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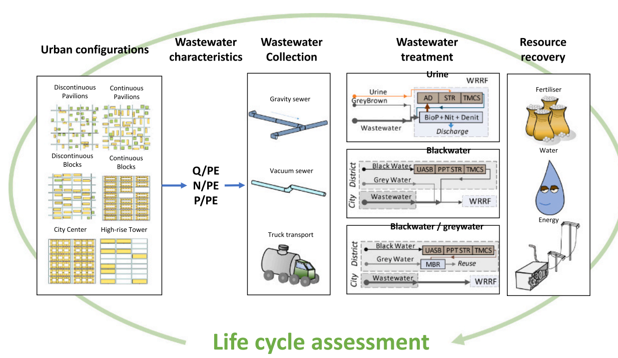
HIGHLIGHTS

- The environmental benefits of source separation systems increase with urban density.
- Urine separation is always beneficial whatever the urban configuration.
- Blackwater separation could be beneficial for all urbanism except pavilions.
- The energy needs for decentralised greywater treatment is detrimental for all configuration.
- Sewer is the first contributor on climate change impact for low density district.

GRAPHICAL ABSTRACT



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ABSTRACT

This study aims to assess the effect of different urban configuration regarding the choice of wastewater management of the district with source separation systems. Understanding this link can guide researchers, and also urban actors, in order to choose the best source separation solution to implement in a specific urban configuration.

For this purpose, an integrated modelling approach was used to model the district with different types of urban planning, the water resources recovery facility (WRRF) and create a life cycle inventory to carry out a life cycle assessment (LCA). Six different urban configurations were tested with three different source separation scenarios and compared with an advanced WRRF with high level of nutrients and organic matter recovery.

This study concludes that urine source separation is beneficial compared to advanced WWRF for all the urban configurations. Sewer construction was identified as the main contributor to environmental impact for the low-density configuration (pavilions), limiting the benefits of source separation in this urban settlement. Blackwater separation with a decentralised treatment is only beneficial for high densely populated area. Treatment of blackwater and greywater for reuse, has greater impact than reference scenario, in all urban configurations, due to high energy consumption for greywater treatment. Future research should therefore explore technical solutions for limiting the energy consumption.

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Nomenclature

BOD_5	Biological oxygen demand at 5 days.
COD	Chemical oxygen demand.
GHG	Greenhouse gases.
Inh	Inhabitant.
LCA	Life Cycle Assessment.
PE	Population equivalent (1PE = 60 $gDBO_5/d$).
TN	Total nitrogen.
TP	Total phosphorus.
WRRF	Water resources recovery facility.
WWTP	Wastewater treatment plant

1. Introduction

Wastewater treatment plants (WWTP) are progressively considered as water resource recovery facilities (WRRF) that can include nutrients recovery, energy production and water reclamation. However, in practice, the energy and nutrients recovery processes are mainly feasible for high strength effluent in side streams of treatment plant, in which only a small proportion of the nutrients can be recovered (Devos et al., 2023). Moreover, resource recovery is not environmental free (Diaz-Elsayed et al., 2020) and assessment is needed to identify the best strategies to implement.

To increase nutrient recovery, source separation is an emerging strategy. In particular urine and blackwater collection offer better potential than diluted sewage for nitrogen recovery (Besson et al., 2021; Lehtoranta et al., 2022; Malila et al., 2019; Martin et al., 2023). The literature seems to agree that urine source separation shows better environmental impact for most of environmental criteria thanks to a reduction in the nitrogen mass flow to be treated in WRRF and reduction of N_2O emissions from biological treatment (Besson et al., 2021; Bisinella de Faria et al., 2015; Igos et al., 2017; Ishii and Boyer, 2015; Landry and Boyer, 2016; Lehtoranta et al., 2022; Malila et al., 2019; Martin et al., 2023). The stabilisation and spreading processes are crucial to limit ammonia emissions and consequently acidification (Lehtoranta et al., 2022; Martin et al., 2023; Tidåker et al., 2007). On the other hand, blackwater separation scenario presents contradictory results with higher impacts (Lundin et al., 2000; Thibodeau et al., 2014), and lower impacts (Remy, 2010).

Differences in urban typologies (detached houses or collective buildings) can affect the type of sanitation system to be installed. For example, the population density, and the space available at the district or building scale, determine the feasibility of decentralised wastewater systems. Assessing the links between urban planning and source separation systems could facilitate the choice of scenario to be implemented in future urban projects. Source separation leads, indeed, to a number of feasible technical scenarios with different types of separation, treatment techniques and sizing, different locations for treatment and possible links with the conventional sanitation system.

Several studies have already focused on the scale of decentralisation but only for water reuse, with or without greywater separation. (Zhang et al., 2023) investigated the optimisation of WWTP decentralisation in China for water reuse based on technical and economical parameters. (Santana et al., 2019) compared water reuse for hotel in Spain at different decentralisation levels. Moreover, (Jeong et al., 2018, 2016) studied the influence of urban planning on greywater, as well as on rainwater reuse on the environmental or economical assessment. (Kavvada et al., 2018, 2016) compared in the case of San Francisco, USA, a non-potable network for centralised or decentralised solution and analysed the results depending on the urban configuration and topography. Finally, (Meinzinger et al., 2010) is the only attempt of an economical assessment for urine collection based on different urban planning. All these studies have identified an impact of scale of decentralisation and of urban planning, but nutrient recovery was not included. The operation of WWTP is usually simplified by calculating energy consumption based on treated flowrate which may lead to overestimation. Energy consumption mainly depends on the need for aeration to treat the organic and nitrogen load (Tchobanoglous et al., 2003).

As a result, there is as yet no comparison between the different source separations, including grey, black and urine separations, for different urban planning. The effect of urban planning (building density, building use and population density), on wastewater characteristic (quality and quantity), wastewater collection and treatment have not been investigated. The previous studies do not provide sufficient information to draw up guidelines on the type of source separation that offers the greatest environmental benefits for a given urban typology. Moreover, these new systems have not been compared to the best technologies available for WRRFs which include nutrients and energy recovery in centralised systems.

The aim of this study is to investigate the impact of urban configurations (density) on the life cycle assessment of different prospective source separation scenarios for alternative wastewater management. A modelling framework and a complete inventory are proposed. The LCA results are discussed in order to narrow down the best source separation solutions for different types of urban planning, on the basis of generalised results that are not specific to a case study.

2. Material and methods

This study used the well-known life cycle assessment methodology (ISO 14040, 2006; ISO 14044, 2006), with four interdependent phases: (1) goal and scope definition, (2) quantification of material and energy flows in a life cycle inventory (LCI), (3) transformation into potential environmental impacts with life cycle impact assessment (LCIA) methodologies and (4) review, recommendations and improvement strategies.

2.1. Goal and scope

The goal of this LCA study is to model and quantitatively assess the influence of different urban configurations of a new district, on several sanitation systems that aim to recover wastewater resource while protecting the receiving environment.

2.2. Scenarios description

The six urban configurations from (Bonhomme, 2013) were compared (Fig. 1A)), for a district of 6.25 ha. The urban configurations can be defined as archetypical representations of urban forms found in most European cities. For each urban configuration, the number of inhabitants and employees varies, implying different wastewater flowrate and quality. The 6 urbans configurations are based on statistical analysis on Paris and Toulouse (French cities). There are named according to the main type of buildings in the district (see also Table 1 for their characteristics):

- *Discontinuous pavilion* (DP) is representative of suburban neighbourhood with detached houses, a low building density and a high density of green space (gardens).
- *Continuous pavilion* (CP) is very similar to discontinuous pavilion but with a slightly higher building density and height (3 storeys instead of 2). The gardens are also smaller.
- *Discontinuous block* (DB) is a combination of housing and offices (11.5 % of the buildings are dedicated to offices) with a similar building density than continuous pavilion and higher buildings (5 storeys).

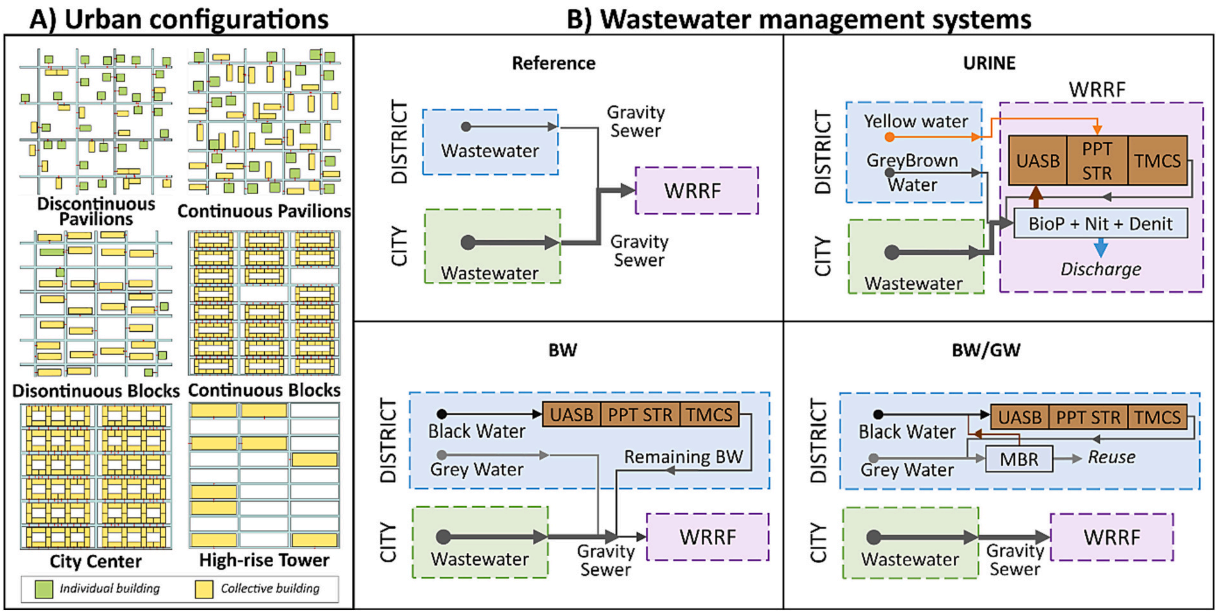

Fig. 1. Presentation of the six urban configurations (A) and the four wastewater management systems (B). WRRF: Wastewater resource recovery facility, AD: Anaerobic digester, PPT STR: Struvite precipitation, TMCS: transmembrane chemisorption, UASB: upflow active sludge blanket, MBR: membrane bioreactor. Adapted from (Besson et al., 2021).

Table 1
Parameters used for district generation for each urban configuration from (Bonhomme, 2013)).

	DP	CP	DB	CB	CC	HT
Building density (m^2_{floor}/$m^2_{district}$)	0.27	0.7	0.82	2.13	3.16	2.64
Land coverage ratio (m^2_{built}/$m^2_{district}$)	0.12	0.22	0.19	0.36	0.48	0.21
Average height (m)	6.64	9.94	13.91	18.37	19.92	40.13
Contiguity ($m^2_{shared\text{-}wall}$/m^2_{built})	0.03	0.04	0.12	0.29	0.39	0.18
Density of road surface (m^2_{road}/$m^2_{district}$)	0.11	0.13	0.18	0.19	0.21	0.22
Road width (m)	3.39	3.49	4.01	4.47	4.89	4.02
% of number of collective buildings	0	0	84 %	97 %	99 %	97 %
% of floor surface for housing building[a]	100 %	100 %	89 %	89 %	89 %	34 %

[a] The remaining part is for office buildings with employees.

- *Continuous block* (CB) has a higher building density and height (6 levels) thanks to more contiguity between buildings. Here again, the majority are residential but with a small part of offices (11.1 %).
- *City centre* (CC) is similar to continuous block in term of building density but the morphology of the buildings is characterised by a courtyard in the middle of the block. There is a mix of housing and offices (11.4 % of offices).
- *High-rise tower* (HT) is representative of sky-scrapers. It is determined by a high height (around 13 storeys) but the building density is lower than in the city centre. This district has small footprint and many green spaces. There is also a high proportion of office space (66 %).

In term of wastewater management, three source separation strategies were compared with an advanced reference scenario representing the best available technologies to recover nutrients at the WRRF. The following scenarios are thus studied (the same four wastewater management systems described in (Besson et al., 2021), see also Fig. 1):

- centralised management at WRRF (*Reference* scenario),
- urine separation and centralised treatment of both streams at the WRRF (*Urine* scenario),
- separation of blackwater and greywater with decentralised treatment of blackwater (*BW*)
- separation of blackwater and greywater with a fully decentralised treatment system (*BW-GW*).

2.3. Functional unit and system boundaries

The functions of the system can be defined as "collect and treat wastewater produced in the district while respecting the discharge limit of 10 mg-N/L and 1 mg-P/L, and producing recovered nutrients usable as fertiliser and recovered water".

Given than wastewater flowrate and quality vary according to urban configuration and wastewater management, it is mandatory to use a representative functional unit for all scenarios. For this purpose, the population equivalent (PE), defined as the BOD_5 load to treat (1 PE = 60 gDBO5/d), was chosen. This functional unit respects the guideline of (Corominas et al., 2020).

The system boundaries (Fig. 2) covered wastewater collection and treatment, including sludge management to end-of-life. It should be noted that the boundaries only included the wastewater produced in the new district. The inventory was therefore calculated by comparing the operation of WRRF with and without the new district.

Finally, an expansion of the system was applied to consider the substitution of energy, fertiliser, and water within an attributional framework. European data was used in the background processes and especially for the electricity production.

2.4. Life cycle inventory

2.4.1. Modelling strategy

In order to investigate the effect of scale and urban configuration on environmental assessments, several scenarios have been simulated. 18 case studies were created with 3 different district sizes (6.25 ha, 16 ha and 36 ha) and 6 urban configurations.

To collect the data of each scenario, the following methodology developed in (Besson et al., 2021) was applied:

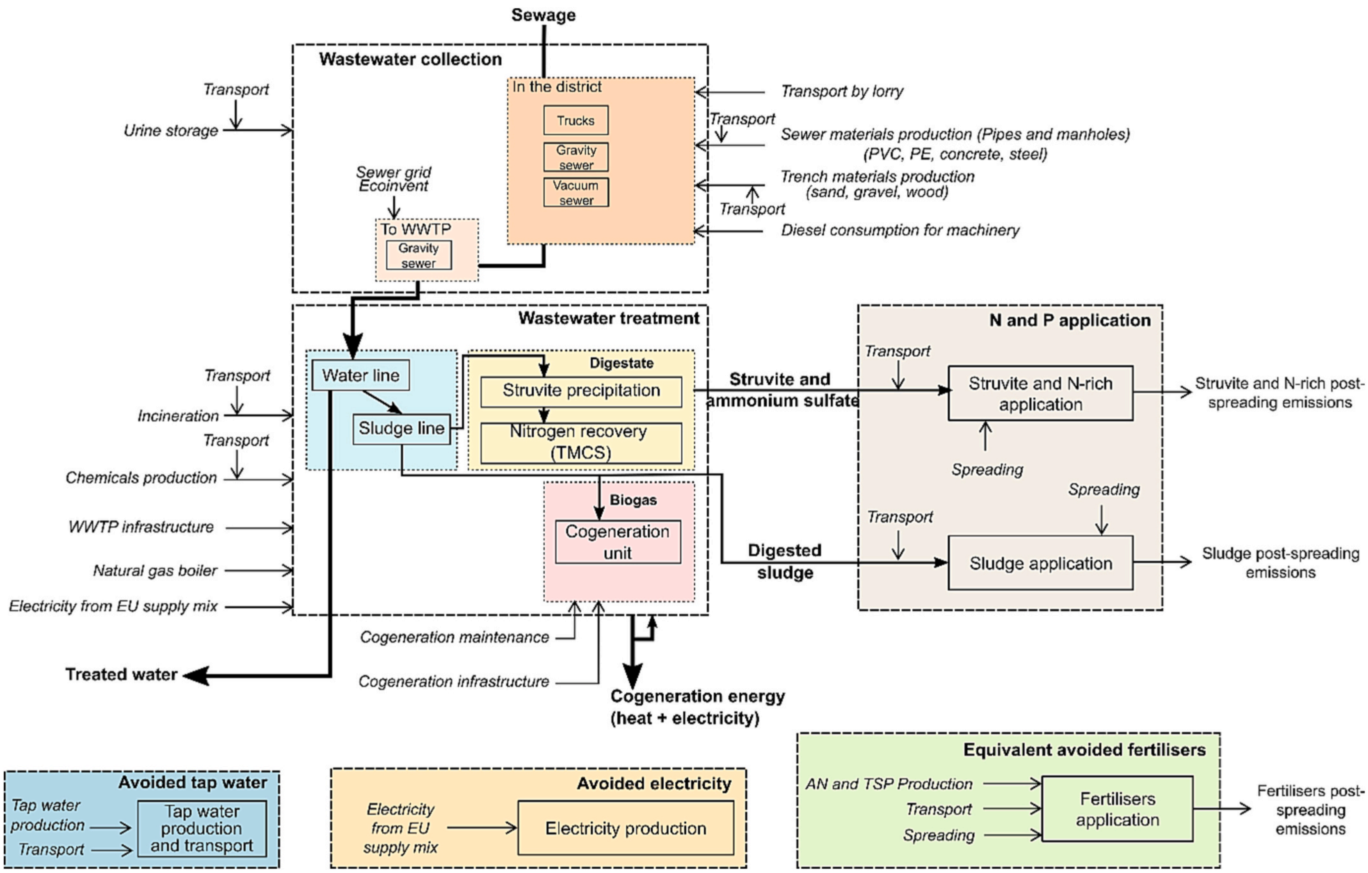

Fig. 2. Extended system boundaries for LCA (published in (Besson et al., 2021) and adapted from (Bisinella de Faria et al., 2015)).

- Creation of the district with the different urban configuration
- Modelling of the WWRF without the new district by using SUMO model. (More information can be found in (Besson et al., 2021) and in Section 4 in SI) (1 simulation)
- Modelling of each case study at a decentralised scale for each sanitation system (72 simulations)
- Modelling of the WWRF with the new connected district with a determined flow and concentration obtained from the previous step (72 simulations on SUMO)
- Calculation of the LCA inventory for each case study and sanitation system (73 simulations)
- Life cycle assessment for each scenario (73 simulations with ReCiPe methods and cumulative energy demand).
- Calculation of the contribution of the district only, by removing the impact of WWRF without the new district
- Normalisation of results using functional unit.
- For each case study, calculation of improvements in alternative scenarios compared with the reference sanitation system.

2.4.2. District creation

Each district was created using geographical information system (GIS) tool in order to spatialise the buildings according to urban configurations and to be able to design the sewer.

The data from (Bonhomme, 2013) was used to recreate district by: (1) Positioning the road according to its width and its density. (2) Defining the number of buildings considering the land coverage ratio and the surface of one building. (3) Randomly positioning buildings in the district. A detailed description of the creation of districts can be found section 2 of the SI. At that stage of the work, only flat topography was considered.

2.4.3. Population density

Population density in the different urban configurations is a key point of the model, because it influences the wastewater generation. It varies within each urban configuration because it is also correlated to the location of the district in the city and attractiveness of the city. Population density has been established from a small sample (from 4 to 6) of districts for each urban configuration based on two French databases used in the city of Toulouse, France (details in Table S 4 of the SI). Thanks to the building density (Table S 1 in SI), population density expressed per surface of district were obtained. As this methodology is based on a small sample, the determination of inhabitant per building considers the standard deviation of the density (see methodology in section 2 in SI).

2.4.4. Wastewater production

At the household level, domestic wastewater production depends on time, lifestyle and number of people per households, age, and social level (Corbella and Pujol, 2009; Henze, 2008). At the district level, it depends on the use of buildings (office or household) and the human density.

The model includes the production of wastewater from household but also from the working population. For this purpose, the working population has been quantified based on a number of buildings dedicated to tertiary activities (see Table S 1 in SI.). In activities buildings, occupation of 13 square meter per person was assumed (Le Sommer Environnement, 2018). French regulations impose a minimum of 10 m^2 per person (Article R*4228-10*, n.d.).

The influent generation is based on average data (Table S 5 in SI) obtained from a literature review already published in (Besson et al., 2021). The influent is divided into urine, faeces, greywater.

The wastewater is produced both at home and at office location. A ratio of 2/3 of the time spent at home is considered (Jönsson et al., 2005). 1.07 ± 1.07 defecation per day and per person is considered and 5.3 ± 2.9 urination per day and per person (Friedler et al., 1996; Rauch et al., 2003). Greywater production was also spread into housing and offices, considering 110 L/pers./day of total greywater thanks to the literature review, and 26 L/pers./day at office. This last value comes from the baseline situation of BREEAM certification (BREEAM, 2016) for office building (shower are included with wash hand basin taps and kitchen taps).

The volume of water flushed was 3 L after urination and 6 L after defecation for *Reference* and *Urine* scenarios. But for *Urine* scenario, it was considered that only 0.2 L of every flush goes into the urine compartment and storage, while the remaining volume goes with faeces. Finally, only 80 % of urine was collected which corresponds to the best performances observed in pilot projects (Jönsson et al., 1998; Peter-Fröhlich et al., 2007). In *BW* and *BW-GW* scenarios, blackwater was supposed to be collected through a vacuum toilet (1.2 L per flush).

2.4.5. Wastewater collection

Wastewater collection was modelled considering gravity sewer, vacuum sewer or truck transport (see Fig. 1). In the *Reference* scenario, wastewater was collected with a gravity sewer line. In the *Urine* scenario, urine was collected in tanks and then transported once a week by truck (10 m^3) to the WRRF at 10 km away. The remaining wastewater was transported as usual through the gravity sewer line. In *BW* and *BW-GW* scenario, blackwater are collected with vacuum sewer until reaching a vacuum station in the middle of the district where the treatment of blackwater takes place. The greywater obtained in the *BW* scenario was sent to the WRRF through a gravity sewer line.

The construction phase for the new district and the operational phase (energy consumption) were designed based on the district map. More details can be found in (Besson et al., 2021).

2.4.6. Centralised wastewater treatment

The WRRF was treating 56,003 PE with a flow rate of 12,900 m^3/d. Treatment was modelled as steady state, with the use of SUMO software (v19). All wastewater was treated in a centralised treatment plant with advanced treatments for nutrients and organic matter recovery. Primary decantation and anaerobic digestion with cogeneration of biogas allowed to recover COD into energy. Struvite precipitation was assumed for treating the supernatant of digestate dewatering for P recovery, while transmembrane chemisorption (TMCS) was used to recover the remaining nitrogen. In the water line, enhanced biological removal of phosphorus was performed to increase P content of the sludge and thus the P recovery. In case of urine separation, the collected urine is added to the output effluent of the digester to undergo struvite precipitation and TMCS filtration. More details of the model are given section 4 of the SI.

2.4.7. Decentralised wastewater treatment

The three source separation scenarios systems are representative of several pilot projects already undertaken across Europe with urine and blackwater separation. However, nitrogen recovery is the only treatment which is not implemented in these projects. It was added in the studied scenarios due to the impact of nitrogen recovery on climate change (Bisinella de Faria et al., 2015). Transmembrane chemisorption (TMCS) is currently one of the best emerging technologies for nitrogen recovery from high strength wastewater with its low energy consumption (2.55 $kWh_{elec}/kgNH_4\text{-}N_{recovered}$ (Böhler et al., 2018) compared to 76 kWh_{elec}/kgN for nitrification/distillation (Udert and Jenni, 2013; Udert and Wächter, 2012) and 7.2 kWh_{elec}/kgN for ammonia stripping (Maurer et al., 2003)). It consists on hydrophobic membranes which allow ammonia gas to transfer to an acidic solution and form a nitrogen salt. This technology has been tested at pilot scale for urine treatment (Damtie et al., 2020; Zhang et al., 2013) but it is already installed at full scale in the WWTP of Altenrhein and Yverdon-les-(Böhler et al., 2018) treating approximately 37 m^3/day of rejected water from anaerobic digestion.

In the *BW-GW* scenario, blackwater and greywater were treated in decentralised systems in the middle of the district. Blackwater (for *BW* and *BW-GW* scenario) was treated with an upflow anaerobic sludge blanket (UASB, SRT = 75 d, T = 25 °C, 60 % of coming COD converting into biogas (de Graaff et al., 2010) followed by a struvite precipitation (removal of 86 % of phosphate with a Mg/P molar ratio of 1.5 (de Graaff and van Hell, 2014) and TMCS (T = 45 °C, pH = 9.6, 90 % recovery of ammonia). The greywater from *BW-GW* scenario was treated in a membrane bioreactor (MBR). The MBR was designed with biological removal of phosphorus, nitrification and denitrification, and depending on the respect of discharge limit, a chemical removal of remaining phosphorus can be added.

All the scenarios were designed and simulated to respect the discharge standard of 10 mg/L of total nitrogen and 1 mg/L of total phosphorus. More details can be found in (Besson et al., 2021).

2.5. LCIA

The endpoint and midpoint impact assessment methods from ReCiPe 2008, Hierarchist v1.13 have been chosen. The environmental impacts were calculated in Umberto® LCA+ software using the LCA Ecoinvent database v3.8.

3. Results

The first results present the LCA inventory for all of the scenarios. The LCA results are then discussed at midpoint and endpoint level, regarding the improvements compared to the reference sanitation system.

3.1. Life cycle inventory analysis

The life cycle inventory is summarised in the Table 2 below, more details can be found in the section 5 of the SI.

3.1.1. Influence of urban configurations on the production of wastewater

The quality of wastewater and the number of treated PE depended on the number of inhabitants and employees. A higher proportion of employees reduced the flowrate of greywater and thus wastewater (see Fig. 3A and Table 3). In the meantime, it reduced also the COD load and modified the ratio of nitrogen and phosphorus per PE (Fig. 3B) and C)). This is due to different ratios between greywater and human excreta within the urban configurations as described in Fig. S 3 of the SI for COD loads.

The flowrate decreased by 8 % between *blackwater* separation and the other scenario due to the use of vacuum toilets.

Finally, although there is a combination between human density, the number of employees and the PE treated, for the sake of clarity in the rest of this document, the increase in urban density refers to the N/PE ratio, i.e. the following order: DP, CP, DB, CB, CC, HT.

3.1.2. Influence of urban configurations on the wastewater collection

The sewer length was strongly influenced by urban configuration for all the wastewater management. The sewer requirement per PE was higher than 10 m/PE for pavilions configurations (DP, CP) compared with less than 2 m/PE for all the other urban configurations. The total sewer length is quite similar in all urban configuration, but in pavilions, the number of treated PE is lower (less than 200 PE).

Energy consumption for gravity sewer was not influenced by urban configurations, unlike the vacuum sewer. For the vacuum sewer, the consumption increased with the urban density. By design, the energy consumption is directly correlated to the blackwater flowrate. Therefore, the increase of Q/PE ratio with the urban density explained the higher consumption for a highly dense district.

Finally, vacuum sewer had an energy consumption more than 6 times higher than gravity sewer.

Table 2
Main inventory data for the scenarios. (Negative values mean that less is needed than before the collection and treatment of the new district, Positive values means more is needed to treat the new district).

		Collection				Treatment							Recovery		
		Length of sewer (m/PE)		Net electricity cons. sewer (kWh/year/PE)	Distance of urine transport (km/year/PE)	Chemicals (kg/year/PE)					Net heat cons. (kWh/year/PE)	Net electricity cons. (kWh/year/PE)	Resource recovery (kgN/year/PE)		
		Gravity	Vacuum			$FeCl_3$	H_2SO_4	MeOH	MgO	NaOH			Sludge	Struvite	Ammo. Sulph.
REFERENCE	DP	24.8		1.5		1.8	1.1	2.5	0.3	0.9	−16.1	−4.4	0.7	0.1	0.3
	CP	11.6		1.4		1.7	1.1	2.5	0.2	0.9	−16.0	−4.3	0.7	0.1	0.3
	DB	2.2		1.3		1.9	1.1	3.2	0.2	0.9	−16.0	−4.2	0.7	0.1	0.3
	CB	3.1		1.3		2.1	1.2	3.7	0.2	1.0	−16.1	−4.3	0.7	0.1	0.3
	CC	2.9		1.3		2.3	1.2	4.2	0.2	1.0	−16.2	−4.3	0.7	0.1	0.3
	HT	0.4		1.0		2.9	1.4	6.4	0.2	1.3	−16.5	−4.4	0.8	0.0	0.4
URINE	DP	24.8		1.4	18.1	−0.7	8.9	−2.1	0.9	3.7	3.8	−1.8	0.6	0.2	2.3
	CP	11.4		1.5	7.0	−0.8	8.3	−2.1	0.9	3.7	3.9	−1.7	0.6	0.2	2.3
	DB	2.1		1.5	3.1	−1.0	8.7	−1.7	0.9	3.9	5.5	−1.7	0.6	0.3	2.5
	CB	3.2		1.3	2.0	−1.1	9.1	−1.4	1.0	4.1	6.7	−1.6	0.6	0.3	2.6
	CC	2.8		1.2	2.3	−1.2	9.6	−1.1	1.0	4.4	7.9	−1.6	0.6	0.3	2.7
	HT	0.5		0.9	2.8	−2.2	11.6	0.0	1.3	5.0	12.7	−1.7	0.7	0.4	3.3
BW	DP	24.3	2.2	7.3		−2.8	9.0	−2.8	1.3	6.9	58.0	−2.5	0.7	0.3	2.6
	CP	11.0	1.0	7.4		−2.9	9.0	−2.8	1.4	6.9	50.8	−4.4	0.7	0.3	2.6
	DB	1.9	0.2	8.3		−3.0	9.8	−2.2	1.4	7.5	51.0	−8.0	0.7	0.3	2.8
	CB	2.9	0.2	9.2		−2.8	10.4	−1.7	1.5	8.1	54.3	−9.6	0.7	0.3	3.0
	CC	2.8	0.2	10.4		−2.5	11.0	−1.4	1.5	8.7	58.4	−9.7	0.7	0.3	3.1
	HT	0.3	0.0	14.6		−1.6	13.5	0.3	1.6	10.9	74.0	−14.8	0.7	0.3	3.9
BW-GW	DP	24.3	2.2	7.3		0.0	9.7	0.0	1.4	12.8	113.5	85.4	0.3	0.2	2.8
	CP	11.0	1.0	7.4		0.0	9.7	0.0	1.4	12.8	105.3	83.1	0.3	0.2	2.8
	DB	1.9	0.2	8.3		0.0	10.3	0.0	1.5	13.1	101.9	73.5	0.3	0.3	2.9
	CB	2.9	0.2	9.2		0.0	10.8	0.0	1.5	13.4	102.8	67.3	0.3	0.3	3.1
	CC	2.8	0.2	10.4		0.0	11.3	0.0	1.6	13.6	104.7	63.0	0.4	0.3	3.2
	HT	0.3	0.0	14.6		2.5	13.1	0.0	1.8	14.6	111.1	40.8	0.4	0.3	3.8

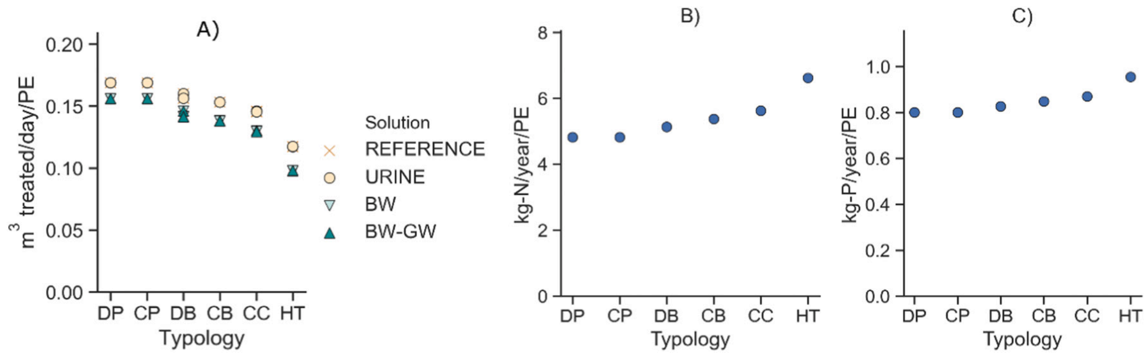

Fig. 3. Description of the reference flows: A); evolution of treated wastewater with urban configuration; B), mass flow of nitrogen; C) and phosphorus. DP: discontinuous pavilions, CP: continuous pavilions, DB: discontinuous buildings, CB: continuous buildings, CC: city centre, HT: high-rise tower.

Table 3
Reference flows of each urban configuration.

	Inh	Empl	PE	kg-COD/ year	kg-N/ year	kg-P/ year	Flowrate m^3/year
DP	101	0	62	3139	301	50	3835
CP	264	0	162	8206	786	130	10,024
DB	951	470	696	35,139	3582	577	40,665
CB	1307	1355	1123	56,711	6055	955	62,758
CC	910	1662	951	48,015	5363	829	50,658
HT	288	8795	2244	113,353	14,897	2151	96,158

More information of the energy consumption can be found in the section 6 of the SI.

3.1.3. Influence of urban configurations on the wastewater treatment

As shown in Table 2, chemicals consumption increased with the urban density and, in fact, with the N/PE and P/PE ratio. When urine or blackwater was separated, iron chloride was not necessary to treat the wastewater from the district in the centralised treatment. The change in N/COD ratio entering the WRRF was even beneficial for the biological removal of phosphorus and less iron chloride was needed than before the treatment of the district. Only in the *BW-GW* scenario for HT urban configuration iron chloride was needed due to less organic matter available for treatment.

Net electricity balance for treatment showed no influence of urban configuration for Reference and Urine scenario. In contrast for *BW* and *BW-GW* scenarios, increasing the urban density decreased the demand of electricity. It was due to the increase of the PE treated and the size of the cogeneration unit which allow to produce more electricity than heat. Heat consumption presents an optimum consumption for medium urban density. Larger unit of UASB reduced the heat loss but less heat was produced with the CHP unit. More information of the energy consumption can be found in the section 6 of the SI.

3.1.4. Influence of urban configurations on the resource recovery

Source separation significantly increased the nutrient recovery rate (see Fig. 4) compared to a recovery at the WRRF (*Reference*).

The nitrogen recovery rate (Fig. 4B) in ammonium sulphate form was only 6 % for the reference scenario, against 48 % for *Urine* separation, 55 % for *BW*, and 57 % for *BW-GW* scenarios. The influence of the urban configuration was relatively minor, since only a small increase was observed when increasing the population density in the *BW* scenario. Discontinuous pavilions had only 53 % of nitrogen recovery against 58 % for high-rise tower blocks. This was directly linked to the ratio of nitrogen to PE treated as explained in the Section 3.1.1. Additionally, the size of the district did not affect the recovery of nitrogen (data shown in section 7 of the SI).

Concerning phosphorus, the recovery as struvite (Fig. 4C) was improved by applying source separation, but the recovery rate remained comparable between each alternative sanitation system (from 60 % to up to 73 %). In addition, urban configurations had a more significant influence for *Urine* and *BW* systems. Moreover, the scale for implementing *BW* systems is also an influencing parameter. For instance, the recovery rate of phosphorus as struvite in the WRRF and for continuous buildings increases from 30 % to 37 % for 6.25 ha and 36 ha size districts respectively and *BW* solution (see Fig. S7 of the SI).

The recovery of COD (Fig. 4A) is not affected by the urban configuration nor by the size of the district, for both *Reference* and *Urine* scenarios, unlike *BW* system. The biogas produced at the district scale increased with the urban density. This is directly linked to the proportion of COD brought by blackwater as illustrated in Fig. S9 of the SI. Less COD is recovered in the *BW-GW* system compared to the *BW*, since greywater is treated directly in the MBR without any primary sedimentation, in opposition to the WRRF. In this sense, the COD from greywater is more aerobically degraded than recovered in sludge at WRRF. As a possible alternative, highly loaded reactors would be able to increase the COD recovery rate (de Graaff and van Hell, 2014).

3.2. LCA results

3.2.1. Midpoint level

The impacts of all midpoint impact categories are expressed as improvements compared to the *Reference* scenario, and are presented in the radar chart (Fig. 5, the red circles indicate the impact of the Reference system, and the absolute value in Table S7 in SI). A higher value indicates that the impact is degraded and a lower value indicates a benefit. The scale of the district had less influence compared to the urban configuration, and only the 6 ha scale is presented in the following graphs.

The threshold value of (Guérin-Schneider et al., 2018) have been used to identified the significant differences between each scenario. The Table S7 in SI presents these thresholds.

Urban configurations tend to decrease the number of impact categories with unknown differences between scenarios. *Urine* scenario improved between 1 and 8 of the 18 midpoint impact categories, and this increase is correlated to the density of the urban configurations. Only one category of impact is degraded: ionising radiation. Those benefits generally increased for high urban density. However, the improvement of benefits was not systematically observed. For instance, ionising radiation increased with the urban density due to an increased use of chemicals and especially sodium hydroxide, the production of which requires a large amount of electricity, partly originating from nuclear energy.

BW scenario improved between 2 and 5 impact categories, which was also directly linked to denser urban configuration. Compared to *Urine* scenario, fossil depletion is not improved, and ozone depletion is degraded. In the meantime, water depletion and particulate matter formation are also degraded for denser urban configurations. Finally,

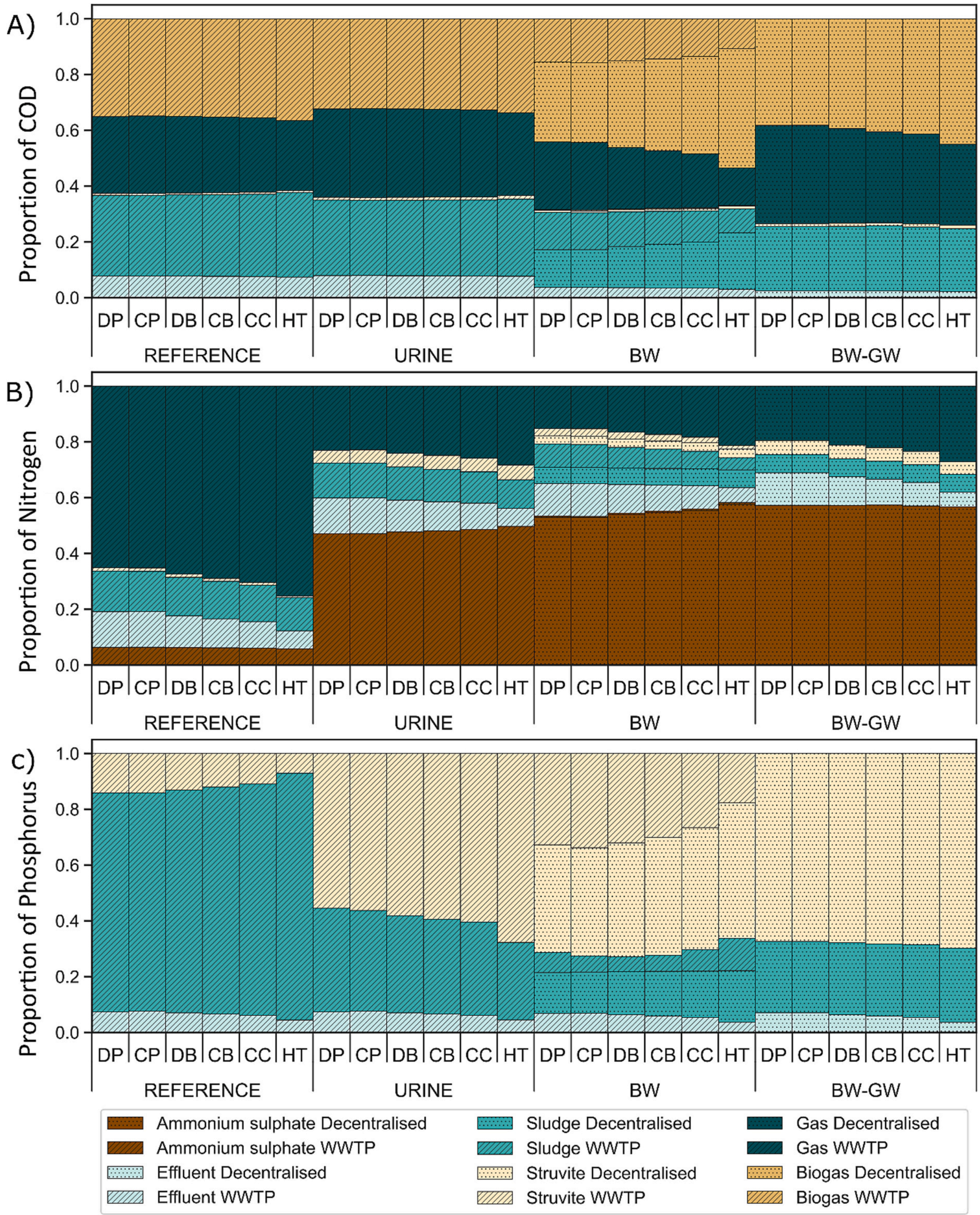

Fig. 4. Mass balance for different scenarios A) COD, B) Nitrogen, C) Phosphorus.
DP: discontinuous pavilions, CP: continuous pavilions, DB: discontinuous buildings, CB: continuous buildings, CC: city centre, HT: high-rise tower.

the greywater treatment scenario (*BW-GW*) leads to higher impacts than centralised systems for most of LCA impacts (10 to 12 impact categories), and this was reinforced for high density. Only 1 impact category (metal depletion) was improved. This trend was explained by a higher energy demand and therefore higher production of fossil resources and nuclear power compared with the *Reference*.

Fossil depletion and climate change had similar trend and will be discussed in the following section with contribution analysis.

Human toxicity increased with *BW-GW* scenario (+40 % compared to *Reference*) due to electricity consumption and tends to increase with urban configuration. For *Urine* and *BW* scenario no major difference was reported compared to *Reference*, except for HT configuration.

For all source separation scenarios, metal depletion impact was smaller compared to Reference. For *Urine* scenario the decrease is higher for denser urban configurations. This is only explained by the contribution of sewer which was reduced with denser urban configuration. For

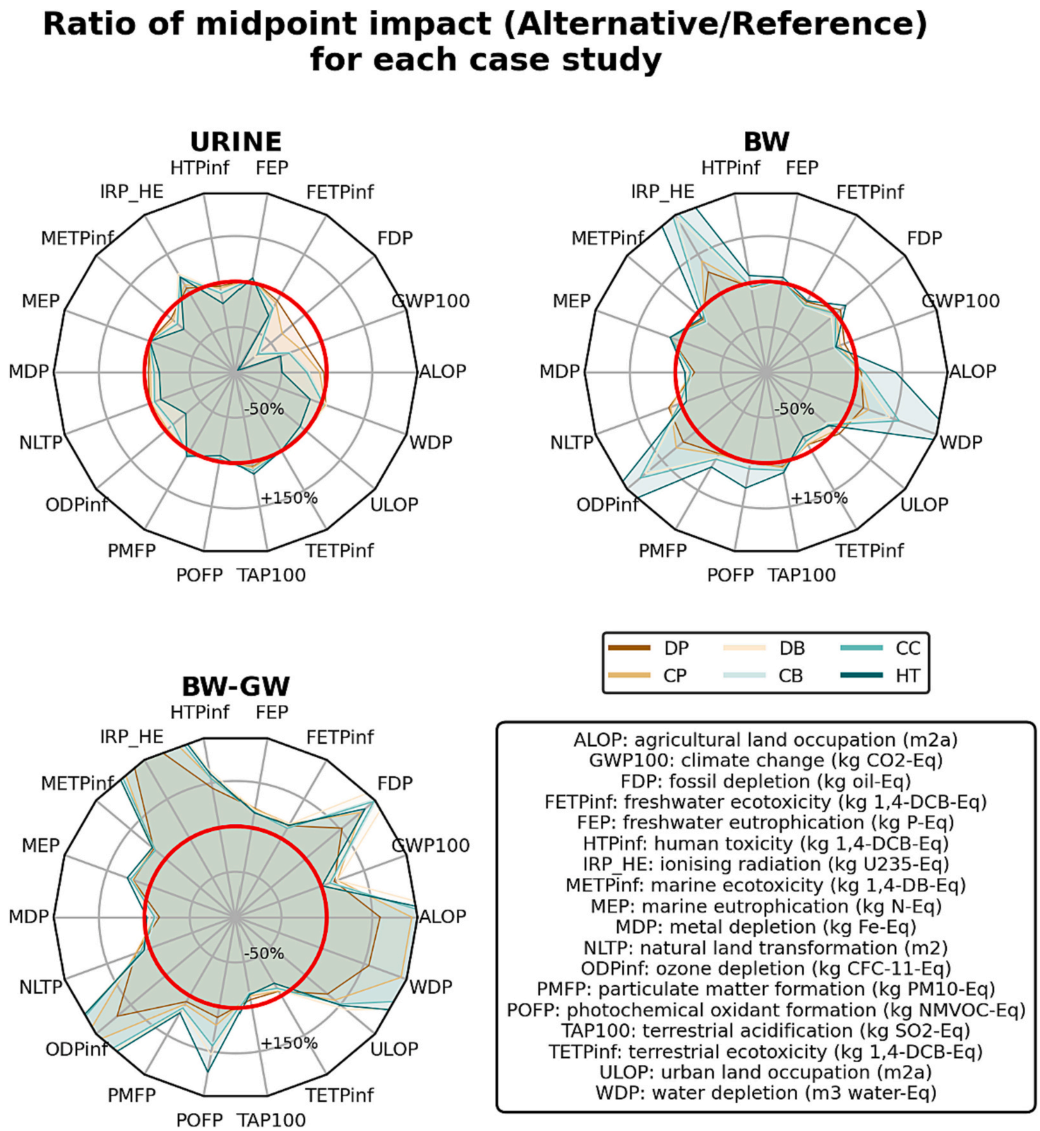

Fig. 5. Improvement of the different sanitation systems for each category of midpoint impacts. The red circle corresponds to the impact of reference. A higher value means a degradation and a lower means a benefit. (See Table S7 in SI for absolute value). DP: discontinuous pavilions, CP: continuous pavilions, DB: discontinuous buildings, CB: continuous buildings, CC: city centre, HT: high-rise tower.

the two other scenarios (*BW* and *BW-GW*) the contribution of chemicals and especially sodium hydroxide.

For all scenarios, the degradation of particulate matter formation is influenced by urban configuration and especially by chemicals needs for all source separation scenarios and by the electricity balance of the treatments for *GW-BW* scenario.

Water depletion increased with urine source separation, however, the absolute value remained very low (less than 1.5 m^3/PE/year) and was directly related to the production of sulfuric acid. For the *BW* and *BW-GW* scenarios, the water depletion increased due energy consumption and was not balanced by the decrease of water consumption with vacuum toilet or greywater reuse.

Finally, for *BW* and *BW-GW*, the impact from ionising radiation was again significantly increased with urban configuration and especially for dense configuration due to increase in the energy consumption for vacuum sewer and greywater treatment.

3.2.2. *Contribution analysis for climate change (midpoint)*

Climate change was identified as the main contributor to damage to ecosystem quality and human health at endpoint level (see Fig. S11 in SI). The contribution for climate change indicator (at midpoint level) is here analysed (Fig. 6, the red points represent the balance between avoided and the produced impacts). All the contribution analysis can be found in the section 10 in SI.

For the *Reference* sanitation, with a low-density urban configuration (DP, CP), the construction and operation of the sewer systems was the main contributions to climate change. The major differences were observed between pavilions configurations (DP, CP) and others (DB, CB, CC, HT). For example, the sewer for DP accounted for 59 % of the impact, while it accounted for only 7 % for high-rise towers. The impact of sewer was explained by the need of diesel for construction machinery. Unfortunately, the implementation of source separation systems did not change significantly the size and impacts of the sewer (because most of the water was still transported to the plant). As a consequence, the benefits of all the source separation scenarios increased as the sewer contribution decreased, i.e. with increasing of urban density.

Source separation helped reduce the impact of direct emissions in the wastewater treatment through a reduction in the nitrogen load of the water line. The emission factor from (IPCC, 2019) was, indeed, used (1.6 % of N entering the waterline as N-N_2O). The influence of urban configuration on direct emission was directly linked to the N/PE ratio of the wastewater to treat. As already explained in Fig. 3, high-rise towers

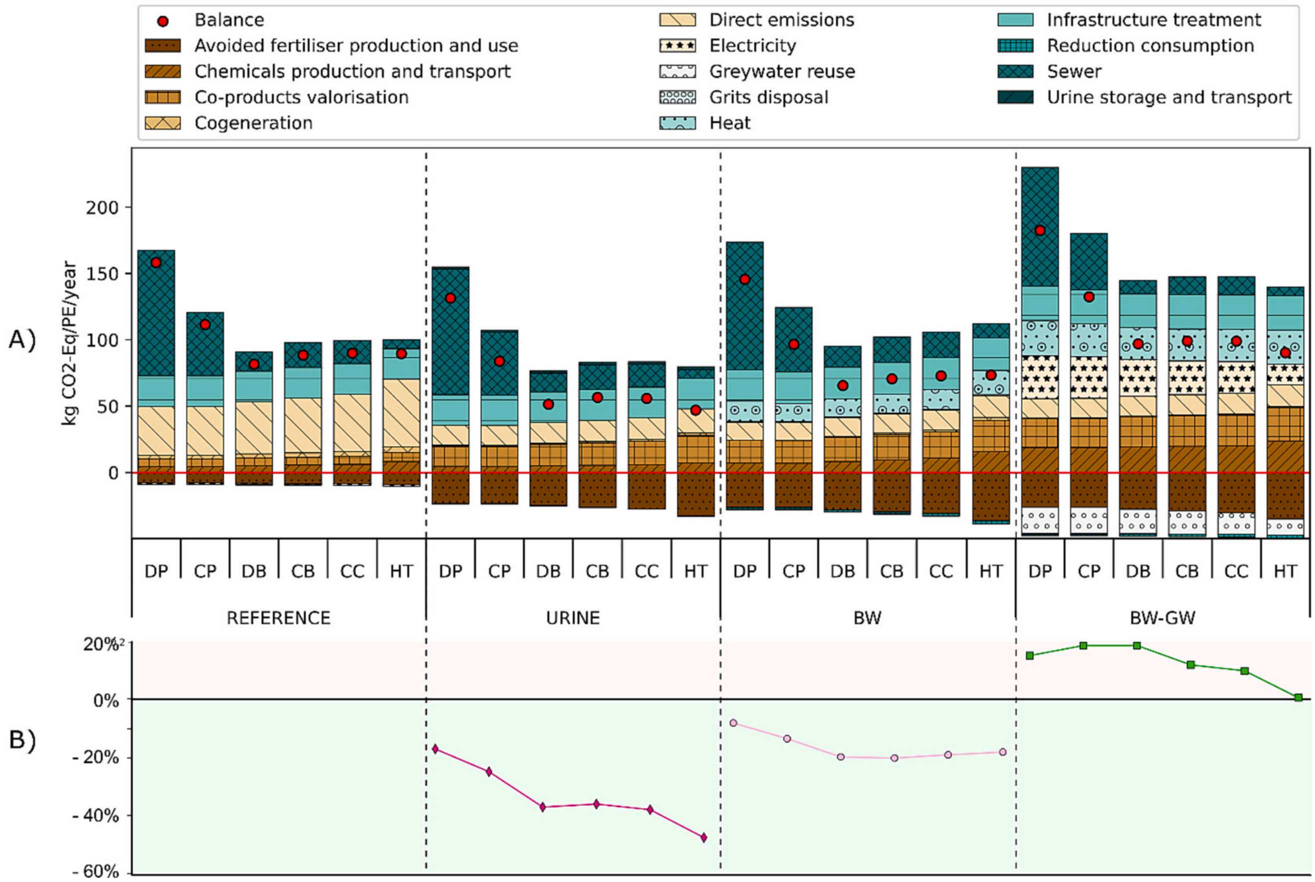

Fig. 6. Climate change impact for all scenario A) Contribution analysis; B) Improvements for each alternative sanitation systems compared to Reference. DP: discontinuous pavilions, CP: continuous pavilions, DB: discontinuous buildings, CB: continuous buildings, CC: city centre, HT: high-rise tower.

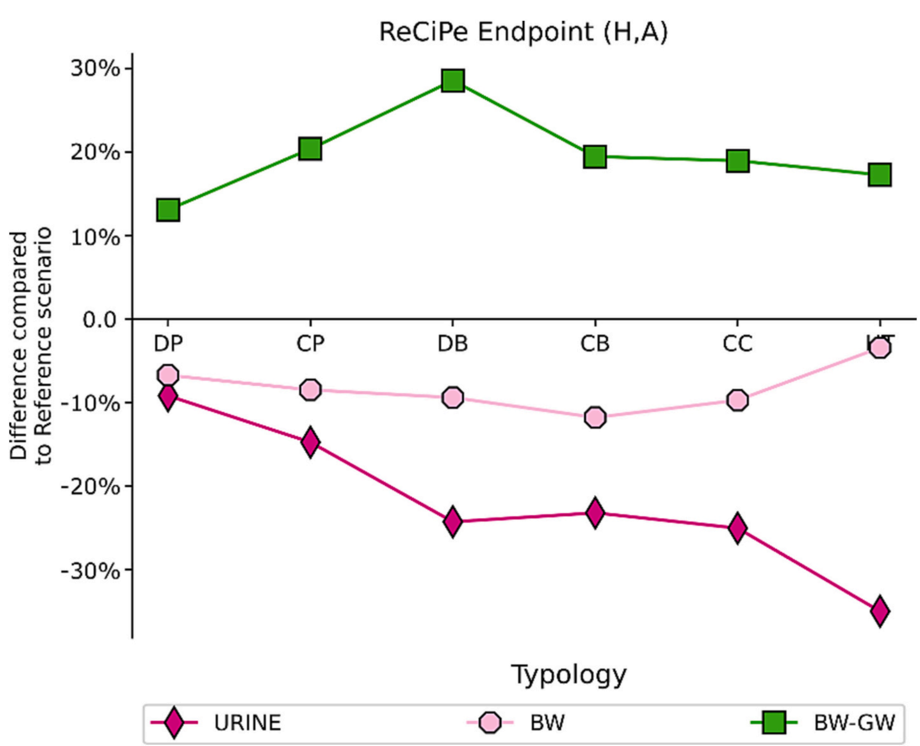

Fig. 7. Improvements for each alternative sanitation systems at endpoint impact. DP: discontinuous pavilions, CP: continuous pavilions, DB: discontinuous buildings, CB: continuous buildings, CC: city centre, HT: high-rise tower.

presented the highest N/PE ratio and this led to high direct emissions per treated PE, but also to a higher avoided fertiliser production.

In comparison urine transport was not significant in terms of climate change impact and did not vary between each case study.

For both *BW* and *BW-GW* sanitation systems, heat impact depends slightly on the scale and the urban typology. Electricity demand, on the other hand, depended on urban configurations. With higher urban density the organic load increased as well as the size of the CHP unit increased and the electricity production rate.

In order to analyse improvements obtained from each case study compared to the *Reference*, the Fig. 6B) has been drawn (negative values mean improvement). The greatest reduction of climate change impact was observed at high urban density (HT), with *Urine* scenario (48 %) and *BW* scenario (18 %), whereas *BW-GW* systems only provided the same impact than the *reference* scenario for High Tower.

3.2.3. Endpoint level

Despite the fact that some of the impact categories present a degradation with higher urban density, endpoint aggregation shows similar trends than climate change impact (Fig. 7). Both the same order of scenarios and the same effects of urban density was observed. For *Urine* and *BW* scenarios low urban density configuration had similar environmental impact than the *Reference*. *BW-GW* presented in any urban configuration an impact more than 15 % worse than *Reference*. The only difference is for *BW* scenario and HT urban configuration, which presented a similar impact than *Reference*. This is due to higher contribution of fossil depletion for this case.

4. Discussion

4.1. Results representativeness

In this study, results showed that urban configurations had a great impact on the environmental assessment of different sanitation options.

Globally but especially for GWP, the beneficial effects of source separation scenarios increased with the urban density. This result emphasized the strong impact of sewer infrastructure for low urban density (continuous and discontinuous pavilions) which limited the benefit of source separation scenario. (Roux et al., 2011) found similar results when performing an LCA assessment on both gravity sewer and wastewater treatment plants, based on real case studies. Authors reported that the contribution of sewer infrastructure to climate change decreased by 71 % when increasing the population density from low (similar to CP) to high (comparable to CB), which is comparable to our study (decreased by 63 %).

Urine source separation systems was beneficial for most of the impacts, and this was especially the case for high urban density (−48 % of climate change impact). This last result is in agreement with (Martin et al., 2023) showing a decrease of around 60 % for climate change impact with the Paris, France case study. The urine source separation was still well adapted to low densely populated areas, since climate change impact was reduced by at least 17 % compared to the reference system. Only on-site treatment of urine-free wastewater, should allow to reduce more the impact. For other urban configurations, *Urine* and *BW* systems performed well with more than 20 % of climate change impact reduction compared to the *Reference* system.

The results also underlined the influence of urban density on the different urban configurations for *BW* and *BW-GW* systems. High urban density involves larger facilities, especially the cogeneration unit, and hence provide a better energy balance compared to low urban density areas.

Moreover, the impact of the category of uses of buildings was for the first time addressed. Increasing the proportion of employees in the district, changed the composition of wastewater by decreasing the flowrate of greywater produced per PE and the load of COD. In terms of environmental assessment, the increase of urban density increased both direct emissions from the WRRF and avoided fertiliser production. In the *BW-GW* system, the presence of more employees reduced the total amount of greywater, the flowrate treated in the MBR was also reduced, which improved the electricity balance of the system.

Finally, it should be noted that this study referred to an optimal WRRF, which is different from most of the current treatment plants. Indeed, phosphorus recovery as struvite is only scarcely installed and nitrogen recovery is almost absent.

4.2. Sensitivity analysis

N_2O emissions factor and energy consumption especially for greywater treatment were found to be one of the main contributors explaining the impacts of the source separation scenarios. Both have a fairly wide range of variation.

The emission factor of N_2O was the one established by (IPCC, 2019), however N_2O emissions is strongly linked to the treatments implemented in the WWTP and the emissions can vary with seasons. Indeed a recent survey (Vasilaki et al., 2019) showed that activated sludge with Modified Ludzack-Ettinger configurations (MLE) has a median N_2O emissions factor equal to 0.857 % of N-load, whereas values between 2.26 % and 4.86 % was measured in intensively operated biofilters (Bollon et al., 2016). Therefore, if we refer to this intensive process as a reference (assuming N_2O emission factor of 3 %), then the *BW-GW* scenario will only present 10 % more impact on climate change for low urban density, and 20 % of improvement for high urban density.

The *BW-GW* system was not beneficial for most of the environmental impacts mostly due to a high energy consumption related to the treatment of greywater by MBR and to the European mix of electricity. In this study, energy requirements for the MBR were assumed to be the same for all the investigated district scales. However, Jeong et al. (2018) studied the consumption of MBRs treating greywater with regards to the treated flowrate at building scale. Based on manufactured MBRs, authors calculated a range of consumption values between 0.41 kWh/m^3 and 0.67 kWh/m^3, for 0.6 to 1.8 m^3/d flowrates respectively. But more research and development in this area is needed to consolidate these data and lowering the energy consumption of small decentralised treatment systems.

For *BW* systems, vacuum consumption was not negligible. Calculated values reached approximately 2 to 4 kWh/m^3 (or 5 and 20 kWh/PE/year) but these values can vary depending on the topology. Moreover, the model calculates the consumption without considering possible pipe leaks which can increase the loss of pressure. This range was thus lower than some values reported in the literature, between 21.9 and 36.5 kWh/inh/y (i.e. between 5.6 and 21 kWh/m^3) in the project of Waterschoon (Netherlands) and Flintenbreite (Germany), (Albold, 2013; de Graaff and van Hell, 2014; OtterWasser GmbH, 2009). Moreover, both these projects had measured their energy consumptions before the district reached the designed capacity, leading to the use of oversized pumps and hence higher consumption. Finally, in the project of Waterschoon the kitchen waste was transported into the vacuum sewer after a grinder, which was not considered in this study. Sensitivity analysis (Fig. S30 of the SI) showed that *BW* scenario would present a higher climate change impact than *Reference* for all urban configuration if energy consumption of 21 kWh/m^3 was considered for vacuum sewer. Whereas with 15 kWh/m^3 all the non-pavilions configuration presents similar impact than *Reference* (reduction of around 5 %).

Finally, water reuse is not driven by climate change mitigation but rather by water depletion and water scarcity. If new sources of water are needed, water reuse must be done with the best available technologies, to limit climate change impact. As electricity consumption was a major contributor, the energy mix had a strong impact on this assessment. A mix with more renewable energy could indeed reduce the contribution of electricity consumption on the climate change impact. But other side effects can also be raised. The study of (Santana et al., 2019) is a perfect example, as authors reported that greywater reuse in Spain, in the city of

Lloret del Mar, increased impact on water depletion due to water consumption related to additional electricity production needed for treating greywater. Hydroelectricity is a major contributor to an electricity mix and evaporation represent a sink of water resource. In this perspective, an LCA assessment is necessary to avoid solving local issues which are liable to generate other impacts at a more global scale.

5. Conclusions and future work

The aim of this study was to carry out a life cycle assessment of different source separation systems in order to analyse their sensitivity to urban configurations. Among the different possible systems urine diversion, blackwater and greywater management were successfully compared to centralised treatment, assuming optimised treatment solutions.

The study reveals that the benefits of source separation systems regarding global warming potential systematically increased with urban density. It was not systematically similar for all the other impacts, but climate change causes the highest damage at endpoint level.

Urine separation shows the highest benefits compared to other scenarios especially in high density area. At the contrary the greywater treatment scenario leads to higher impacts than centralised systems for most of LCA impacts. The benefit of urine diversion scenario in terms of global warming potential is significant, except for low urban density for which emissions are comparable to centralised resource recovery systems due to sewer contribution. The blackwater treatment scenario performs better than centralised system only for the highest urban density.

This study clearly shows the importance of considering the urban typology when choosing source separation techniques. Future effort should be dedicated to minimize energy and infrastructure needs of such systems for lowering the impacts, especially for greywater treatment.

CRediT authorship contribution statement

Mathilde Besson: Writing – original draft, Validation, Software, Methodology, Conceptualization. **Ligia Tiruta-Barna:** Writing – review & editing, Supervision, Funding acquisition. **Etienne Paul:** Writing – review & editing, Supervision. **Mathieu Spérandio:** Writing – review & editing, Supervision, Funding acquisition.

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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.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.171050.

References

Albold, A., 2013. Flintenbreite.

Article R4228-10, n.d., Droit du Travail Français (French Labor Code).

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, 126868 https://doi.org/10.1016/j.jclepro.2021.126868.

Bisinella de Faria, A.B., Spérandio, M., Ahmadi, A., Tiruta-Barna, L., 2015. Evaluation of new alternatives in wastewater treatment plants based on dynamic modelling and life cycle assessment (DM-LCA). Water Res. 84, 99–111. https://doi.org/10.1016/j.watres.2015.06.048.

Böhler, M., Hernandez, J., Fleiner, J., Gruber, W., Seyfried, 2018. POWERSTEP. WP4: Nitrogen Management in Side Stream. D 4.3: Operation and Optimization of Membrane Ammonia Stripping (Deliverable No. 4.3). Eawag.

Bollon, J., Filali, A., Fayolle, Y., Guerin, S., Rocher, V., Gillot, S., 2016. N2O emissions from full-scale nitrifying biofilters. Water Res. 102, 41–51. https://doi.org/10.1016/j.watres.2016.05.091.

Bonhomme, M., 2013. Contribution à la génération de bases de données multi-scalaires et évolutives pour une approche pluridisciplinaire de l'énergétique urbaine (Thèse de doctorat en Génie Civil). Laboratoire de recherche en architecture et Laboratoire matériaux et durabilité des constructions - Université de Toulouse, France.

BREEAM, 2016. International Wat 01 Water Consumption Calculator.

Corbella, H.M., Pujol, D.S.I., 2009. What lies behind domestic water use?: A review essay on the drivers of domestic water consumption. Bol. Asoc. Geógrafos Esp. 297–314.

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, 116058 https://doi.org/10.1016/j.watres.2020.116058.

Damtie, M.M., Volpin, F., Yao, M., Tijing, L.D., Hailemariam, R.H., Bao, T., Park, K.-D., Shon, H.K., Choi, J.-S., 2020. Ammonia recovery from human urine as liquid fertilizers in hollow fiber membrane contactor: effects of permeate chemistry. Environ. Eng. Res. 26 https://doi.org/10.4491/eer.2019.523.

de Graaff, R., van Hell, A.J., 2014. Nieuwe Sanitatie Noorderhoek, Sneek deelonderzoeken (New Sanitation Noorderhoek, Sneek sub-studies) (No. 2014–48). STOWA. STOWA, Amersfoort - Netherlands.

de Graaff, M.S., Temmink, H., Zeeman, G., Buisman, C.J.N., 2010. Anaerobic treatment of concentrated black water in a UASB reactor at a Short HRT. Water 2, 101–119. https://doi.org/10.3390/w2010101.

Devos, P., Filali, A., Grau, P., Gillot, S., 2023. Sidestream characteristics in water resource recovery facilities: a critical review. Water Res. 232, 119620 https://doi.org/10.1016/j.watres.2023.119620.

Diaz-Elsayed, N., Rezaei, N., Ndiaye, A., Zhang, Q., 2020. Trends in the environmental and economic sustainability of wastewater-based resource recovery: a review. J. Clean. Prod. 265, 121598 https://doi.org/10.1016/j.jclepro.2020.121598.

Friedler, E., Butler, D., Brown, D.M., 1996. Domestic WC usage patterns. Build. Environ. 31, 385–392.

Guérin-Schneider, L., Tsanga-Tabi, M., Roux, P., Catel, L., Biard, Y., 2018. How to better include environmental assessment in public decision-making: lessons from the use of an LCA-calculator for wastewater systems. J. Clean. Prod. 187, 1057–1068. https://doi.org/10.1016/j.jclepro.2018.03.168.

Henze, M. (Ed.), 2008. Biological Wastewater Treatment: Principles, Modelling and Design. IWA Publ, London.

Igos, E., Besson, M., Navarrete Gutiérrez, T., Bisinella de Faria, A.B., Benetto, E., Barna, L., Ahmadi, A., Spérandio, M., 2017. Assessment of environmental impacts and operational costs of the implementation of an innovative source-separated urine treatment. Water Res. 126, 50–59. https://doi.org/10.1016/j.watres.2017.09.016.

IPCC, 2019. Wastewater treatment and discharge. In: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC, Switzerland.

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 14040, 2006. ISO Standard 14040, 2006. NF EN ISO 14040:2006 e Environmental Management - Life Cycle Assessment - Principles and Framework.

ISO 14044, 2006. Environmental Management - Life Cycle Assessment - Requirements and Guidelines.

Jeong, H., Broesicke, O.A., Drew, B., Li, D., Crittenden, J.C., 2016. Life cycle assessment of low impact development technologies combined with conventional centralized water systems for the City of Atlanta, Georgia. Front. Environ. Sci. Eng. 10, 1. https://doi.org/10.1007/s11783-016-0851-0.

Jeong, H., Broesicke, O.A., Drew, B., Crittenden, J.C., 2018. Life cycle assessment of small-scale greywater reclamation systems combined with conventional centralized water systems for the City of Atlanta, Georgia. J. Clean. Prod. 174, 333–342. https://doi.org/10.1016/j.jclepro.2017.10.193.

Jönsson, H., Burström, A., Svensson, J., 1998. Mätning på två urinsorterande avloppssystem (Report No. 228). Uppsala.

Jönsson, H., Baky, A., Jeppsson, U., Hellström, D., Kärrman, E., 2005. Composition of Urine, Faeces, Greywater and Biowaste for Utilisation in the URWARE Model.

Kavvada, O., Horvath, A., Stokes-Draut, J.R., Hendrickson, T.P., Eisenstein, W.A., Nelson, K.L., 2016. Assessing location and scale of urban nonpotable water reuse systems for life-cycle energy consumption and greenhouse gas emissions. Environ. Sci. Technol. 50, 13184–13194. https://doi.org/10.1021/acs.est.6b02386.

Kavvada, O., Nelson, K.L., Horvath, A., 2018. Spatial optimization for decentralized non-potable water reuse. Environ. Res. Lett. 13, 064001 https://doi.org/10.1088/1748-9326/aabef0.

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.

Le Sommer Environnement, 2018. Personal communication.
Lehtoranta, S., Malila, R., Särkilahti, M., Viskari, E.-L., 2022. To separate or not? A comparison of wastewater management systems for the new city district of Hiedanranta, Finland. Environ. Res. 208, 112764 https://doi.org/10.1016/j.envres.2022.112764.
Lundin, M., Bengtsson, M., Molander, S., 2000. Life cycle assessment of wastewater systems: influence of system boundaries and scale on calculated environmental loads. Environ. Sci. Technol. 34, 180–186. https://doi.org/10.1021/es990003f.
Malila, R., Lehtoranta, S., Viskari, E.-L., 2019. The role of source separation in nutrient recovery – comparison of alternative wastewater treatment systems. J. Clean. Prod. 219, 350–358. https://doi.org/10.1016/j.jclepro.2019.02.024.
Martin, T.M.P., Aubin, J., Gilles, E., Auberger, J., Esculier, F., Levavasseur, F., McConville, J., Houot, S., 2023. Comparative study of environmental impacts related to wheat production with human-urine based fertilizers versus mineral fertilizers. J. Clean. Prod. 382, 135123 https://doi.org/10.1016/j.jclepro.2022.135123.
Maurer, M., Schwegler, P., Larsen, T.A., 2003. Nutrients in urine: energetic aspects of removal and recovery. Water Sci. Technol. J. Int. Assoc. Water Pollut. Res. 48, 37–46.
Meinzinger, F., Ziedorn, V., Peters, I., 2010. Interactions between urban forms and source-separating sanitation technologies. In: van Vliet, B., Spaargaren, G., Oosterveer, P. (Eds.), Social Perspectives on the Sanitation Challenge. Springer, Netherlands, Dordrecht, pp. 125–144. https://doi.org/10.1007/978-90-481-3721-3_8.
OtterWasser GmbH, 2009. Ecological housing estate. In: Flintenbreite, Lübeck, Germany (Case Study of Sustainable Sanitation Projects). Sanitation Alliance (SuSanA), Sustainable.
Peter-Fröhlich, A., Bonhomme, A., Oldenburg, M., 2007. Sanitation Concepts for Separate Treatment of Urine, Faeces and Greywater (SCST) (Final Report: EU-demonstration Project No. Contract: LIFE03ENV/D000025). KompetenzZentrum Wasser Berlin gGmbH.
Rauch, W., Brockmann, D., Peters, I., Larsen, T.A., Gujer, W., 2003. Combining urine separation with waste design: an analysis using a stochastic model for urine production. Water Res. 37, 681–689. https://doi.org/10.1016/S0043-1354(02)00364-0.
Remy, C., 2010. Life Cycle Assessment of Conventional and Source Separation Systems for Urban Wastewater Management. https://doi.org/10.14279/depositonce-2370.
Roux, P., Mur, I., Risch, E., Boutin, C., 2011. Urban Planning of Sewer Infrastructure: Impact of Population Density and Land Topography on Environmental Performances of Wastewater Treatment Systems, in: Proceedings of the LCM 2011 International Conference on Life Cycle Management. Germany, Berlin.
Santana, M.V.E., Cornejo, P.K., Rodríguez-Roda, I., Buttiglieri, G., Corominas, L., 2019. Holistic life cycle assessment of water reuse in a tourist-based community. J. Clean. Prod. 233, 743–752. https://doi.org/10.1016/j.jclepro.2019.05.290.
Tchobanoglous, G., Burton, F.L., Stensel, H.D., Metcalf & Eddy, Inc (Eds.), 2003. Wastewater Engineering: Treatment and Reuse, 4. Ed., Internat. Ed., [Nachdr.]. Ed, McGraw-Hill Series in Civil and Environmental Engineering. McGraw-Hill, Boston, Mass.
Thibodeau, C., Monette, F., Bulle, C., Glaus, M., 2014. Comparison of black water source-separation and conventional sanitation systems using life cycle assessment. J. Clean. Prod. 67, 45–57. https://doi.org/10.1016/j.jclepro.2013.12.012.
Tidåker, P., Mattsson, B., Jönsson, H., 2007. Environmental impact of wheat production using human urine and mineral fertilisers – a scenario study. J. Clean. Prod. 15, 52–62. https://doi.org/10.1016/j.jclepro.2005.04.019.
Udert, K.M., Jenni, S. (Eds.), 2013. Biological Nitrogen Conversion Processes, in: Source Separation and Decentralization for Wastewater Management. IWA Publ, London.
Udert, K.M., Wächter, M., 2012. Complete nutrient recovery from source-separated urine by nitrification and distillation. Water Res. 46, 453–464. https://doi.org/10.1016/j.watres.2011.11.020.
Vasilaki, V., Massara, T.M., Stanchev, P., Fatone, F., Katsou, E., 2019. A decade of nitrous oxide (N2O) monitoring in full-scale wastewater treatment processes: a critical review. Water Res. 161, 392–412. https://doi.org/10.1016/j.watres.2019.04.022.
Zhang, Y., Li, Z., Zhao, Y., Chen, S., Mahmood, I.B., 2013. Stabilization of source-separated human urine by chemical oxidation. Water Sci. Technol. J. Int. Assoc. Water Pollut. Res. 67, 1901–1907. https://doi.org/10.2166/wst.2013.055.
Zhang, D., Dong, X., Zeng, S., Wang, X., Gong, D., Mo, L., 2023. Wastewater reuse and energy saving require a more decentralized urban wastewater system? Evidence from multi-objective optimal design at the city scale. Water Res. 235, 119923 https://doi.org/10.1016/j.watres.2023.119923.