public acceptance, they could benefit from a tool capable of identifying options for planning sanitation systems that take into account the growing number of available technologies and the many possible system configurations.

SANitation system Alternative GeneratOr (Santiago) is a free software capable of generating system options for urban planning based on a set of criteria. The approach has been tested in different locations, such as the cities of Arba Minch (Ethiopia), Lima (Peru), and Katarniya (Nepal), where it has been found to be systematic and reproducible (Nisaa et al., 2021; Spuhler et al., 2018, 2021). The cases showed it to be capable of providing substantial benefits, as it opens up the decision space with novel and potentially more appropriate solutions. It also enables decisions based on strategic objectives in line with the United Nation Sustainable Development Goals (SDGs).

However, current inputs to Santiago are physical conditions and management capacity in the local context, rather than potential impacts associated with the systems (Spuhler et al., 2018). Different wastewater treatment technologies have different characteristics and different impacts on the environment. Life Cycle Assessment (LCA) is the most commonly used tool to assess environmental performance. It relies on the definition of scenarios and assumptions that can be limiting (Morera et al., 2017; Gallego-Schmid and Tarpani, 2019). Lopes et al. (2020) suggest that the LCA approach should be associated with plans and actions to face the challenges of providing wastewater treatment in developing countries, as only then can compliance with eco-efficiency targets and protection of public health be guaranteed. Thus, Santiago and LCA each have weaknesses that could be overcome by the coupled use of these tools. Combining Santiago and LCA could support decision-makers by showing the potential environmental impacts associated with different technical systems for resource recovery.

This study explored the potential of a coupled use of Santiago and LCA for decision-support in sanitation planning aiming for resource recovery. Specific objectives of the study were to: a) use Santiago to generate resource-recovery efficient scenarios for a case study in west-central Brazil; b) use LCA to assess the environmental impacts of these scenarios compared with the baseline in the case city; and c) provide recommendations on coupling the tools for improved decision-making.

2. Material and methods

The coupled Santiago and LCA approach was tested in a case study in west-central Brazil. A description of the case and of steps involved in the coupled approach is presented below.

2.1. Case study

The case study focused on the urban part, mainly the center, of the city of Campo Grande, capital of Mato Grosso do Sul state, west-central Brazil. It is the second largest state in Brazil in terms of land area (1.6 million km^2) and is characterized by intensive agricultural and livestock activities, e.g., it currently has the largest cattle herd in Brazil. It is also one of the places with the highest volume of freshwater in the world. The Pantanal is the main biome in Mato Grosso do Sul, despite occupying only 7.2% of the state's area, and is recognized by UNESCO as a World Natural Heritage and Biosphere Reserve. The west-central region is the least populated region in Brazil and has the second lowest population density and large demographic gaps.

Urban Campo Grande has approximately 906,902 inhabitants (IBGE, 2021). The majority of the wastewater generated and collected in the city is currently conducted to a wastewater treatment plant (WWTP) called Los Angeles. Its WWTP process uses ten upflow anaerobic sludge blanket (UASB) reactors, each with 90 l/s capacity, and the effluent is discharged with no tertiary treatment. The biological sludge is currently used for land application on-site at the WWTP site, which was previously a dumping site for construction rubble and has poor agronomic conditions. The sludge is stored for 10 days and then fed out by pipes, using a pump. This was defined as the baseline scenario in the present study, and is shown in Fig. 1 together with all other comparative scenarios assessed.

2.2. Santiago software

The Santiago software uses an algorithm for generating a set of locally appropriate sanitation system options, which can then be used in a structured decision-making process. Its systematic and partly automated procedure is designed to: (i) enhance the reproducibility of option generation; (ii) consider all types of conventional and novel technologies; (iii) provide a set of sanitation systems that is technologically diverse; and (iv) formally account for uncertainties linked to technology specifications and local conditions (Spuhler et al., 2018). The software, which is currently based on the programming language Julia®, is available free of charge at https://github.com/santiago-sanitation-systems/Santiago.jl and can be run in Visual Studio Code®. Based on the detailed description given on the website, the user can provide input files or use the examples given by the software library. The inputs needed for a case are: case file, technology library, and masses. The *case file* is the main input that a user needs to submit in order to create the appropriate systems for the local situation. From the list of 27 attributes provided (Spuhler et al., 2021), the user can define those most relevant to the case study, as shown in Table 1 for the case of Campo Grande. The software contains a full description of each attribute and how to fill in the information in the input file. The user can add their own attributes if needed, as long as they have enough data to adapt the technology library to match these attributes.

The *technology library* currently consists of 41 different technologies designed to manage excreta, not considering greywater treatment. The technologies in the software are divided into five functional groups along the sanitation service chain: user interface (U), collection and storage (S), conveyance (C), treatment (T), and reuse or disposal (D). For example, pour flush and dry toilet are components of U and single pits and vermicomposting are components of S. The technologies considered by Santiago are taken from the Compendium of Sanitation Systems and Technologies (Tilley et al., 2014)

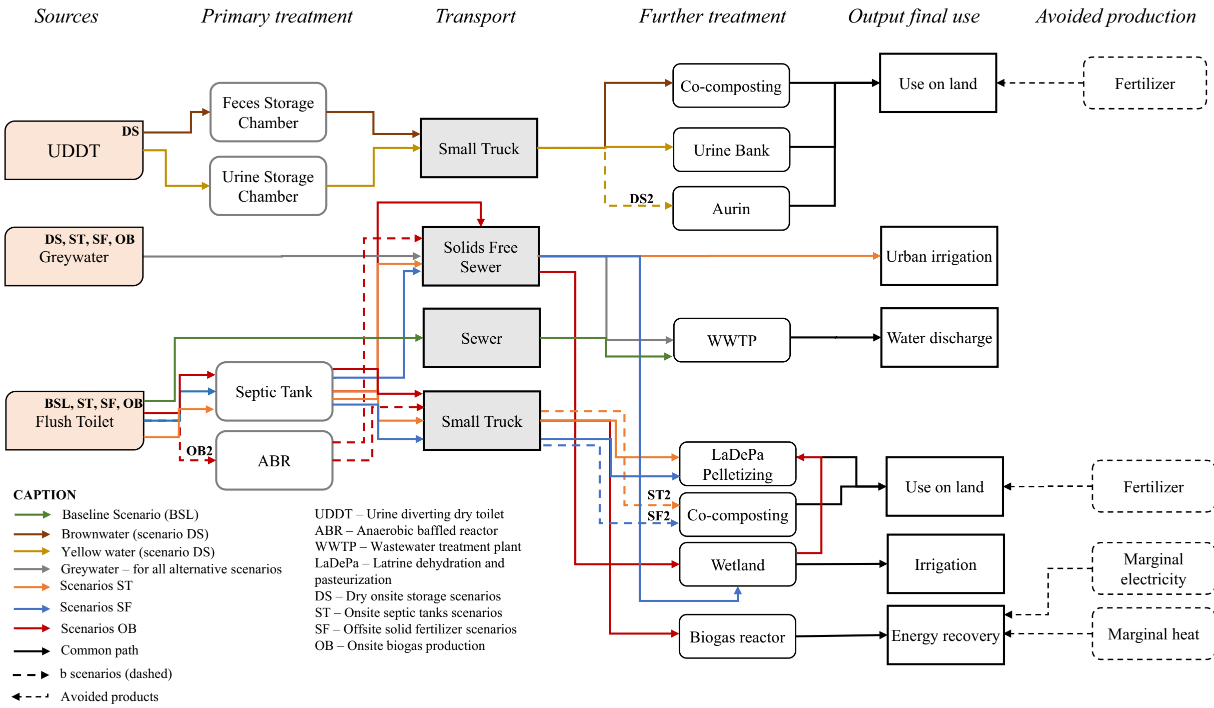


Fig. 1. Graphical illustration of the system boundaries and scenarios assessed in life cycle assessment (LCA).

and the Guide to Sanitation Resource Recovery Products & Technologies (McConville et al., 2020). Technologies can be added to the Santiago library, with corresponding data for the attributes, but for the case of Campo Grande the existing library was used.

The *masses* file contains input values in kg/year for total phosphorus (TP), total nitrogen (TN), water (H_2O), and total solids (TS). These values are distributed according to transfer coefficients (TCs) to the different environmental compartments: products, air, soil, and water emissions. The TCs are embedded in the software for each technology. In this study we used values from the Santiago database, due to lack of primary data. Using the input masses, the software performs Monte Carlo simulations, for which we defined 150 runs, considering that Spuhler et al. (2021) found that the simulations of recovered nitrogen and phosphorus stabilize between 130 and 170 runs.

Table 1
Attributes included in the case file defining the context in central urban Campo Grande.

Attribute	Units	Campo Grande
Water supply	Categories based on performance	Water = 1.0 No water = 0.0
Temperature range	Celsius (°C)	Lowest = 12 Highest = 32 Medium = 21
Vehicular access	Street width (m)	Minimum = 5 Maximum = 16
Slope	Percentage (%)	Low = 0 Upper = 15
Soil type	Categories based on performance	Clay = 0.5 Silt = 0.3 Sand = 0 Gravel = 0.2
Groundwater depth	Water depth (m)	Lower = 4 Upper = 7
Excavation	Categories based on performance	Easy = 0.5 Hard = 0.5
Management	Categories based on performance	Household = 0.5 Shared = 0.25 Public = 0.25

After the software generates all possible systems, the user can use the “option selector” to define how many systems should be selected and how they should be selected. The software also gives scores that rank the technologies most suited for the case under study. For example, the user can request selection of the 10 systems with the highest appropriateness scores, or systems with the highest nitrogen recovery. An example of how the systems are exported from the software is provided in Fig. S1 in Supplementary Material (SM). We selected the 32 overall most appropriate systems, and from those selected the six most efficient for nitrogen recovery and the six most efficient for phosphorus recovery. These 12 systems were then manually screened and synthesized into eight systems representing the different technical components and systems generated by Santiago, e.g., systems with the same technologies used in different orders were combined into a single scenario.

In addition, we replaced the “human-powered transport” suggested by Santiago for most systems with “small truck transport”, as it better matched the perceived cultural norms of the city. The resulting eight scenarios (Fig. 1) represented a broad range of novel alternatives and were deemed by Santiago as suited to the conditions of Campo Grande.

2.3. Scenarios

The eight Santiago scenarios were divided into four groups: Dry onsite storage (DS); onsite septic tank (ST), offsite solid fertilizer (SF), and onsite biogas (OB). These are described in Table 2 and the flows are shown in Fig. 1.

The Santiago software does not consider the greywater contribution when generating alternative systems, so this fraction was added to all Santiago scenarios to enable comparison with the baseline, which handled all household wastewater generated. The greywater was assumed to be collected separately in a solids-free sewer and sent to the existing WWTP (Los Angeles). Fertilization and irrigation from treated greywater were thus included in all scenarios, but the baseline. This was done for a hypothetical farm of 0.2 ha with maize as the crop to be fertilized with the products generated, and for a 0.2 ha eucalyptus plantation to be irrigated using the treated effluent.

The dry onsite (DS) scenarios represented alternatives with source separation of feces and urine. Feces are sent to co-composting and two types of

Table 2
System description of the baseline scenario and the eight Santiago scenarios and groups.

Group	System description	Scenario	Further treatment
Baseline	Existing WWTP compost for UASB reactor operating in real scale, without post treatment.	BSL	–
Dry onsite storage	Urine-diverting toilets (UDDT) with onsite storage and treatment. Source separation of feces and urine, collected separately in on-site storage chambers.	DS1	Urine treatment/stabilization considered: urine bank.
		DS2	Urine treatment/stabilization considered: aurin production, also known as nitrification and distillation (Fumasoli et al., 2016).
Onsite septic tank	Regular flush toilet collects blackwater to an on-site septic tank. The effluent from the septic tank flows into a solids-free sewer and the sludge is transported by small truck to further treatment.	ST1	Sludge treatment considered: latrine dehydration and pasteurization (LaDePa) (Septien et al., 2018).
		ST2	Sludge treatment considered: Co-composting.
Offsite solid fertilizer	Regular flush toilet collects blackwater to an on-site septic tank. The effluent from the septic tank flows into a solids-free sewer and on to a horizontal subsurface flow constructed wetland (HSSFCW) for irrigation of eucalyptus plantations with the treated effluent. The sludge is transported by small truck for further treatment.	SF1	Sludge treatment considered: LaDePa Pelletizing.
		SF2	Sludge treatment considered: co-composting.
Onsite biogas production	Onsite biogas production, with effluent transport. The effluent from a septic tank also flows to a solids-free sewer and to a HSSFCW and irrigation. The sludge from on-site blackwater treatment is sent to a biogas reactor, which produces heat and electricity that are used within the system.	OB1	Primary on-site treatment unit: a septic tank.
		OB2	Primary on-site treatment unit: anaerobic baffled reactor (ABR).

urine treatment/stabilization were considered: (DS1) urine bank and (DS2) Aurin production, also known as nitrification and distillation (Fumasoli et al., 2016). The treated urine and composted feces were both used as fertilizers.

The septic tank (ST) scenarios assumed an on-site septic tank for blackwater collection. Two alternatives for treatment of sludge from the septic tank were considered: (ST1) Latrine Dehydration and Pasteurization (LaDePa) (Septien et al., 2018) and (ST2) co-composting. The resulting products, pellets and compost, were transported and applied as fertilizers. Since the septic tank by itself cannot remove enough organic load from the effluent to make it suitable for agricultural irrigation, the effluent water was instead used for urban irrigation (e.g., parks and lawns).

The solid fertilizer (SF) scenarios also used on-site septic tanks for blackwater collection and had a similar configuration to the ST systems as regards the sludge stream, i.e., (SF1) LaDePa and (SF2) co-composting. The main difference was in further treatment of the water effluent from the septic tanks in a horizontal subsurface flow constructed wetland (HSSFCW) and subsequent irrigation of eucalyptus plantations with the treated effluent.

The onsite biogas (OB) scenarios also used on-site collection of blackwater, but with the sludge from on-site blackwater treatment sent to a biogas reactor to produce heat and electricity used within the system (biogas reactor and LaDePa process). The LaDePa technology was used to treat both the sludge coming from the wetland and the reactor. Variations in the scenario concerned the primary on-site treatment unit: (OB1) a septic tank and (OB2) an anaerobic baffled reactor (ABR). Effluent water was transported by a solids-free sewer and used for urban irrigation.

2.4. Life cycle assessment

To assess the potential environmental impacts of the scenarios generated by Santiago, LCA was performed in accordance with ISO standards (14,040 and 14,044) (ISO, 2006a, 2006b), including the recommended steps: goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation (of the results).

2.4.1. Goal and scope

The goal of the LCA was to find out the environmental performance of the current wastewater treatment in Campo Grande city and of the technologies suggested by Santiago. As the focus of the sanitation systems assessed is the wastewater to be treated, the scope included a generation-based functional unit (FU) and not a nutrient-oriented one. Hence, the FU was defined as the domestic effluent generated by one household (four inhabitants) for a period of one year. Based on per capita generation of 120 l per day (Gonçalves, 2009) and 30 days per month, the FU used was 173 m^3/year of wastewater collected, transported, treated, and sometimes reused.

The system boundaries that contemplated all the inputs and outputs for materials, nutrients, water and energy for the operation of the systems are presented in Fig. 1. The construction and end-of-life phases of the scenarios are not considered in the LCA and the systems were modelled in Simapro® version 9.1.0 – PhD.

Wastewater characteristics were calculated based on primary input data from the Los Angeles WWTP and characteristics of the separated flow streams were based on Meinzinger and Oldenburg (2009) (Table 3).

2.4.2. Inventory

The input materials for the operation phase were electricity, ferric chloride, and defoamer (silicone). The output considered was the preliminary treatment solid waste, which was calculated for the FU based on primary data provided by the Los Angeles WWTP. Details of the life cycle inventory (LCI) are presented in Table 4.

Methane (CH_4), carbon dioxide (CO_2), ammonia (NH_3), and water emissions, such as Phosphorus (P) and Nitrogen (N) from every technology, including the baseline scenario, as for the mass flows were estimated using TC values in Santiago (Spuhler et al., 2021).

Two types of toilets were considered in the assessment of different scenarios: Urine-diverting toilets (UDDT) (no water) and cistern flush toilets (6 l/flush). In a sensitivity analysis, a tankless flush toilet (18 l/flush) was considered, as it is very common in Brazil.

Windrow composting was considered for the sludge co-composting treatment. Thus, no inputs were included, and only emissions and avoided products were calculated. For biogas combustion, the electricity and heat potential of the biogas generated were calculated from FNR and e. V. (2013), as the energy requirements for the plant to operate and the avoided energy obtained. As done in Lima et al. (2018), a grid electricity loss of 3.9% was assumed from medium voltage (consumption) to high voltage (substitution). Natural gas was adopted as the marginal electricity, as it is the source most likely to suffer from market changes (Bernstad Saraiva et al., 2017).

For field application of products (fertilizers and irrigation water), a manure spreader was assumed, for liquids (urine and irrigation water) and solids (compost and pellets). Human urine fertilization and water reuse require intensive use of transportation due to the water content. According to Medeiros et al. (2020), the energy break-even point for human urine fertilization being advantageous when compared to mineral fertilizer is a transportation distance of maximum 134 km. Based on this, it was assumed that for fertilization, the farm was located 50 km from Campo Grande,

Table 3
Characteristics of the different input wastewater streams considered in (kg/year).

	Raw wastewater	Blackwater	Greywater	Sludge[a]
Total phosphorus	7.46	5.60	1.87	7.46
Total nitrogen	138	127	10.7	133
H_2O	173,000	57,600	115,000	161,000
Total solids	577	344	233	357

[a] Sludge generated in the WWTP. Blackwater in Santiago was used to derive brown water and yellow water, by applying the transfer coefficients for urine-diverting toilets.

Table 4
Summary of life cycle inventory for the scenarios assessed (units/year). For scenario abbreviations, see Table 2.

	Parameter	Units	BSL	DS1	DS2	ST1	ST2	SF1	SF2	OB1	OB2
Toilet	Tap water	m^3	13.1	–	–	13.1	39.4	13.1	13.1	39.4	13.1
WWTP	Electricity	kWh	0.540	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	Ferric chloride	kg	1.24	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
	Silicone	kg	0.0350	0.0320	0.0320	0.0320	0.0320	0.0320	0.0320	0.0320	0.0320
	Waste	kg	9.01	8.31	8.31	8.31	8.31	8.31	8.31	8.31	8.31
Sludge application	Electricity	kWh	0.0300	–	–	–	–	–	–	–	–
Pre-treatment transportation	Small truck	tkm	–	1150	1150	58.6	58.6	18.9	18.9	18.8	16.1
Post-treatment transportation	Large lorry	tkm	–	3554	453	45.5	171	16,200	16,200	16,200	16,500
Energy consumption	Electricity	kWh	–	–	9430	643	–	643	–	657	653
	Diesel	MJ	–	–	–	1150	–	1150	–	1150	1150
	Heat	MJ	–	–	–	–	–	–	–	57.6	39.9
Product application	Liquid spreader	m^3	–	62.0	36.4	60.7	60.7	53.9	53.9	53.9	55.1
	Solid spreader	kg	–	–	–	–	3340	1200	4500	1200	1020
Avoided products	Fertilizer	kg N	–	92.0	100	20.9	13.8	83.1	76.3	82.5	86.0
	Electricity	kWh	–	–	–	–	–	–	–	160	281
	Heat	MJ	–	–	–	–	–	–	–	623	1090
Air emissions	Ammonia	kg	7.36	27.6	19.0	13.1	19.2	25.5	37.1	26.2	23.5
	Phosphorus	kg	–	–	0.0500	0.0200	–	0.0300	–	0.0300	0.0300
	Methane	kg	132	31.0	111	0.670	24.0	1.06	38.3	7.03	4.87
	Carbon Dioxide	kg	87.6	20.7	74.1	0.440	16.0	0.710	25.6	4.68	3.25
Water emissions	Nitrogen	kg	93.7	5.70	4.82	1.19	1.20	2.85	2.87	2.83	3.21
	Phosphorus	kg	5.37	–	–	0.0800	0.0800	0.170	0.170	0.170	0.170
	COD[a]	kg	294	30.1	20.5	11.1	8.58	20.2	16.2	17.7	20.8
Soil emissions	Nitrogen	kg	0.400	1.48	1.51	18.5	19.4	15.3	17.0	15.3	14.0
	Phosphorus	kg	0.0200	0.270	0.240	0.760	0.780	0.630	0.660	0.630	0.600
	COD	kg	127	10.8	8.15	152	134	175	146	155	147

[a] Chemical oxygen demand.

considering the city's current layout and land distribution. For the eucalyptus plantation, irrigated with the treated effluent, 150 km from Campo Grande was defined, also considering the current common practices of the state, i.e. where the eucalyptus plantations could most likely be located.

For the urban irrigation in scenarios ST1 and ST2, nitrogen was not considered an avoided product (fertilizer) as there is no agronomic use in the application land nor fertilizer requirements. Finally, it was assumed that all the technologies were situated in the local area or near the current location of Los Angeles WWTP, so all "small truck transport" was considered as travelling 15 km per emptying event.

The inventory values were inserted on Simapro® and the Ecoinvent database processes selected are listed in Table S2 in SM.

2.4.3. Impact assessment

For the impact assessment we used the Recipe® 2016 method (Midpoint, World – Hierachist version), as it is one of the most commonly used methods in LCA studies of wastewater treatment systems, for characterization and normalization factors. The environmental impact categories selected were related to emissions to water, soil and air, associated with nitrogen, phosphorus, heavy metals and carbon emissions, considering the following: global warming potential (GWP) in kg CO_2 eq., terrestrial acidification (TAD) in kg SO_2 eq., freshwater eutrophication (FET) in kg P eq., marine eutrophication (MET) in kg N eq., terrestrial ecotoxicity (TEC) in kg 1.4-DCB, freshwater ecotoxicity (FEC) in kg 1.4-DCB, human carcinogenic toxicity (HCT) in kg 1.4-DCB, and human non-carcinogenic toxicity (HNCT) in kg 1.4-DCB. As the study included water reclamation, it was also relevant to analyze water consumption (WC) in m^3, according to Huijbregts et al. (2017).

2.5. Sensitivity analysis

Sensitivity analysis was performed for a few extra modifications of the scenarios. We changed the following parameters: toilet type (in the flush scenarios it was considered a tankless flush toilet with 18 instead of 6 l/flush), transport distance (increased from 50 to 150 km), electricity consumption (from Brazilian mix to global mix), marginal electricity (from natural gas to the country mix), and the process for diesel consumption (different machinery). The description of the parameters varied in the scenarios, as shown in Table 5.

2.6. Limitations

According to Spuhler et al. (2021), the application of the Santiago tool brings some limitations as it does not represent a detailed mass flows analysis of the systems, and it cannot replace one as such. In this sense, the calculations obtained from the mass flows and TCs from the software brings with them a certain level of uncertainty.

Further, the flows are restricted to solids, nitrogen and phosphorus, requiring specific data for heavy metals, which was not possible to obtain. Hence, the heavy metals were not modelled in this assessment what could potentially underestimate some impacts especially when it comes to water reuse.

3. Results and discussion

3.1. Characterization results

The characterized net results for all impact categories are presented in Fig. 2 and the normalized results in Table 6. It is important to note that positive values represent environmental burdens and negative values represent savings. Detailed results for each impact category for every scenario assessed can be found in Table S3 in SM.

The results showed that in all categories, most scenarios gave net burdens, i.e., environmental impacts. The baseline scenario (BSL) showed

Table 5
Summary of parameters altered in sensitivity analysis. For scenario abbreviations, see Table 2.

Sensitivity (parameter)	Description	Scenarios where applied
Toilet type	Water consumption increased from 6 to 18 l/flush	BSL, ST1, ST2, SF1, SF2, OB1, OB2
Transportation	Transportation increased from 50 to 150 km	DS1, DS2, ST1, ST2
Electricity	"Electricity, medium voltage {GLO}| market group for | APOS, S"	DS2, ST1
Electricity marginal	"Electricity, high voltage {BR}| market for | APOS, S"	OB1, OB2
Diesel	"Machine operation, diesel, ≥18.64 kW and <74.57 kW, generators {GLO}| market for | APOS, S"	ST1, SF1

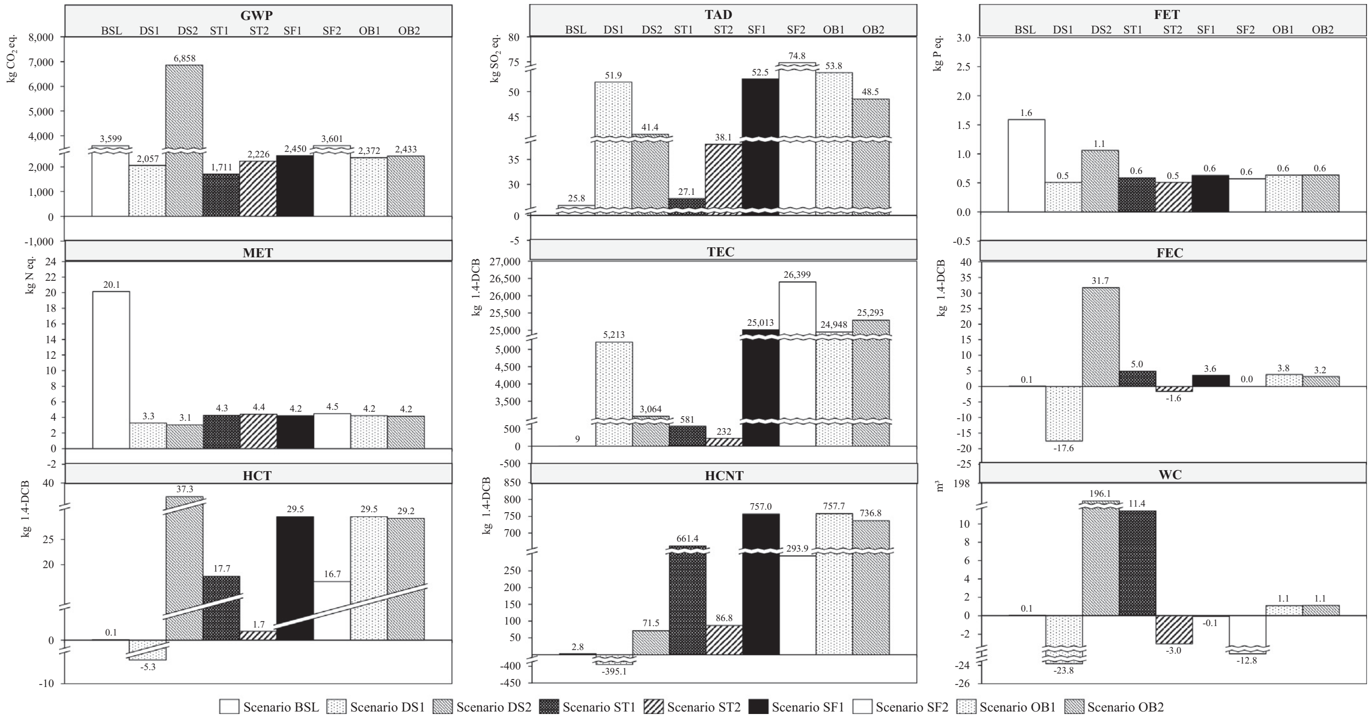


Fig. 2. Characterized results for global warming potential (GWP), terrestrial acidification (TAD), freshwater eutrophication (FET), marine eutrophication (MET), terrestrial ecotoxicity (TEC), freshwater ecotoxicity (FEC), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HNCT) and water consumption (WC) in the different scenarios. For scenario abbreviations, see Table 2.

low potential impacts for acidification, the toxicity categories, and water consumption. However, as expected it showed significant impacts for global warming and the eutrophication categories, due to gaseous emissions and nutrient emissions to water, respectively.

Scenario DS1, with urine and feces storage, gave net savings in four (FEC, HTC, HNTC, WC) out of the nine impact categories, making it the scenario with the best environmental performance. The separation of feces and urine gave benefits compared with the conventional treatment, as did the scenarios with UDDT that also ranked high in Santiago. The same happened for phosphorus recovery, as the Santiago scenarios with the highest potential in the software were based on UDDTs, while most phosphorus was lost in greywater treatment in the UASB reactors at Los Angeles WWTP. Landry and Boyer (2016) also found that scenarios with source separation had 90% lower environmental impacts (using TRACI method), due to reductions in water consumption and electricity use. For the source-separated brownwater treated at a decentralized alternative, the emissions were decreased in scenario DS1 but not in scenario DS2, which had high electricity consumption and consequently high overall emissions because of the Aurin treatment. According to Besson et al. (2021), urine source separation has a low environmental footprint, with potential impacts on global warming decreased by 45% compared with centralized treatment. In the LCA performed by Spångberg et al. (2014), a source separation scenario also performed well in terms of conserving energy and reducing GWP, but it increased the eutrophication and acidification impacts. As shown in Fig. 2, this was also found here on comparing scenarios BSL and DS1, i.e., lower GWP but higher terrestrial acidification impacts. This is likely due to ammonia emissions from storage and fertilizer application. On the other hand for eutrophication, the BSL scenarios showed higher impacts for both categories, as the UASB reactor does not remove nutrients.

Reuse of effluent in urban reclamation was beneficial in decreasing impacts in several categories, confirming findings by Opher and Friedler (2016). However, the assumption that the existing WWTP was used for greywater treatment did not allow greater environmental gains for the solid fertilizer and onsite biogas scenarios (SF1, SF2, OB1, and OB2).

In the case study area, electricity consumption was the main burden in the GWP, FET and WC impact categories (Table S3 in SM). This is in line with the study by Shi et al. (2018), in which electricity consumption increased the burdens to terrestrial ecotoxicity in resource-oriented toilet systems. In their study, electricity consumption was the main contributor to GWP, acidification potential, eutrophication potential, FEC, human toxicity potential, marine ecotoxicity, and TEC.

Table 6
Normalized net results (expressed in person equivalents (PE)) obtained for the different environmental impact categories in the nine scenarios considered. For scenario abbreviations, see Table 2.

	GWP	TAD	FET	MET	TEC	FEC	HCT	HNCT	WC
BSL	0.571	0.352	8.27	6.05	0.00858	0.0756	0.0328	0.0189	0.000194
DS1	0.306	1.27	3.11	1.02	5.03	−14.3	−1.91	−2.65	−0.0756
DS2	0.907	1.01	3.96	0.972	2.96	25.9	13.5	0.480	0.742
ST1	0.263	0.662	3.24	1.24	0.561	4.04	6.39	4.44	0.0432
ST2	0.327	0.928	3.11	1.27	0.224	−1.31	0.627	0.582	−0.0107
SF1	0.355	1.28	3.30	1.27	24.1	2.94	10.7	5.08	0.00415
SF2	0.499	1.83	3.21	1.28	25.5	0.00133	6.02	1.97	−0.0430
OB1	0.345	1.31	3.30	1.22	24.1	3.10	10.6	5.08	0.00862
OB2	0.353	1.18	3.31	1.21	24.4	2.58	10.5	4.94	0.00871

Note: Red indicates the highest value in the category and green the lowest.

3.1.1. Global warming potential (GWP)

As climate change is currently one of the main concerns worldwide, the specific contributions to this category were further analyzed (Fig. 3).

The scenario with the greatest contribution to GWP was DS2 (Aurin treatment), followed by SF2 (ABR + LaDePa) and the BSL scenario. The high emissions in these scenarios were mostly due to the large electricity consumption for the Aurin and LaDePa treatment processes, and from the biogas released in the baseline (CH_4 and CO_2 emissions). The high emissions from the WWTP were replicated in all scenarios, as a result of the assumed greywater treatment. UASB reactors are designed to treat raw wastewater, achieving good organic matter removal efficiency, and can achieve better environmental performance with biogas recovery and sludge for land application, according to Bressani-Ribeiro et al. (2019).

According to Lopes et al. (2020), UASB reactors make large contributions to GWP when methane is not recovered or flared, which is the case in Campo Grande and also in the study by Cornejo et al. (2013). The biogas generated in the reactor plays a crucial role, as it can bring savings to the system if it is recovered. When it is emitted directly to the atmosphere, it has high environmental impacts in terms of climate change, as shown here for the BSL scenario and for greywater treatment in the WWTP.

In an assessment by Risch et al. (2021), a septic tank scenario had the greatest impacts on endpoint categories due to CH_4 and NH_3 emissions. In the case studied here, the main contributions to GWP from septic tank scenarios was due to emissions from transportation (scenarios SF and OB). In fact, scenario ST1 presented the lowest emissions to GWP, with an on-site septic tank and the effluent going to urban irrigation.

Co-composting presented considerably higher emissions than constructed wetlands (represented by “effluent” in scenarios SF and OB). Wetlands have been shown to be beneficial for reducing climate impacts in several studies, mainly for small communities and when compared with technologies with high energy consumption, such as activated sludge (Garfí et al., 2017; Kobayashi et al., 2020). Co-composting was considered as windrows, hence the high CO_2 emissions, which could be improved by an enclosed setting with gas capture, but it requires more operation and maintenance and it is more costly.

Transport is also an important contributor to climate change, due to the carbon emissions from combustion, as indicated particularly in scenarios SF1, SF2, OB1, and OB2. These emissions were more significant than electricity consumption in more scenarios and the CH_4 emissions from greywater treatment by the UASB reactors. By changing the suggested human-powered transport to small trucks, the transport contributions to GWP were high, representing more than half of total emissions for the aforementioned scenarios.

Thus, none of the scenarios studied brought net savings to the system in Campo Grande and even the one with the lowest net value (scenario ST1) still represented a considerable environmental burden. However, most scenarios reduced the net CO_2 emissions by 30–50% from the baseline, which can be considered significant savings in terms of climate change, with the greatest savings achieved in scenario DS2, followed by OB2. This highlights the potential trade-offs between nutrient recovery and greenhouse gas (GHG) emissions. Since the Santiago software does not consider GHG emissions, it is difficult to capture these trade-offs simply by using it alone. A pathway for improvement could be to implement additional trade-off factors in the software.

3.1.2. Terrestrial acidification (TAD)

The TAD category is affected mainly by gaseous emissions, especially ammonia, sulfur dioxide and nitrogen compounds (such as nitrogen oxides and nitrate). Hence, the highest contributor to the category was scenario SF2, with co-composting of sludge, followed by OB1, SF1, and DS1. This was mainly due to specific air emissions, as ammonia and nitrogen oxides, from the treatment processes, such as co-composting and constructed wetlands, and product transportation. The lowest result was for ST1 - LaDePa and urban irrigation. Both ST1 and SF1 employ the LaDePa process, however the addition of a wetland in the SF1 scenario raises the ammonia emissions by almost 100%.

Remy and Jekel (2008) also found that composting of feces and urine application gave high ammonia emissions, contributing to acidification. Emissions could be minimized by using more advanced techniques for urine application, such as drag hoses and liquid injection, and enclosed composting with off-gas cleaning. However, these additions would make the systems more complicated and could thus reduce net benefits through increased operational and maintenance tasks and costs. Compared with the BSL scenario these alternatives suggested by Santiago would be even less attractive for Campo Grande, as they would demand extra skilled labor and investments.

3.1.3. Eutrophication (FET, MET)

Eutrophication is one of the fundamental categories considered in LCA of WWTP because the main goal of a WWTP is to remove organic matter

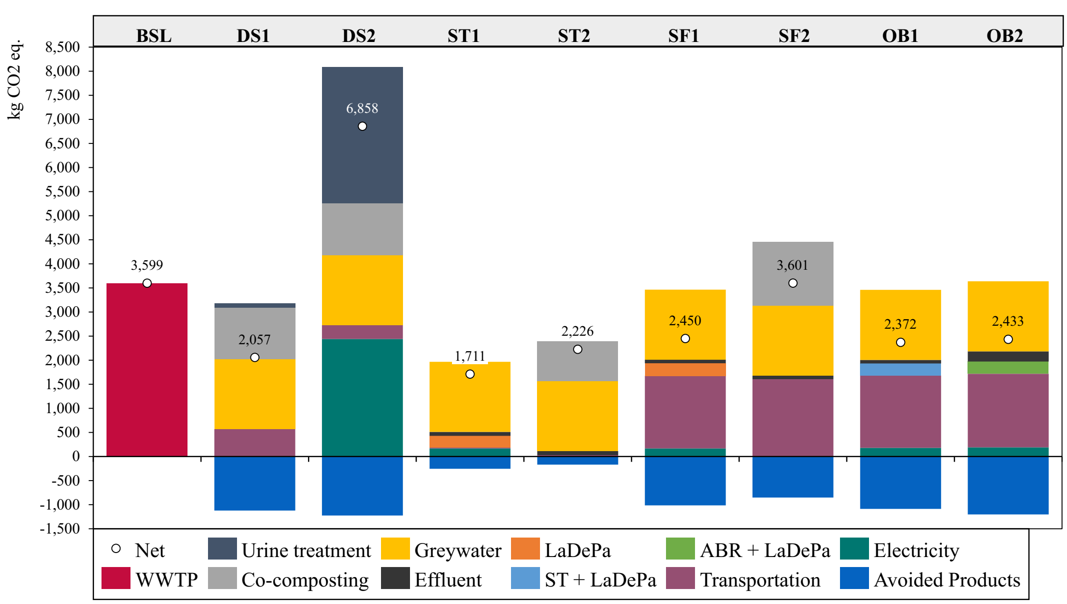


Fig. 3. Global warming impact and individual contributions from each scenario, in kg CO_2 eq. For scenario abbreviations, see Table 2. Note: “Effluent” refers to all the processes in the stream used to treat the effluents, such as wetlands (scenarios ST, SF, and OB) and the savings from irrigation; “Transportation” is the sum of all transport by different trucks in the scenarios; and “Electricity” refers to consumption in the treatment processes. All technologies include consumption, emissions, and savings.

and nutrients that would otherwise end up in water streams (Corominas et al., 2020). The category with the lowest variation in the results was freshwater eutrophication (FET), with an average contribution of 0.750 kg $P_{eq.}$ from the different alternative scenarios. This is compared to the BSL scenario at 1.60 kg $P_{eq.}/m^3$ of treated wastewater. For comparison, Lopes et al. (2020) found emissions of 0.046 kg PO_4/m^3 and Cornejo et al. (2013) emissions of 0.051 kg PO_4/m^3 from UASB reactors. This discrepancy can be explained by the WWTP being re-calculated for a single-family flow in our assessment, so the emissions were higher than in the real system with industrial influents and the lack of tertiary treatment. However, in all alternative scenarios most of the FET and MET contributions were from greywater treatment, due to discharge of phosphorus by the WWTP to water and application on infertile soil. In scenario DS2, the second largest contribution to FET was from the high electricity consumption, due to hydropower plants requiring dams and reservoirs and involving reduction of river flows, affecting the water quality. Therefore, phosphorus recovery from greywater treatment (not included in this study) could reduce overall environmental impacts by producing water for reuse and nutrients that can be applied in agriculture.

In marine eutrophication (MET), the highest contribution was from the sludge treatment and soil application, followed by nitrogen discharge to water from the WWTP, in scenario BSL. However, the nitrogen was not offset as a fertilizer, since the land to which it is currently applied has no agronomic use and does not require fertilizer, so it did not provide any savings for the system.

3.1.4. Toxicity (TEC, FEC, HTC, HNTC)

In general, heavy metals are the main contributors to toxicity categories and during the wastewater treatment they can accumulate in the sludge. As the specific heavy metals flows from the wastewater were not considered in this assessment due to lack of data, combustion of transport fuels in vehicles and electricity consumption are of the main sources of heavy metals that were considered among the Simapro® processes.

Terrestrial ecotoxicity (TEC) showed the highest values of the four toxicity categories. Scenario SF2 had the highest emissions of copper (Cu) and zinc (Zn) from the transportation, followed by scenarios OB2, SF1 and OB1. As a result of the sanitation system transporting wastewater with gravity pipes and keeping the by-products on-site, the BSL scenario made the smallest contribution to TEC, 8.89 kg 1.4-DCB eq. Comparing this value with the highest in the category (26,399.03 kg 1.4-DCB eq. in scenario SF2) revealed the major role of transport for TEC. In regards to scenarios SF1 and SF2 that have the same transportation level, the difference lies in the LaDePa process that consumed diesel and electricity and contributes with higher burdens to the category in scenario SF1.

For the freshwater ecotoxicity (FEC), human carcinogenic toxicity (HCT), and human non-carcinogenic toxicity (HNTC) categories, the impacts were much smaller, but varied widely between the categories and scenarios. For example, for FEC and HCT the highest contribution was from scenario DS2, due to electricity consumption. For HCT, scenarios SF1 and OB1 made the highest contributions, from the large lorry combined with diesel consumption in the LaDePa process. Therefore, even with the same treatment technologies these categories had quite different characterization factors depending on the different elements that were significant for them.

3.1.5. Water consumption (WC)

For the WC category, scenario DS2 also displayed the worst performance, due to high electricity consumption, as discussed below in connection with the sensitivity analysis results. On the other hand, large net savings were achieved in scenarios DS1 (dry toilet) and SF2. The difference between scenarios SF1 and SF2 was the LaDePa process in SF1, which also consumed electricity and therefore had a WC burden similar to scenario DS2, while scenario SF2 only had savings in the category, performing better than the other scenarios.

According to Canaj et al. (2021), reuse of treated wastewater may increase global impacts, such as GWP and toxicities, and decrease local impacts, such as WC and eutrophication. Although there are more overall benefits than impacts when aggregating physical and monetary weights, the trade-off in each situation needs to be assessed in order to draw reliable conclusions. This was found in the case of Campo Grande, as water reuse represented large savings for water consumption, but posed burdens for climate change due to the transportation of such large volumes, as shown in Figs. 2 and 3.

According to Risch et al. (2014), understanding and considering water consumption and its impacts in wastewater treatment systems is important for decision-making on mitigating water deprivation. Therefore, toilet types and different water consumption patterns were further assessed in the sensitivity analysis. However, it was already possible to see that, water consumption in flush toilets did not play a large role when compared with the high electricity consumption from hydropower. That is the reason why scenario BSL had such low impact values, because it did not require electricity, transport, or diesel. However, the relationship between the treatment technology chosen (and its water consumption) and the treatment location can affect the deprivation impacts. West-central Brazil has one of the largest freshwater reserves in the world, so high water consumption does not pose a problem, but in arid and semi-arid locations it can be critical (Risch et al., 2014).

3.2. Normalization results

The normalized results are shown in Table 6, with red and green representing best and worst performance, respectively, within the categories. Ecotoxicity categories were most relevant according to the normalization factors, with TEC, FEC, HCT, and HNCT having almost 10-fold higher values than the other impact categories. Ecotoxicity categories have high characterization factors, and therefore greater impact potential than other categories, in the ReCiPe method. Normalization compares the categories in terms of potential impact on global scale and ecotoxicity categories directly affect human health and ecosystem quality, increasing the relevance of these categories globally.

Scenario DS1, which employed a urine bank and tank with no energy consumption, not only had the lowest impacts in the categories but also gave negative contributions, i.e., savings, for FEC, HTC, HNCT, and WC, as the savings from the nitrogen fertilizer outweighed the emissions from the process. This is in agreement with Remy and Jekel (2008), who showed that source separation systems are not necessarily more sustainable than conventional systems in a highly urbanized context, but can be sustainable when the end-products are used in agriculture. Storage recommendations for disinfection of human urine separated at the source can vary from 30 to 180 days, according to Schönning and Stenström (2004), with a minimum of 30 days most commonly used. However, the storage step may require large tanks that occupy a large area and require attention in terms of maintenance and operation, which indicates that further analysis of these factors is necessary to support decision-making (Ishii and Boyer, 2015). For the case of Campo Grande or even the west-central region of Brazil, this would not be a problem, as the population density is low and there is much available land, especially in rural areas. Therefore, there is good potential for implementing this type of system in rural and peri-urban areas, which commonly lack proper sanitation systems.

The best environmental performance was shown by a urine-diversion system, but also the worst performance. Scenario DS2 had the worst performance in four categories (GWP, FEC, HCT, and WC), due to the nitrification and distillation process with high electricity consumption. Shi et al. (2018) also found that high energy consumption in urine treatment systems contributes to environmental impacts, which is similar to our results for the Aurin treatment. However, that study concluded that resource-oriented toilet systems (source separation) are more beneficial than conventional systems in both economic and environmental terms. Use of urine and other products in agriculture can increase the benefits and trade-offs can be achieved by reducing chemical fertilizer consumption. Maurer et al. (2003) demonstrated this, with reductions in GWP impact compared with conventional treatment in a WWTP. A review by Lam et al. (2020) showed that, regardless of the specific parameters adopted, most studies comparing source separation for nutrient recovery with conventional treatment report lower GWP (over 50% reduction in half of the studies analyzed). This was true for most of our alternative scenarios, but not for those with high electricity consumption (DS2 and SF2).

Previous studies have found that, due to high ammonia emissions during urine storage and application, and composting of feces, scenarios with source-separated urine/feces application have higher acidification potential (+50%) and eutrophication potential (+10%) than centralized treatment scenarios (Maurer et al., 2003; Remy and Jekel, 2008; Spångberg et al., 2014). This was also true for TAD in the present assessment when comparing the alternative scenarios with the BSL. These impacts can be reduced by ensuring that storage tanks are sealed to retain the ammonia and by using enclosed composting instead of windrows.

3.3. Sensitivity results

The outcomes for climate change and water consumption of changes tested in the sensitivity analysis (see Table 5) are summarized in Fig. 4. Detailed results for all parameters and impact categories can be found in the SM.

Values on or near the x-axis in Fig. 4 indicate little or no change in GWP or WC compared with the "baseline" results (see Fig. 2). For GWP, the most significant change was found by varying transportation in scenario DS1, with an increase of more than 2-fold, due to increased transport of liquid urine. The next largest change was found in the change in electricity, from the Brazilian mix to the global mix, increased the GWP contribution by 67.2% in scenario DS2 and 18.4% in scenario ST1. This is due to the global electricity matrix being based more on fossil fuels. The change in marginal electricity from natural gas to the mix for "avoided elec" gave only a small increase in the impacts (0.90 and 1.60% for OB1 and OB2 respectively). For diesel, the impacts were reduced when considering a "machine operation, diesel" rather than "diesel burned in agricultural machinery" for combustion (Table 5). In this case scenario ST1 gave an 8.50% reduction and scenario SF1 a 5.90% reduction.

For water consumption (lower panel in Fig. 4), a change in toilet type, represented by "tankless", did not make a great contribution. However, this may be because the study region is not water-stressed, and different results could be expected in places facing severe water scarcity.

The impacts of electricity consumption on WC more than halved in scenarios DS2 and ST1 and decreased by more than 200% for the avoided electricity scenarios (OB1 and OB2), yielding considerable savings. This confirmed that electricity was a critical parameter for WC in the analysis, and therefore it should be explored further and taken into consideration in the decision-making process.

Overall, it can be inferred that, for countries with water issues, water consumption in general, and not just in toilets, needs to be assessed in combination with electricity consumption and water resource in the study location.

3.4. Improvements towards resource recovery

In comparative LCA, the focus is not on forecasting impacts but on determining potential differences between the alternatives assessed (Lam et al., 2020). This assessment showed that most alternative scenarios, besides being uncommon in Brazil, did not give significantly better environmental performance than the current WWTP, BSL scenario. The exception was source separation in scenario DS1, which proved to be beneficial in several impact categories.

These results indicate that the UASB reactors can achieve satisfactory environmental performance, when involving gravity transport of wastewater, compared with technologies involving high energy consumption. The environmental performance can be further improved if simpler systems with low electricity consumption and high rates of resource recovery are used.

Many WWTPs employ activated sludge as the main treatment, which requires a large amount of electricity. In such cases electricity consumption increases the environmental impacts, making other alternatives more beneficial, nature-based technologies for example (Garfí et al., 2017). However, none of the alternative systems assessed here was fully satisfactory and showed good performance in all impact categories. The high emissions from the UASB reactor, which contributed greatly to climate change, cannot be overlooked and should be rectified.

Therefore, all systems needed some kind of change or adaptation for resource recovery efficiency and better environmental performance. The current environmental impacts from the BSL scenario could be greatly reduced by adding resource recovery alternatives, such as nutrient recovery (P and N), energy recovery from biogas, and water reuse (represented by scenarios DS1, SF2, OB1, and OB2).

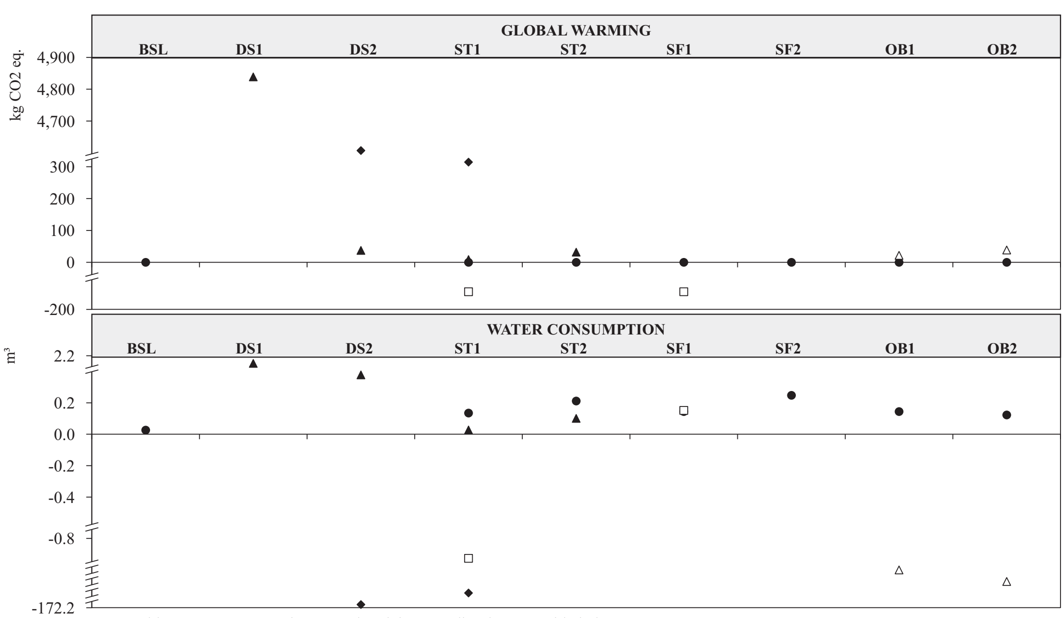


Fig. 4. Outcomes of the sensitivity analysis for (upper panel) global warming and (lower panel) water consumption. The x-axis shows the original "baseline" values, while "tankless" refers to a change of toilet type from 6 to 18 l/flush; "transportation" to a change in distance travelled from 50 to 150 km; "electricity" a change from the Brazilian to the world mix; "diesel" a machinery change for diesel consumption; and "avoided elec" a change in the marginal electricity to high voltage.

According to Cornejo et al. (2013), energy recovery from UASB reactors can greatly reduce the carbon footprint, e.g. when combined with water reuse it can reduce the carbon footprint by more than 56%. Awad et al. (2019) found that including a tertiary treatment for water reuse in WWTPs positively affected all impact categories, with the benefits far exceeding the impacts of consumption of energy and materials for the treatment itself. Lutterbeck et al. (2017) concluded that UASB reactors followed by tertiary treatment has the potential to make the entire system environmentally friendly, due to major reductions in negative impacts.

Brazil uses the largest quantity of UASB reactors per capita for wastewater treatment in the world (Chernicharo et al., 2017). Incorporating recovery of resources in existing systems could thus provide great opportunities to achieve sustainability in the Brazilian sanitation sector.

3.5. Recommendations for Santiago

Nisaa et al. (2021) used Santiago to generate systems for Lima, Peru, and concluded that the software is applicable to Latin America. However, their case study was a peri-urban area with no sanitation system in place. When generating scenarios for Campo Grande, Santiago did not consider the greywater stream for the alternative systems, which proved to be the greatest weakness of the software in this case. Greywater is the main fraction of household wastewater and not considering it in an urban context with a wastewater system already implemented is unrealistic. Rural and peri-urban areas may be more flexible in managing greywater, as infiltration can be an option.

When comparing systems, especially in LCA, they need to have the same structure. By adding the greywater stream to make scenarios comparable to the baseline, we altered the appropriateness scores provided by the software and also the entire system. This must be considered in decision-making, and also to enable comparison with current systems that most likely handle the entire wastewater fraction.

The lack of heavy metal mass flows, calls for data gathering when coupling the software with any other systems analysis. Since these elements can be hard to remove, they can remain in the products obtained by their systems and affect the usage/application. Therefore, it is important to consider this aspect in the tool and further studies assessing the environmental impacts connected to these elements in novel technologies are necessary.

Scenario DS2 had the worst performance in five categories (GWP, FET, FEC, HCT, WC), largely due to high electricity use, indicating that appropriate systems provided by Santiago are not necessarily the most environmentally friendly or sustainable. However, selection of systems could be adapted in the tool, e.g., to exclude the most energy-intensive technologies when decision-makers are considering environmental performance. Such definitions should be introduced in the software to produce results more in line with high environmental performance.

The Santiago software is currently not designed to provide the most suitable alternatives from an environmental perspective, e.g., co-composting treatment may be appropriate due to physical attributes but it still has emissions to climate change and does not enable water savings. The best nutrient-capture technologies have other negative drawbacks that should be considered in Santiago, e.g., through addition of a function to weight or rank the attributes in terms of local environmental needs.

The prevalence of “human-powered transportation” in systems generated by Santiago should be reviewed, as we had to change the transportation type in order to better match existing transportation patterns. Input categories should be adjusted so that the outputs from Santiago can better match established practices and transportation infrastructure, perhaps by introducing a local parameter reflecting existence of a mechanical emptying service or current extent of human-powered emptying. In the case of Campo Grande, where manual emptying and human-powered transport is rare, the Santiago solutions including such transport were unrealistic.

In selecting systems for resource recovery, Santiago provided systems that are not very common in Brazil. These more advanced alternatives may be suited for the reality of developed countries, but Brazil and most low- and middle-income countries are still facing challenges with collecting all wastewater generated. However, some of the alternatives provided by Santiago show the potential of new decentralized systems in the country. It is easier and less expensive to establish small-scale decentralized systems in different areas of a city than to build new sewer networks. Therefore, some adjustments should be made in the software to include more environmental benefits in other scenarios generated for specific cases, since the only scenario that matched both requirements of most appropriate system in Santiago and the best environmental performance, was DS1.

4. Conclusions

Life cycle assessment of novel sanitation scenarios produced using the Santiago software showed that none of the scenarios had good overall environmental performance compared with the baseline. Our overall results are mainly useful for LCA practitioners looking to couple different approaches and decision-makers trying to assess novel alternatives. Due to the lack of data for heavy metals, further studies should follow addressing this aspect.

The Santiago scenario with the best overall environmental performance was source separation of urine and feces for storage and application as fertilizer. This suggests that source separation should be considered and evaluated by decision-makers. However, this study also revealed trade-offs between different impact categories, with several of the alternative resource recovery systems suggested by Santiago coming at the cost of negative environmental impacts in other categories. It is important to consider these trade-offs in decision-making. The main benefits of the current system are low electricity consumption and good performance in a tropical climate, but greater resource recovery would improve the environmental performance. Measures such as energy recovery from biogas and tertiary treatment for water reuse could add savings to the system and reduce the environmental burden.

For the case of Campo Grande in west-central Brazil, the existing UASB reactors for wastewater treatment performed relatively well in the LCA. The Santiago software was able to suggest some alternatives which, in addition to recovering nutrients, also performed better in some impact categories. Transportation played a major role in climate change and terrestrial ecotoxicity, which was confirmed in the sensitivity analysis. Electricity consumption was the second most critical parameter and was associated with the highest emissions in several categories, also confirmed by the sensitivity. Using different volumes of water in toilets did not have significant impacts on water consumption in Campo Grande, but can be critical in regions with water scarcity.

Thus some additional features should be added to the software, to consider more environmental factors and select technologies based on several categories, since e.g., selection for low GWP may lead to exclusion of technologies with high energy consumption. In addition, the software should be adapted to allow existing sanitation infrastructure, such as transportation systems or treatment units, to be included. Existing infrastructure and associated knowledge capacity can increase public acceptance and enable rapid implementation of technologies.

CRediT authorship contribution statement

Priscila de Morais Lima: Conceptualization, Methodology, Investigation, Writing – original draft. **Thais Andrade de Sampaio Lopes:** Validation, Writing – original draft. **Luciano Matos Queiroz:** Writing – review & editing, Supervision. **Jennifer Rae McConville:** Conceptualization, Validation, Writing – review & editing.

Declaration of competing interest

Priscila de Morais Lima reports financial support was provided by Swedish Research Council.

Acknowledgements

The authors are grateful for financial support from the Swedish Research Council (project number: 2016-01076).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.155777.

References

ANA, de Á., A.N., 2017. Atlas esgotos: despoluição de bacias hidrográficas.

Awad, H., Gar Alalm, M., El-Etriby, H.K., 2019. Environmental and cost life cycle assessment of different alternatives for improvement of wastewater treatment plants in developing countries. Sci. Total Environ. 660, 57–68. https://doi.org/10.1016/j.scitotenv.2018.12.386.

Bernstad Saraiva, A., Souza, R.G., Valle, R.A.B., 2017. Comparative lifecycle assessment of alternatives for waste management in Rio de Janeiro – investigating the influence of an attributional or consequential approach. Waste Manag. 68, 701–710. https://doi.org/10.1016/j.wasman.2017.07.002.

Besson, M., Berger, S., Tiruta-barna, L., Paul, E., Spérandio, M., 2021. Environmental assessment of urine, black and grey water separation for resource recovery in a new district compared to centralized wastewater resources recovery plant. J. Clean. Prod. 301. https://doi.org/10.1016/j.jclepro.2021.126868.

Bressani-Ribeiro, T., Mota Filho, C.R., de Melo, V.R., Bianchetti, F.J., Chernicharo, C.A.de L., 2019. Planning for achieving low carbon and integrated resources recovery from sewage treatment plants in Minas Gerais, Brazil. J. Environ. Manage. 242, 465–473. https://doi.org/10.1016/j.jenvman.2019.04.103.

Canaj, K., Mehmeti, A., Morrone, D., Toma, P., Todorović, M., 2021. Life cycle-based evaluation of environmental impacts and external costs of treated wastewater reuse for irrigation: a case study in southern Italy. J. Clean. Prod. 293. https://doi.org/10.1016/j.jclepro.2021.126142.

Chernicharo, C.A.L., Brandt, E.M.F., Bressani-Ribeiro, T., Melo, V.R., Bianchetti, F.J., Motafilho, C.R., McAdam, E., 2017. Development of a tool for improving the management of gaseous emissions in UASB-based sewage treatment plants. Water Pract. Technol. 12, 917–926. https://doi.org/10.2166/wpt.2017.097.

Cornejo, P.K., Zhang, Q., Mihelcic, J.R., 2013. Quantifying benefits of resource recovery from sanitation provision ina developing world setting. J. Environ. Manag. 131, 7–15. https://doi.org/10.1016/j.jenvman.2013.09.043.

Corominas, L., Byrne, D.M., Guest, J.S., Hospido, A., Roux, P., Shaw, A., Short, M.D., 2020. The application of life cycle assessment (LCA) to wastewater treatment: a best practice guide and critical review. Water Res. 184. https://doi.org/10.1016/j.watres.2020.116058.

FNR, e. V., F.N.R., 2013. Biogas: An Introduction. https://doi.org/10.1016/S1877-1203(19)30156-9.

Fumasoli, A., Etter, B., Sterkele, B., Morgenroth, E., Udert, K.M., 2016. Operating a pilot-scale nitrification/distillation plant for complete nutrient recovery from urine. Water Sci. Technol. 73, 215–222. https://doi.org/10.2166/wst.2015.485.

Gallego-Schmid, A., Tarpani, R.R.Z., 2019. Life cycle assessment of wastewater treatment in developing countries: a review. Water Res. 153, 63–79. https://doi.org/10.1016/j.watres.2019.01.010.

Garfí, M., Flores, L., Ferrer, I., 2017. Life cycle assessment of wastewater treatment systems for small communities: activated sludge, constructed wetlands and high rate algal ponds. J. Clean. Prod. 161, 211–219. https://doi.org/10.1016/j.jclepro.2017.05.116.

Gonçalves, R.F., 2009. Uso Racional de Água e Energia (Rational Use of Water and Energy). PROSAB edital no 5.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y.

IBGE, I.B.de G.e E., 2021. Campo Grande [WWW Document]. https://cidades.ibge.gov.br/brasil/ms/campo-grande/panorama.

Ishii, S.K.L., Boyer, T.H., 2015. Life cycle comparison of centralized wastewater treatment and urine source separation with struvite precipitation: focus on urine nutrient management. Water Res. 79, 88–103. https://doi.org/10.1016/j.watres.2015.04.010.

ISO, I.S.O., 2006a. ISO 14040 - Environmental Management - Life Cycle Assessment - Principles and Framework.

ISO, I.S.O., 2006b. ISO 14044-Environmental Management - Life Cycle Assessment - Requirements and Guidelines.

Kobayashi, Y., Ashbolt, N.J., Davies, E.G.R., Liu, Y., 2020. Life cycle assessment of decentralized greywater treatment systems with reuse at different scales in cold regions. Environ. Int. 134, 105215. https://doi.org/10.1016/j.envint.2019.105215.

Lam, K.L., Zlatanović, L., van der Hoek, J.P., 2020. Life cycle assessment of nutrient recycling from wastewater: a critical review. Water Res. 173. https://doi.org/10.1016/j.watres.2020.115519.

Landry, K.A., Boyer, T.H., 2016. Life cycle assessment and costing of urine source separation: focus on nonsteroidal anti-inflammatory drug removal. Water Res. 105, 487–495. https://doi.org/10.1016/j.watres.2016.09.024.

Lima, P.D.M., Colvero, D.A., Gomes, A.P., Wenzel, H., Schalch, V., Cimpan, C., 2018. Environmental assessment of existing and alternative options for management of municipal solid waste in Brazil. Waste Manag. 78, 857–870. https://doi.org/10.1016/j.wasman.2018.07.007.

Lopes, T.A.S., Queiroz, L.M., Torres, E.A., Kiperstok, A., 2020. Low complexity wastewater treatment process in developing countries: a LCA approach to evaluate environmental gains. Sci. Total Environ. 720. https://doi.org/10.1016/j.scitotenv.2020.137593.

Lutterbeck, C.A., Kist, L.T., Lopez, D.R., Zerwes, F.V., Machado, E.L., 2017. Life cycle assessment of integrated wastewater treatment systems with constructed wetlands in rural areas. J. Clean. Prod. 148, 527–536. https://doi.org/10.1016/j.jclepro.2017.02.024.

Maurer, M., Schwegler, P., Larsen, T.A., 2003. Nutrients in urine: energetic aspects of removal and recovery. Water Sci. Technol. 48, 37–46. https://doi.org/10.2166/wst.2003.0011.

McCarty, P.L., Bae, J., Kim, J., 2011. Domestic wastewater treatment as a net energy producer-can this be achieved? Environ. Sci. Technol. 45, 7100–7106. https://doi.org/10.1021/es2014264.

McConville, J., Niwagaba, C., Nordin, A., Ahlström, M., Namboozo, V., Kiffe, M., 2020. Guide to Sanitation Resource Recovery Products & Technologies.

Medeiros, D.L., Queiroz, L.M., Cohim, E., de Almeida-Neto, J.A., Kiperstok, A., 2020. Human urine fertiliser in the Brazilian semi-arid: environmental assessment and water-energy-nutrient nexus. Sci. Total Environ. 713, 136145. https://doi.org/10.1016/j.scitotenv.2019.136145.

Meinzinger, F., Oldenburg, M., 2009. Characteristics of source-separated household wastewater flows: a statistical assessment. Water Sci. Technol. 59, 1785–1791. https://doi.org/10.2166/wst.2009.185.

Morera, S., Corominas, L., Rigola, M., Poch, M., Comas, J., 2017. Using a detailed inventory of a large wastewater treatment plant to estimate the relative importance of construction to the overall environmental impacts. Water Res. 122, 614–623. https://doi.org/10.1016/j.watres.2017.05.069.

Muga, H.E., Mihelcic, J.R., 2008. Sustainability of wastewater treatment technologies. J. Environ. Manag. 88, 437–447. https://doi.org/10.1016/j.jenvman.2007.03.008.

Nisaa, A.F., Krauss, M., Spuhler, D., 2021. Adapting Santiago method to determine appropriate and resource efficient sanitation systems for an urban settlement in Lima Peru. Water (Switzerland) 13. https://doi.org/10.3390/w13091197.

Opher, T., Friedler, E., 2016. Comparative LCA of decentralized wastewater treatment alternatives for non-potable urban reuse. J. Environ. Manag. 182, 464–476. https://doi.org/10.1016/j.jenvman.2016.07.080.

Remy, C., Jekel, M., 2008. Sustainable wastewater management: life cycle assessment of conventional and source-separating urban sanitation systems. Water Sci. Technol. 58, 1555–1562. https://doi.org/10.2166/wst.2008.533.

Risch, E., Loubet, P., Núñez, M., Roux, P., 2014. How environmentally significant is water consumption during wastewater treatment?: application of recent developments in LCA to WWT technologies used at 3 contrasted geographical locations. Water Res. 57, 20–30. https://doi.org/10.1016/j.watres.2014.03.023.

Risch, E., Boutin, C., Roux, P., 2021. Applying life cycle assessment to assess the environmental performance of decentralised versus centralised wastewater systems. Water Res. 196, 116991. https://doi.org/10.1016/j.watres.2021.116991.

Schönning, C., Stenström, T.A., 2004. Guidelines for the Safe Use of Urine and Faeces in Ecological Sanitation Systems.

Septien, S., Singh, A., Mirara, S.W., Teba, L., Velkushanova, K., Buckley, C.A., 2018. 'LaDePa' process for the drying and pasteurization of faecal sludge from VIP latrines using infrared radiation. S. Afr. J. Chem. Eng. 25, 147–158. https://doi.org/10.1016/j.sajce.2018.04.005.

Shi, Y., Zhou, L., Xu, Y., Zhou, H., Shi, L., 2018. Life cycle cost and environmental assessment for resource-oriented toilet systems. J. Clean. Prod. 196, 1188–1197. https://doi.org/10.1016/j.jclepro.2018.06.129.

Spångberg, J., Tidåker, P., Jönsson, H., 2014. Environmental impact of recycling nutrients in human excreta to agriculture compared with enhanced wastewater treatment. Sci. Total Environ. 493, 209–219. https://doi.org/10.1016/j.scitotenv.2014.05.123.

Spuhler, D., Scheidegger, A., Maurer, M., 2018. Generation of sanitation system options for urban planning considering novel technologies. Water Res. 145, 259–278. https://doi.org/10.1016/j.watres.2018.08.021.

Spuhler, D., Scheidegger, A., Maurer, M., 2021. Ex-ante quantification of nutrient, total solids, and water flows in sanitation systems. J. Environ. Manag. 280, 111785. https://doi.org/10.1016/j.jenvman.2020.111785.

Tilley, E., Lüthi, C., Morel, A., Zurbrügg, C., Schertenleib, R., 2014. Compendium of sanitation systems and technologies. Development 180 https://doi.org/SAN-12.

UN, U.N., 2018. The Sustainable Development Goals Report 2018.