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An integrated assessment of environmental, economic, social and technological parameters of source separated and conventional sanitation concepts: A contribution to sustainability analysis

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ABSTRACT

Resource recovery and reuse from domestic wastewater has become an important subject for the current development of sanitation technologies and infrastructures. Different technologies are available and combined into sanitation concepts, with different performances. This study provides a methodological approach to evaluate the sustainability of these sanitation concepts with focus on resource recovery and reuse. St. Eustatius, a small tropical island in the Caribbean, was used as a case study for the evaluation. Three source separation-community-on-site and two combined sewerage island-scale concepts were selected and compared in terms of environmental (net energy use, nutrient recovery/reuse, BOD/COD, pathogens, and GHG emission, land use), economic (CAPEX and OPEX), social cultural (acceptance, required competences and education), and technological (flexibility/adaptability, reliability/continuity of service) indicators. The best performing concept, is the application of Upflow Anaerobic Sludge Bed (UASB) and Trickling Filter (TF) at island level for combined domestic wastewater treatment with subsequent reuse in agriculture. Its overall average normalised score across the four categories (i.e., average of average per category) is about 15% (0.85) higher than the values of the remaining systems and with a score of 0.73 (conventional activated sludge – centralised level), 0.77 (UASB-septic tank (ST)), 0.76 (UASB-TF - community level), and 0.75 (ST - household level). The higher score of the UASB-TF at community level is mainly due to much better performance in the environmental and economic categories. In conclusion, the case study provides a methodological approach that can support urban planning and decision-making in selecting more sustainable sanitation concepts, allowing resource recovery and reuse in small island context or in other contexts.

1. Introduction

Current developments of sanitation infrastructure have moved away from the focus on end of pipe treatment to the recovery of water, energy and nutrients for agriculture from wastewater. In this way, future sanitation systems do contribute to the achievement of Sustainable Development Goals (SDGs) related to clean water and sanitation (SDG 6) and other SDGs targets such as clean zero hunger (SDG 2), and sustainable consumption and production (SDG 12) (Andersson et al., 2016).

Two basic concepts for resource recovery from wastewater can be distinguished. Firstly, the recovery of water, energy and nutrients from municipal wastewater that is collected and transported in a conventional combined sewer and treated in a centralised treatment (Lee et al., 2013), for example, a Conventional Activated Sludge (CAS) treatment or an Upflow Anaerobic Sludge Blanket (UASB) reactor (Noyola et al., 2012). The second alternative is source separated sanitation (Zeeman, 2012). While many variations of separation at source exist, one common approach is to collect Black Water (BW, the mixture of urine, faeces, and flushing water) and Grey Water (GW, laundry, shower, bath and kitchen water) in two piping systems and treat them separately. Furthermore,

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source separated sanitation concepts often encompass the collection and management of Kitchen Waste (KW), which increases biogas yields (de Graaff et al., 2010).

Source separated sanitation is a system that enables a more (energy) efficient recovery of resources from BW or urine while GW remains relatively low in pollutants. Source separated sanitation is explored and applied as a promising alternative where currently no traditional combined sanitation infrastructure is in place, for instance, in developing countries which have yet to develop sanitation infrastructure (Bisschops et al., 2019). In cases where local economies face water shortage and high costs for agricultural inputs such as fertilisers, source separated sanitation is deemed appropriate to maximise the reuse of water and nutrients while also recovering energy (Larsen et al., 2013; Sharma and Sanghi, 2013). While this applies to developing countries, it might even be more applicable to small islands, where fresh water is typically scarce and agricultural goods such as food and fertiliser are imported (Saint Ville et al., 2015).

As the diversity of sanitation systems grows, a challenge current and future decision makers will face is which sanitation system to select and, maybe more importantly, which aspects to consider when selecting a sanitation system (Spuhler et al., 2020). This entails to find the most sustainable combination of technologies and sewer infrastructure (in the following called sanitation concept) in a given context. Similarly, it has been shown that a well-structured approach to sanitation planning can make decision variables of actors more explicit and hence lead to better decision outcomes in complex situations (Haag et al., 2019).

In this research it is proposed that the selection of a 'sustainable' sanitation system should cover the four dimensions of sustainability namely environmental, social-cultural, economic, and technological indicators. The first three dimensions are commonly described as the triple bottom line of sustainability, while the technological dimension has been proposed as especially important to sanitation systems (Spiller, 2016). The four dimensions need to be assessed across the entire technology train of each sanitation concept (i.e., from user interface to reuse) and include the aspects water reuse and nutrient reuse. However, due to the many indicators inherent in these four dimensions and the complexities of technological concepts, assessments so far are mainly partial. Previous authors are omitting parts of the technology train, such as sewer systems, or not covering all sustainability dimensions, required for a holistic appraisal. A majority of studies focuses on environmental assessments only (Kjerstadius et al., 2015; Prado et al., 2020). A number of studies also include economic aspects. Recent examples of this are Dewalkar and Shastri (2020) who provided an environmental and economic assessment of an on-site wastewater management system in a multi-storey residential building, while Chrispim et al. (2020) was focusing on the resource recovery at a centralized Wastewater Treatment Plant (WWTP).

One of the few approaches that addresses the increasing diversity of sanitation concepts is Spuhler et al. (2020). They developed a software tool (Santiago: SANitation sysTem Alternative GeneratOr) that enables the screening of 41 sanitation technologies and 27 selection criteria to generate a set of sanitation systems. However, in their publication, they do not provide a detailed account for the performance of different technologies along the four sustainability dimensions proposed in this research. Moreover, Spuhler et al. (2021) only focused on the environmental quantification of sanitation systems without considering social-economic indicators.

Following the considerations above, the aim of this study is to develop an approach to evaluate the sustainability of sanitation concepts that include the full train of technology from collection, transport, treatment/recovery, to reuse in agriculture or final disposal across different sustainability indicators (Fig. 1). The approach is intended to provide quantification methods that combine quantitative and qualitative assessment of sustainability indicators. The evaluation has been carried out for the case of a small developing tropical island system (St. Eustatius). Although the selected sanitation concepts in this study are case and context specific (e.g., tropical), the general approach adopted is relevant for a wide range of other contexts.

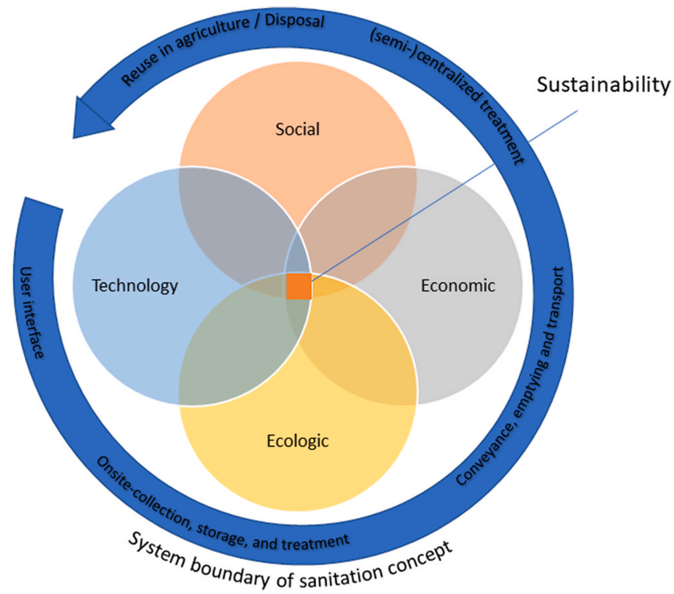

Fig. 1. Underlying theoretical framework of sustainable sanitation systems.

2. Methodology

2.1. Description of study area

St. Eustatius is a small island located in the Caribbean, with a total population of 3877 in 2015 and an average number of 2.0 people per household (CBS, 2015). The total area is 2109 ha and the total urban area is 191 ha, in which houses are scattered on the island in approximately five neighbourhood areas (Smith et al., 2013; Firmansyah et al., 2017) (Fig. 2). Soakage pits are the commonly applied technology for BW treatment, and untreated GW is discharged to the open ground or used for gardening. The disposal of collected solid household waste in an open landfill causes environmental pollution as untreated wastewater and organic waste emit nutrients and greenhouse gases (GHG) that contribute to environmental pollution (Firmansyah et al., 2017) – (Table 1).

2.2. Research approach

The research approach developed in this study is depicted in Fig. 3. The steps include:

(1) Selected suitable sanitation concepts – The selected concepts are based on a review of scientific literature and local conditions. The selection process includes iterations of drafting, redrafting and discussion of flow diagrams of sanitation concepts.
(2) Selected criteria for sustainability evaluation - The selected criteria are based on the most commonly used sustainability indicators in scientific literature and an assessment by sanitation experts.
(3) Assessment of performance – The performance of sanitation concepts includes quantitative and qualitative indicators, which are evaluated using scientific literatures and an assessment by sanitation experts.
(4) Ranking sanitation concepts – The sum of normalised indicator values is applied to rank the performance of sanitation concepts.

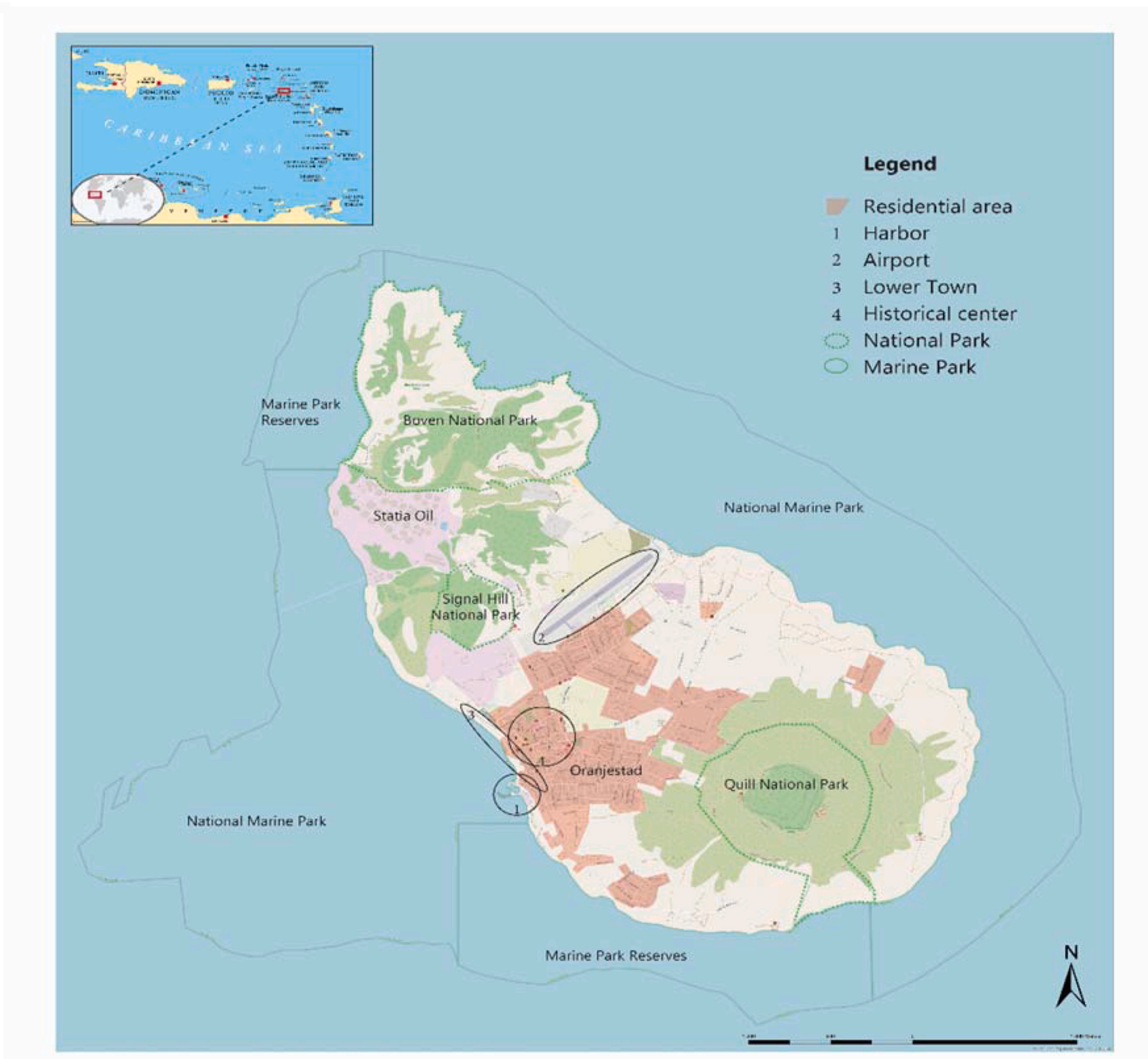

Fig. 2. Map of St. Eustatius adapted from (Hoogenboezem-Lanslots et al., 2010).

Table 1
Characteristics of wastewater constituents generated at household level in St. Eustatius.

Parameters	Unit	BW	GW	KW
Volume	L/cap/d	34[a]	117[a]	0.25[e]
BOD_5	g/cap/d	24[c]	16[c]	37[b]
COD[a]	g/cap/d	48[d]	32[d]	59[b]
TN	g/cap/d	11.2[e]	1.2[b]	1.4[e]
TP	g/cap/d	1.2[e]	0.5[e]	0.2[e]
Faecal Coliforms (FC)	CFU/100 ml	8 log[f]	5 log[g]	0

[a] (Ghisi and Ferreira, 2007).
[b] (Kujawa-Roeleveld et al., 2005).
[c] Calculated based on total BOD of domestic wastewater of Latin America and Caribbean (LAC) countries (IPCC, 2006) and GW/BW ratio of 1.5 (Kerstens et al., 2015).
[d] COD/BOD was calculated based on ratio of 2 (Meinzinger and Oldenburg, 2009).
[e] (Firmansyah et al., 2017).
[f] (Metcalf et al., 2003),
[g] (Finley et al., 2009).
Source.

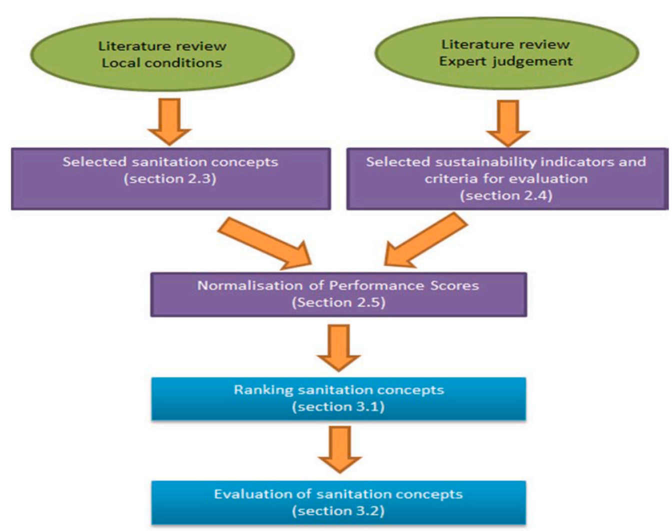

Fig. 3. Methodological framework for assessment and ranking of the performance of sanitation concepts.

2.3. Selected sanitation concepts

Following an extensive study of the literature and considering local tropical conditions, the sanitation concepts selected in this study are described and portrayed in Fig. 4. The key rationale for technology selection was to maximise the use of current infrastructure and to use simple and robust (i.e., easily installed, functional under a range of conditions) infrastructure. Furthermore, it was also aimed to benchmark source separation technologies against the more common forms of collection, transport, and treatment. Therefore, ST, TF, CW, CAS and UASB have been included in the comparison, which are the most commonly applied wastewater treatment systems in LAC countries (Noyola et al., 2012). Low-flush toilets (user interface) are applied at all sanitation concepts.

2.4. Selected sustainability indicators

Four different sustainability domains need to be evaluated to arrive at a comprehensive assessment, including technological, environmental, economic, and societal-cultural aspects (Balkema et al., 2002; Muga and Mihelcic, 2008). Preliminary selection of (qualitative and quantitative) indicators is based on the most cited indicators in scientific literature (Spiller, 2016). A final list of indicators and their criteria of evaluation are identified using literature review and expert judgment. However, the approach presented in the study provides flexibility for the final selection of the indicators depending on the studied areas. The selected sustainability indicators are shown in SM Section 2.

2.4.1. Net energy use

Net energy use (kJ/cap per day) was calculated based on the difference between energy production and consumption. The energy consumption per sanitation concept includes the energy requirement for the collection and transport of BW, GW, KW and sludge, as well as the treatment process. The methodology for calculating energy requirement and production are shown in Table 2.

2.4.2. Nutrient recovery

The amount of nutrients recovered in each sanitation concept was

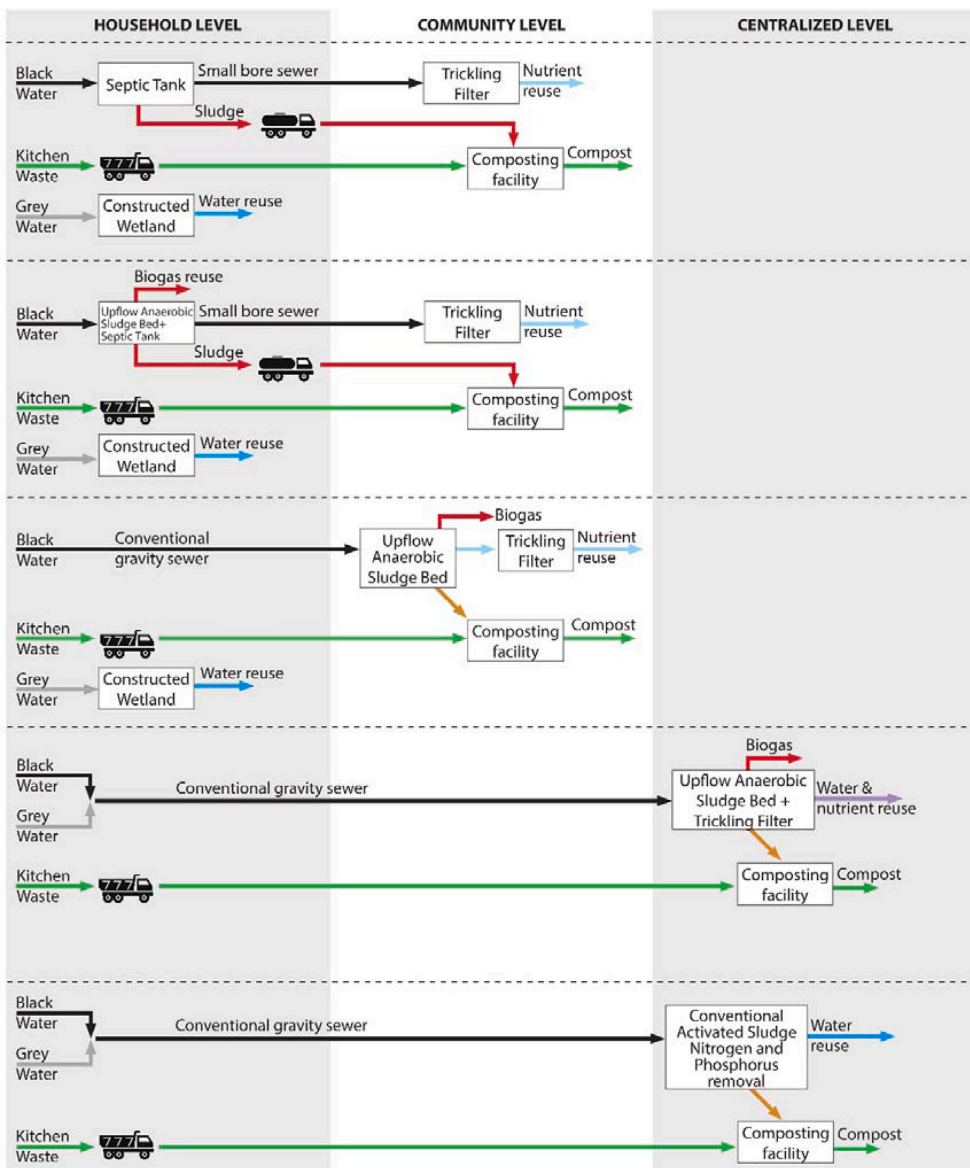

Fig. 4. Graphical representation of the sanitation concepts selected for comparison with different application of treatment technology; see Supplementary Materials (SM) section 1 for detailed explanation.

Table 2
Methodologies applied to calculate energy requirement and production per concept.

Description	Methodology	Concepts
Transport	20 kWh/cap per year (for a pumping station) (van Buuren, 2010)	4, 5
	4.8 MJ/t/km^2; 1 km (van Buuren, 2010) for sludge	1,2,3
	4.8 MJ/t/km^2; 5 km (van Buuren, 2010) for KW	4,5
Treatment	2.2 MJ/kg COD removed and 14 MJ/kgN removed, 5 MJ/kg P removed (Maurer et al., 2003)	5
	104.4 MJ/t for turning compost (Henze et al., 2008)	1,2,3,4,5
Production	0.35 m^3 CH_4/kg COD converted; anaerobic biodegradability of BW (71%) (Elmitwalli et al., 2001)	2,3
	0.35 m^3 CH_4/kg COD converted; anaerobic biodegradability of BW and GW (74%) (Elmitwalli et al., 2001)	4

calculated based on the removal efficiency of the treatment technologies as reported in literature (Table 3). Since the literature based removal efficiencies show some variabilities, an average of the different values found has been derived for calculation in this study (SM section 3). Since the sludge produced in each concept is co-composted with KW, the nutrient recovery and reuse indicator of compost was calculated based on the amount of TN and TP remaining in the sludge and KW (SM section 4).

2.4.3. GHG emissions

Direct GHG emissions were calculated based on the amount of CO_2, CH_4 and N_2O produced during wastewater treatment. Whilst the indirect GHG emission (CO_2) was calculated based on the energy demand for wastewater treatment or transportation of sludge. CO_2 emissions as a result of biological conversion were not included, because it is considered short cycle CO_2 (i.e., from biogenic sources (Heffernan et al., 2012)). The amount of GHG emissions emitted were converted into the CO_2 equivalent emissions in each sanitation concept (CH_4 = 21 and N_2O = 310) (IPCC, 2006). Methodologies applied to calculate GHG emission can be seen in Table 4 below.

2.4.4. Land area requirement

For source-separation concepts (concept 1, 2 and 3), the land area requirement was calculated from the typical Organic Loading Rate (OLR) of ST, UASB and UASB-ST as well as TF. For GW treatment at household level using CW, the total land area was calculated based on the methodology described by UN-HABITAT (2008). For centralized concepts, the total land area included the land area of UASB and TF (concept 4) or CAS system (concept 5) including secondary clarifier (Tervahauta et al., 2013) (SM section 5).

2.4.5. CAPEX and OPEX

The Capital Expenditures (CAPEX) and Operational Expenditures (OPEX) for sewer system, treatment system and land use were included in the assessment. The methodologies for the calculation were based on several references that can be seen in Table 5.

The detailed methodology of the sewer system calculation, including

Table 4
Methodologies applied to calculate GHG emission.

Description	Methodology	Concepts
CO_2 emission	725 gCO_2/kWh for electricity from diesel oil combustion (IEA, 2015)	1,2,3
	1594 gCO_2/L diesel with a diesel demand of 0.33 l/km of a 2 m^3 truck for sludge transport	1,2
CH_4 emission	0.35 m^3/kg COD removed; anaerobic biodegradability of BW (71%) for ST	1
	0.35 m^3/kg COD removed; a correction factor of 0.01 for VSSF wetlands for CW	1,2,3
	Dissolved CH_4 in the effluent, in the range of 18–22 mg/l (Souza et al., 2011)	2,3,4
N_2O emission	0.016 kgN_2O–N/kgN (IPCC, 2019) for TF and CAS	1,2,3,4,5
	0.00023 kgN_2O–N/kgN (IPCC, 2006) for CW	1,2,3
	2.5% of the initial N content are converted to N_2O gas in a composting plant (IPCC, 2006)	1,2,3

Table 5
List of methodologies to calculate CAPEX and OPEX.

Description	Methodology		Concepts
	CAPEX	OPEX	
Sewer system	small bore sewer: €120–140 per person; includes material and labour costs	Cleaning pipes	1,2
	conventional gravity sewer:(Maurer et al., 2013)	Cleaning pipes	3,4,5
	manholes and pumping station	Electricity costs for pumping the wastewater in a pumping station was calculated based on the energy use (20 kWh of a pumping station with wet sump installation and a capacity of 60 m3/h), maintenance was calculated with 5% of the mechanical and electrical costs and 2.5% of the construction costs	4,5
Treatment system	empirical cost functions using commercial cost models from DESAH BV and RoyalHaskoningDHV (Roefs et al., 2017)	(0.5% of total civil engineering costs plus 1.5% of total mechanical engineering costs), while chemicals, laboratory costs, and sludge handling were not included	3,4,5
	ST based on (Loetscher and Keller, 2002)		1
	UASB-ST based on (van Buuren, 2010)		2
	TF based on (Gratziou et al., 2006)		1,2,3,4
	CW based on (Nanninga, 2011)		1,2,3
	Composting facilities based on (Wei et al., 2001)		1,2,3,4,5
Land use	52 Euro/m^2 (van den Bergh, 2013)		1,2,3,4,5

Table 3
Removal efficiencies of selected sanitation concepts for comparison. The removal efficiency describes the reduction of the relevant concentrations in the liquid phase (Details in SM section 3).

Parameter	Concept 1		Concept 2		Concept 3		Concept 4	Concept 5
	BW	GW	BW	GW	BW	GW	BW + GW	BW + GW
	ST + TF	CW	UASB-ST + TF	CW	UASB + TF	CW	UASB + TF	CAS + N/P removal
BOD	95%	93%	97%	93%	97%	93%	87%	98%
COD	91%	79%	95%	79%	87%	79%	82%	92%
TN	27%	67%	27%	67%	27%	67%	27%	80%
TP	5%	65%	5%	65%	5%	65%	5%	82%
FC	2 log	4.8 log	4 log	4.8 log	4 log	4.8 log	4 log	4 log

CAPEX and OPEX, can be seen in SM Section 6. Calculation of the treatment system can be accessed in SM Section 7.

In order to compare the CAPEX of all sanitation concepts over their planning period, the CAPEX was calculated using Net Present Value (NPV) (Eq. (1)) (Maurer, 2009).

$$CAPEX\left(\frac{Euro}{cap}per\ year\right)=\frac{\left[I*\frac{r(1+r)^{TD}}{(1+r)^{TD}-1}*T_D\right]}{Pt} \quad (1)$$

where, CAPEX (Euro/cap per year), I = investment cost, r = the discount factor of 5%, TD = planning horizon (20 years), and Pt = total population connected.

2.4.6. Qualitative indicators assessment

Four sustainability indicators were assessed using expert judgment: (1) The level of acceptance of a sanitation concept, (2) The required competences and education for implementing a sanitation concept, (3) Flexibility/adaptability of the technology and infrastructure to be changed, and (4) The reliability of the treatment system.

Five sanitation experts (three practitioners and two academics) from the Netherlands evaluated all sanitation concepts for these criteria. In a questionnaire, each criterion was scored along a five-point Likert scale from "bad" (1) to "good" performance (5).

2.5. Normalisation of performance scores

All evaluated indicators were normalised to enable an evaluation of the trade-off between different performance characteristics. To normalise, it was first decided whether a higher or a lower value was desired. For example, for N recovery a higher value is desired while for CAPEX a lower value is desired. Thereafter, a simple normalisation

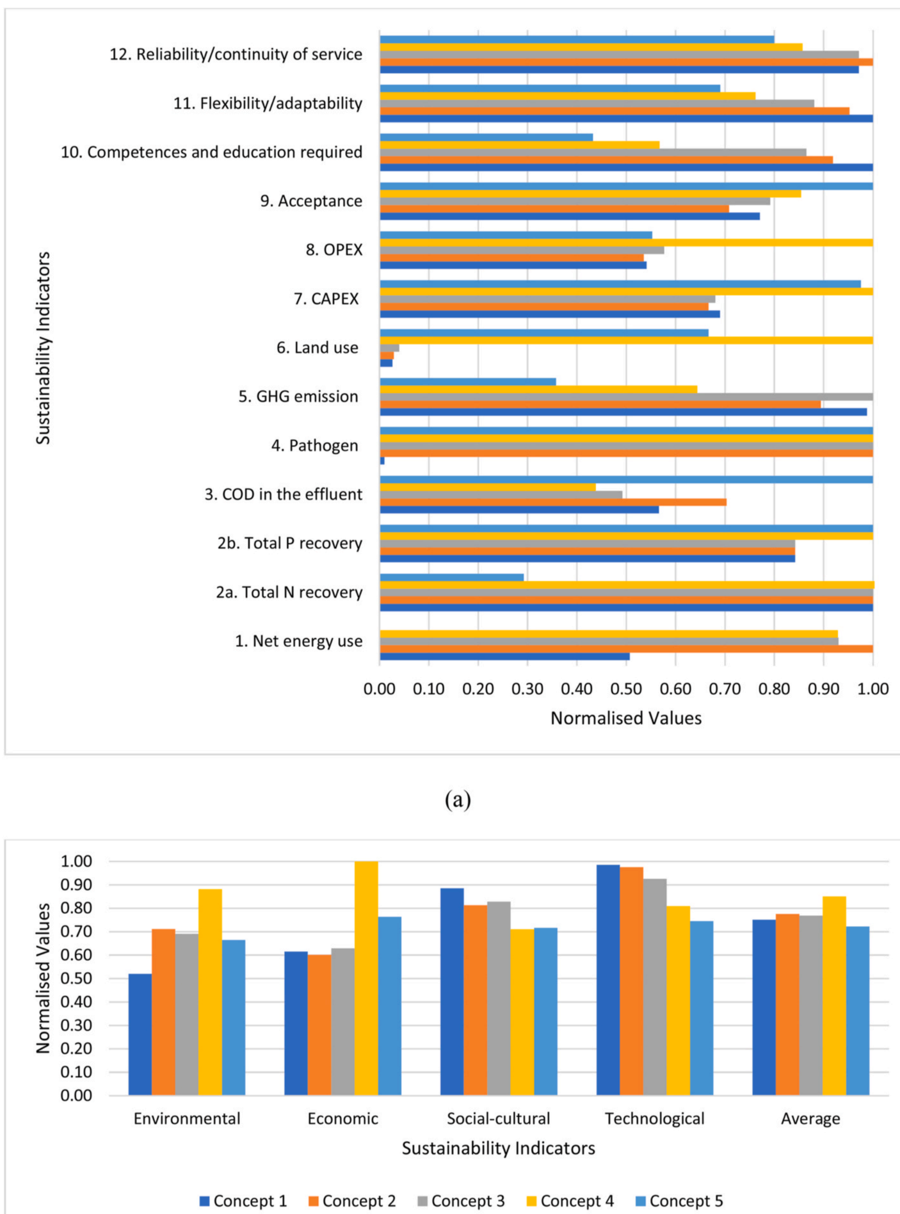

Fig. 5. (a) Normalised values of the performance of sanitation concepts for all indicators; (b) per domains of sustainability indicators and average: Maximum value (1) indicates the best performance of sanitation concepts.

method was used for each individual score (Eqs (2) and (3)):

$$\text{Max. values: } r_{ij} = \frac{x_{ij}}{max_{ij}},\ i = 1, \ldots, m; j = 1, \ldots, n \tag{2}$$

$$\text{Min values: } r_{ij} = -\left(\frac{min_{ij}}{X_{ij}}\right) \div -1,\ i = 1, \ldots, m; j = 1, \ldots, n \tag{3}$$

where r_{ij} is the normalised score, for *i* indicator in *j* sanitation concept, and there are *m* indicators and *n* sanitation concepts.

For each of the four sustainability categories the average of the normalised values was determined and subsequently summed over the four categories to arrive at a total score, with higher values representing a better score.

2.6. Sensitivity analysis

A sensitivity analysis was performed to determine the impact of uncertainties on the performance of sanitation concepts. Parameters such as removal efficiencies of BOD, COD, TN, TP, and pathogens, N_2O emissions, as well as the qualitative indicators were selected to assess the overall performance of each sanitation concept by using 1000 Monte Carlo simulation runs and uniform distribution between minimum and maximum values (SM Section 8).

3. Results and discussion

3.1. Ranking of sanitation concepts

The comparison of normalised values for all indicators shows that the centralized concept with UASB and TF treatment (concept 4) has the highest overall performance (Fig. 5). Its overall average across the four categories (i.e., average of average per category) is about 15% (0.85) higher than the values of the remaining systems and with a score of 0.72 (concept 5), 0.77 (concept 2), 0.76 (concept 3), and 0.75 (concept 1). In particular, concept 4 has the highest overall performance in the category of environmental and economic indicators. In the following the reasons for the different performances of the sanitation systems are analysed.

3.1.1. Quantitative indicators

Net energy use: The results show that the highest net energy production occurs in concept 4 (559.55 kJ/cap per day) followed by concepts 2 and 3 (424.59 and 363.73 kJ/cap per day, respectively) (Table 6). These concepts are all energy positive due to the application of anaerobic treatment (converting COD into CH_4), a low operational energy demand and suitable warm conditions to promote anaerobic digestion without additional heating (Mainardis et al., 2020). As concept 4 receives about 1.6 times more COD, due to the addition of GW, it has the highest energy production. The additional energy generated from this can more than compensate for the higher energy demand (197.7 kJ/cap per day) for pumping of sewage. This finding is rather novel as most studies that investigate biogas production in WWTP (Shen et al., 2015), or as the recent study of Prado et al. (2020) do considered that biogas is flared without energy recovery. Finally, the highest total net energy use occurs in concept 5 (437.53 kJ/cap per day) mainly due to aeration in the CAS system and the necessity for pumping of sewage. Concept 1 (ST) has a net energy demand, because of sludge transport, energy for composting and absent biogas recovery (0.5 kJ/cap per day).

Nutrient recovery: For the nutrient (N and P) loads, it can be noted that the CAS system (concept 5) results in a loss of more than 70% of the N through the nitrification-denitrification process. The other systems have the advantage of conserving about 80% of the N thereby highlighting the relevance of alternatives to CAS in order to avoid Haber-Bosch N production and progress towards nutrient self-sufficiency (Verstraete and Vlaeminck, 2011). As a result of the high N removal efficiency, concept 5 scores the lowest in this category. All P contained in the wastewater is reused, either contained in the liquid or the solid fraction. Concept 4 has the highest TP load in the effluent (1.9 gTP/cap per day), due to the low P removal in the UASB and the contribution of the GW (detergents contain P). Concept 5 has the lowest TP remaining in the effluent (0.2 gTP/cap per day) as most of P is diverted into the sludge in the enhanced biological phosphorus removal (1.7 gTP/cap per day). This however does not affect the overall assessment as the total recovery in water and solids is considered.

*BOD/COD:*The highest organic contamination of the effluent can be found in Concept 4 (5.3 gBOD/cap per day; 14.6 gCOD/cap per day). Concept 4 has a lower removal efficiency than concept 1 and 3. On the contrary, concept 5 has the lowest amount of COD due to the high removal efficiency of organics in the activated sludge (0.8 gBOD/cap per day; 6.4 gCOD/cap per day).

GHG emissions: Concept 5 has the highest GHG emissions of all concepts (0.45 $kgCO_2$-eq/cap per day), mainly attributable to the high net energy demand resulting in CO_2 emission and the nitrification-denitrification process resulting in high N_2O emission in the CAS system. In concepts 1–4, the mechanical composting and the TF contributed

Table 6
Comparison of performance of the sanitation systems (for more detail see the SM Section 9).

Category	Indicators	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Environmental	1. Net energy use (kJ/cap per day)	0.5	−423.9	−363.7	−362.3	437.53
	a. Energy consumption (kJ/cap per day)	0.5	0.7	0.01	197.7	437.53
	b. Energy production (kJ/cap per day)	0	424.59	363.73	559.55	0
	2. Nutrient recovery/reuse					
	a. TN recovery (gTN/cap per day)	10.6	10.6	10.6	11.1	4.4
	b. TP recovery (gTP/cap per day)	1.4	1.4	1.4	1.9	1.9
	3. BOD/COD in the effluent					
	a. BOD in the effluent (gBOD/cap per day)	2.4	1.9	3.7	5.3	0.8
	b. COD in the effluent (gCOD/cap per day)*	11.3	9.1	13	14.6	6.4
	4. Pathogen (CFU/100 ml)	1,000, 000	10,000	10,000	10,000	10,000
	5. GHG emission ($kgCO_2$-eq/cap per day)	0.163	0.18	0.161	0.25	0.45
	a. CH_4 emission ($kgCH_4$/cap per day)	0.0016	0.0023	0.0023	0.00578	0.013
	b. N_2O emission (kgN_2O/cap per day)	0.000281	0.000286	0.000294	0.000337	0.000385
	c. CO_2 emission ($kgCO_2$/cap per day)	0.04247	0.04265	0.02239	0.02299	0.06545
	6. Land use (m^2/cap)	1.53	1.37	1.00	0.04	0.06
Economic	7. CAPEX (EUR/cap per year)	28.7	29.7	29.1	19.8	20.3
	8. OPEX (EUR/cap per year)	19.4	19.6	18.2	10.5	19.0
Social-Cultural	9. Acceptance	3.7	3.4	3.8	4.1	4.8
	10. Competences and education required	3.7	3.4	3.2	2.1	1.6
Technological	11. Flexibility/adaptability	4.2	4.0	3.7	3.2	2.9
	12. Reliability/continuity of service	3.4	3.5	3.4	3.0	2.8

*To prevent double counting in ranking the sanitation concepts, only COD in the effluent that was included in the normalisation.

between 33 and 47% to the CO_2-eq emissions (see SM Table A15). Differences between GHG emissions (CO_2 and N_2O) during composting are the function of the sludge volume and therefore highest in concept 5 (0.1 $kgCO_2$-eq/cap per day).

*Pathogens:*The values of FC in the effluent of concepts 2–5 comply with the microbiological standard of WHO guidelines (WHO, 2006) for unrestricted and restricted irrigation in agriculture. The effluent of the concepts reaches 4 log removal. Concept 1 has the lowest performance due to the low pathogen removals in a ST. The application of fecal sludge and effluent from on-site technologies such as STs for reuse in agriculture provides a high risk to farmers as well as consumers in Uganda (Butte et al., 2021), and Chile (Livia et al., 2020). However, the application of fecal sludge that is co-composted with kitchen waste can reduce adequately enterobacterial pathogens and can inactivate parasites (Mulec et al., 2016).

3.1.1.1. CAPEX and OPEX. Through economies of scale, the CAPEX of the centralised concepts 4 and 5 is nearly 33% lower when compared to the other decentralised concepts. For decentralised systems multiple infrastructures at household level and community level will be needed. This cannot be compensated by the relative cost efficiency of the small-bore sewer system and septic tank installations, applied in concept 1 and 2, (SM Table A16). Furthermore, the OPEX of concept 4 is the lowest compared to the other concepts, due to the efficiency of maintaining one installation and avoiding the household or community-based collection and transport of sludge. The OPEX for concept 5 is comparable to the decentralised systems due to the relatively high demand for energy. The higher costs of the decentralised systems have been described previously in literature (Roefs et al., 2017). However, it has been suggested that this balance may change if the recovery of nutrients and water would be accounted for in the cost estimations (Roefs et al., 2017).

3.1.1.2. Land use. Compared to the decentralised concepts (1–3), concept 4 only requires about 3% of the land use (0.04 m^2/cap), which is a bit less than the CAS system (concept 5, 0.06 m^2/cap). The reason for this is that concepts 1–3 apply CW which requires a higher land use due to a space demand of 0.97 m^2/cap (SM Table A17). The ST concept (concept 1) requires the highest area per capita (1.53 m^2/cap) due to the construction of many septic tanks. Comparing space demand values across literature is challenging as other authors do apply different process configuration (e.g., not including TF and composting). However, values for concept 5 are similar to those of Tervahauta et al. (2013) with an assumption that a CAS has a space demand of 5 m^3/m^2. Furthermore, the calculated footprint of CW in this research is not different with other researches. It was indicated that vertical flow CW systems has a large area footprint of 1–3 m^2/cap (Vymazal, 2011).

3.1.2. Qualitative indicators

3.1.2.1. Acceptance. Interviewees indicated that centralized concepts offer more convenient conditions for the users. In a centralized concept, the users are expected to be not directly involved with the operation and maintenance of the concept as it requires skilled operators. While in the decentralised concepts (concept 1 and 2), the users are responsible to maintain and control the treatment technologies, viz. the ST and UASB-ST at household level. Moreover, some interviewees suspected that anaerobic treatment applied in concept 1 to 4 creates odor nuisance. However, if properly managed odor is not a problem in a decentralised application (Kujawa-Roeleveld et al., 2005). Indeed, more recent research indicates 64% of a representative sample of Dutch citizens are willing to use decentralised sanitation (with a different technological setup), driven by environmental concerns and despite concerns related to the housing market and behavioural change (Poortvliet et al., 2018).

3.1.2.2. Competencies and education required. The requirement of a high skill level for operation and maintenance of the centralized sanitation concepts has resulted in the lowest score for the concept 5 and followed by concept 4, while concepts 1 to 3 do not have a high demand on human resource skills. This was indicated with a consensus among interviewees that concept 1 has the highest score because the application of ST is renowned for its simplicity. No high skilled competency is required for the operation and maintenance of the technology. Compared to concept 1, the score is lower for concept 2 and 3. The application of a UASB-ST at household level and a UASB at community level is expected to require more knowledge on biogas handling and storage.

3.1.2.3. Flexibility/adaptability. Decentralised concepts have advantages with regard to their simplicity of construction and changeability (Larsen et al., 2013). This argument is reflected in the performance score of the flexibility/adaptability indicator assessed by the interviewees. Concept 5 has the lowest score due to its complexity of the construction and operation. However, some interviewees indicated that concept 4 is the most complex system, because of the requirement of a centralized gas collection system. However, for the purpose of this analysis it was considered that the UASB of concept 4, is simpler to operate than a CAS system with biological nitrogen removal. Contrary to this, concept 1 has the highest score due to its simplicity on the construction of the ST and small-bore sewer system.

3.1.2.4. Reliability/continuity of service. Reliability/continuity service indicator reveals the capacity of the system to respond to the failures due to pipe blockage and power failures. The results showed that Concept 5 has the lowest score. If there is a blockage in the sewer system applied in the centralised concepts (concept 4 and 5), high level of maintenance is required which is more challenging compared to the sewer system applied in decentralised concepts (Concept 1 to 3). Concept 1 has the highest score as the concept also does not rely on electrical supply and it has the lowest impact if there is a failure in the system.

3.2. Evaluation of the performance of sanitation concepts

The above analysis presents an attempt for a “rational” comparative evaluation of the different performances of sanitation systems, however the results and methods are, as every model, a simplification of reality. The end responsibility for a decision rests with decision makers and their advising experts. It is at this level that the evaluation presented here must be examined on a case by case basis. The decision can relate to the selection of the technologies, sustainability indicators, aspect of reuse, etc. Below we shed light on some of the potential aspects to take into further consideration and point towards other bodies of work that cover these topics.

3.2.1. The nutrient pathways

The present paper considers tropical conditions with a year-round cropping system. Nutrient recovery from the treated wastewater streams is in the form of liquid (effluent) and solid-based (compost) fertilizer. A decision on the type of fertilizer that can be effectively applied on agricultural fields is necessary to consider, as nutrients in the liquid fraction are readily available to plants, while the solid fraction is a slow release fertilizer (FAO, 2011). Since BW sludge has a lower heavy metal concentration as compared to conventional sewage sludge (Tervahauta et al., 2014), the source separation concepts 1, 2 and 3 are more attractive in this respect. In the present study, reuse of GW in agriculture in the source separation concepts is not included, but the decision for reuse is depending on personal interest at a household level. Alternatively, a community on-site CW could be applied with reuse of the effluent in agriculture. However, since P in GW mainly originates from detergents and the use of it is no longer allowed in a number of European countries (van Dijk et al., 2016), this route of P may not be accounted for in the future. The nutrients reuse indicator in each concept will change considerably.

3.2.2. Local conditions - climate as a choice mediator

Local climatic condition can play an important role in the selection of technologies for implementation. One reason for the preference of municipal UASBs in most of the LAC countries is that they can function well in the tropical climatic conditions. In more temperate climates the costs of heating a diluted sewage are prohibitive for implementation of municipal UASB. Contrary to this, practical examples show that decentralised treatment of BW in a UASB reactor is feasible at a scale of 1200 people or more, when these reactors receive a concentrated BW produced by applying vacuum collection and transport (STOWA, 2014). However, in temperate climates, the reuse of the UASB effluents is not possible due to the seasonality of agricultural activities. In these conditions, UASB effluents are subjected to further refinement processes such as struvite precipitation and ammonia stripping for producing concentrated fertilisers (Bisschops et al., 2019).

3.2.3. Economics – allocation for costs and benefits between actors and development uncertainties

Sewer systems, centralised or decentralised treatment systems may be owned and operated by different insitutions, hence also resulting in a different distribution of the costs and benefits. For example, the costs of construction of STs are likely incurred by a private person as it will be constructed on their property, hence not requiring investment of public money (Kerstens et al., 2015). Due to the novelty of community based sanitation systems various organisational models can be envisioned, but it is likely that one party will own and operate the systems. Indeed, some authors suggest that new business and organisational models may emerge, where communities join to maintain, operate, and own a sewage treatment system (Hegger and van Vliet, 2010).

Another crucial aspect not accounted for in the presented evaluation is the development and change of sanitation systems over time. Using an NPV evaluation, Maurer (2009) and Roefs et al. (2017) have shown that decentralised sanitation with GW and BW separation can, when population growth is over estimated, be a more economic alternative. Indeed, more conceptually a number of authors have suggested that decentralised sanitation systems are more flexible and hence reduce investment risk and adaptability to uncertainty (Spiller et al., 2015). This is reflected in the scores of the experts in this study. Therefore, in situations with large uncertainty opting for more decentralised systems can reduce investment risk and potential losses.

3.2.4. Social – the key barrier to implementation of novel sanitation systems

Social parameters are crucial for adoption of any sanitation system. If systems will not be accepted or cannot be operated adequately, the performance on all other parameters will be compromised. It is clear that there is a trade-off to be made between acceptance and competence requirements for operation and maintenance. Results indicated that systems that require less involvement of the individual, by demanding a higher level of competences, are thought to be more likely to be accepted, while simpler decentralised systems are less acceptable. The acceptance is related to the odor problems and simplification of the system for the users at household level. The present results clearly show that centralised systems (concept 4 and 5) are more accepted because of the low odor and robust systems for the users that tend to flush and forget. However, other studies on the opinion of real users indicated that new systems combining elements of source separation systems, local treatment and reduced water use are accepted by many end-users in the Netherlands and European countries (Lienert and Larsen, 2010; Poortvliet et al., 2018).

3.3. Contributions and limitations of the approach

The suggested approach in this study is generic to be applicable in different contexts under different considerations. Compared to the approach or software provided by Spuhler et al. (2020), this study provided simple steps that can be followed by decision-makers and urban planners to design a sustainable sanitation concepts considering different sustainability indicators. The approach can contribute to the existing theory that the assessment of sanitation concepts should be comprehensive, and able to assess different aspects contributing to the selection of a more sustainable sanitation concept. The quantification methods applied in this study can be generalized and applied in other similar contexts (Tropical regions). In confronting decision makers with the proposed structured stepwise process and a set of defined indicators, the choices will become more explicit and transparant. Thereby, it will also contribute to better decision, lasting implementation, and eventually an achievement of the SDGs (Haag et al., 2019). However, the suggested approach has some limitations that should be overcome through further study or development. The limitations are summarized as follows:

a. Selection of sanitation concepts. The approach applied in the case study focussed to only five sanitation concepts. The pre-selection of sanitation concepts for comparison should be done carefully considering local conditions and it should be supported through a literature review of possible technologies (Spuhler et al., 2020).
b. Selection of sustainable indicators. The selection of the indicators in this study is limited to the most cited indicators. However, in the implementation of the approach, it is possible to add other sustainability indicators considering the purpose of the sanitation concepts. The purpose of comparison should be pre-defined as it can influence the selection of the indicators.
c. Uncertainty of future developments. The suggested approach consider the uncertainty of the data. However, the uncertainty of future developments should be considered in the assessment of the performance of sanitation concepts. For example, future population development will influence the capacity of treatment technologies if it is not well-considered in the planning process.

4. Conclusion

- Conventional sewerage in combination with centralised anaerobic treatment and post treatment with a trickling filter is the best performing collection and treatment system, provided that the liquid effluent can be directly used for irrigation and fertilisation in agriculture. The key reasons for its superior performance can be found in comparatively low costs, land use and high energy production.
- The final ranking of sanitation concepts is sensitive to the selection of sustainability indicators and input variables.
- The approach allows the assessment of the whole train of technologies from collection, transport, treatment/recovery to reuse or final disposal, across the domains environmental, social-cultural, economic and technical. It can support urban planning and policy decision-making in selecting more sustainable sanitation concepts.
- In confronting decision makers with the proposed structured stepwise process and a set of defined indicators, sanitation system choices will become more explicit and transparent. Thereby, it will also contribute to better decisions, lasting implementation, and eventually an achievement of the SDGs.
- A major limitation of the studies is that the research does not account for uncertainty of future development which may affect the performance of wastewater treatment technologies. Such development maybe changes in the population, climate change or economic development. Future research should take this into account for example by developing explorative external scenarios.

Credit author statement

I. Firmansyah: Conceptualization, Methodology, Writing – original draft; G.J. Carsjens: Conceptualization, Methodology, Writing – review & editing, Supervision; F.J. de Ruijter: Conceptualization, Methodology, Writing – review & editing, Supervision; G. Zeeman: Conceptualization, Methodology, Writing – review & editing, Supervision; M. Spiller: Conceptualization, Methodology, Writing – review & editing, Supervision

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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