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Life cycle assessment of ecological sanitation system for small-scale wastewater treatment

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ABSTRACT

Ecological sanitation (EcoSan) concepts, relying on an environmentally sound management of water, nutrient and energy fluxes, have been poorly characterized in literature and are widely ignored by public planning authorities, architects or engineers. A comparative life cycle assessment (LCA) of an EcoSan system at an office building and of conventional systems was carried out in order to provide practical data and information to (partially) fill this gap. Compared to conventional systems, EcoSan can reduce the contribution to ecosystem quality damage by more than 60%. EcoSan leads, however, to higher damages on resources and human health and higher impact on climate change. Key improvement possibilities and research needs related to these results are discussed throughout the paper. Ecological sanitation appears to be a promising alternative to small-scale wastewater treatment. At higher scales, low water consumption conventional systems are better performing and are not likely to be replaced by EcoSan systems in the short term. Standard conventional systems have very poor environmental performances and should be upgraded as far as possible.

1. Introduction and objectives

In order to comply with European legislation concerning wastewater collection and treatment, important financial investments are necessary in Luxembourg until the year 2015. Currently sanitation issues are tackled with the common praxis of building large sewer systems and new centralized treatment plants and continually upgrading and expanding existing infrastructure. This policy not only incurs important costs but also has significant environmental impacts for Luxembourg as the small receiving water bodies are especially vulnerable to point emissions from wastewater treatment facilities. In addition, saving drinking water is becoming an issue of growing concern as reservoirs are under pressure both with respect to quality (chemical pollution) and quantity, due to a strong demographic growth and to a diminished recharge over the last years. EU water policy will also have important social impacts (i.e. the polluter pays-principle), which have found very little attention in water management in Luxembourg so far.

The concept of ecological sanitation (EcoSan) relies on an environmentally and economically sound management of water, nutrient and energy fluxes (Otterpohl, 2002; Werner et al., 2003). EcoSan and alternative sanitation concepts are widely ignored by public planning authorities, architects or engineers in Luxembourg. Decentralized sanitation systems with source control of pollutants and reduced water consumption (e.g. vacuum sanitation technology, waterless urinals or separation toilets) are, however, implemented throughout Europe and certain aspects of their environmental benefits, economic viability and social acceptability have been investigated considering different scales of implementation and wastewater loads (Dallas et al., 2004; Guzha et al., 2005; Langergraber and Muellegger, 2005; Nakagawa et al., 2006; Remy et al., 2006). In order to study the attitude concerning water problems and acceptability towards new sanitation concepts, two survey activities were conducted in

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Luxembourg in the years 2003 and 2004. The surveys focused on, respectively, the attitude of the key actors (public and private investors, regulators, water services, architects, engineers, sanitary firms) in the water and construction sector towards new sanitary concepts in Luxembourg and more broadly the attitude of the end-users towards water related issues. Both surveys indicate that in addition to awareness-raising and information activities, further research and development is needed, concerning the user-friendliness of sanitation technology (e.g. separation toilets), the fate of pollutants such as drug residues in the wastewater stream, especially yellow water, but also on ways on how to communicate the complex issues of environmental impacts at various levels to the stakeholders. The evaluation of the water management scenarios has to be multi-criteria, i.e. has to involve several environmental impacts and include socio-economic aspects in order to contribute to a successful implementation of ecological sanitation concepts (Schosseler et al., 2007). These environmental performances have been poorly characterized in literature so far.

In order to define and evaluate possible approaches and methodologies to fill this gap and to identify research needs, a life cycle assessment (LCA) study of ecological sanitation scenario at an office building in Beckerich (Luxembourg) was carried out. The study is intended to provide specific data and information to stakeholders and decision-makers regarding the advantages and disadvantages of EcoSan systems as compared to classical centralized wastewater treatment systems. This paper presents the lessons learned from the study and identifies the key methodological and practical issues to be investigated further in future research.

2. Scope of the study

2.1. Functional unit

The functional unit is the treatment of the wastewater generated by 40 persons working in the building for 220 days per year. Wastewater treatment corresponds to minimum quality requirements and/or pollutants removal efficiency (which are usually defined by regulations) that have to be fulfilled. These criteria are implicitly considered in the datasets used in the inventory and can hardly be modified by the practitioner. This means that EcoSan and conventional systems could lead to different quality of treated (output) water. This difference is not considered in the functional unit but is taken into account in the impact assessment results. The wastewater flows are generated by the sanitation systems collecting human dejections (urine and faeces leading to yellow water and brown water respectively) and by other equipments (kitchen and sinks leading to grey water). The composition of these inputs is based on the assumptions of Remy et al. (2006). The inputs of faeces and urine were recalculated by considering the mean daily production of faeces and urine by humans according to Lentner (1981) and 60% collection by the sanitation system of the building (Table 1). Sludge arising from the treatment of wastewater is supposed to be used in landfarming. The consideration of the fertilizing function of sludge and of the related advantages in term of avoided use of chemical fertilizers depends on the economic value of sludge. This issue is discussed further in the sensitivity analysis (multi-functionality).

Table 1 – Average composition of urine, faeces and grey water (per person.day)

Quantity	Unit	Urine	Faeces	Grey water
	kg / (p.d)	1.5	0.14	80
Main constituents				
Dry matter	mg / (p.d)	60 000	45 000	120 000
Organic dry mater	mg / (p.d)	45 000	42 000	–
COD	mg / (p.d)	15 000	35 000	60 000
TOD	mg / (p.d)	7000	21 000	18 000
N-total	mg / (p.d)	10 000	1500	1300
P-total	mg / (p.d)	1000	500	500
K	mg / (p.d)	2600	550	2000
Na	mg / (p.d)	3500	150	6000
Ca	mg / (p.d)	210	1000	14 000
Mg	mg / (p.d)	120	200	3000
Cl	mg / (p.d)	4800	60	7000
S -total	mg / (p.d)	800	200	7500
Metals				
Cd	mg / (p.d)	0.0002	0.02	0.2
Cr	mg / (p.d)	0.01	0.02	3
Cu	mg / (p.d)	0.05	1.5	20
Hg	mg / (p.d)	0.0004	0.02	0.02
Ni	mg / (p.d)	0.04	0.2	2
Pb	mg / (p.d)	0.01	0.02	3
Zn	mg / (p.d)	0.25	10	46

2.2. Boundaries

The EcoSan system considered for the office building is illustrated in Fig. 1a. The sanitation devices included are: 11 gravity separation toilets using rainwater for flushing, 4 waterless urinals, 7 sinks and 4 small kitchens (sink and dish-washer). The gravity separation toilets allow the separate collection of 80% of undiluted urine apart from faeces, i.e. 20% of urine is misdirected with faeces flow. Wastewater output from the building consists of 3 main flows: brown water including flushing water, faeces and 20% of misdirected urine; yellow water, corresponding to 80% of urine left; grey water from the utilization of water for sinks, washing machines, and kitchen. Yellow water is collected and discharged by gravity into pump wells, from which it is pumped to the holding tanks. Brown water is drained off by gravity to the pumping station from where the mix is pumped to the solid–liquid separator. The solid fraction is further thickened and transported by truck to the composting plant, where it is treated and applied on farmland. Grey water is collected by gravity drainage and treated, together with the filtrate from faeces dewatering, by sedimentation and through a reed bed. Sludge from primary sedimentation is incinerated, while the reed from constructed wetlands is added to the composting process. Yellow water is stored in the holding tank for at least 6 months in order to meet the sufficient hygienic requirements before the application onto farmland as fertilizer. The efficiency of the solid–liquid separation device is set to 95% and the distance between

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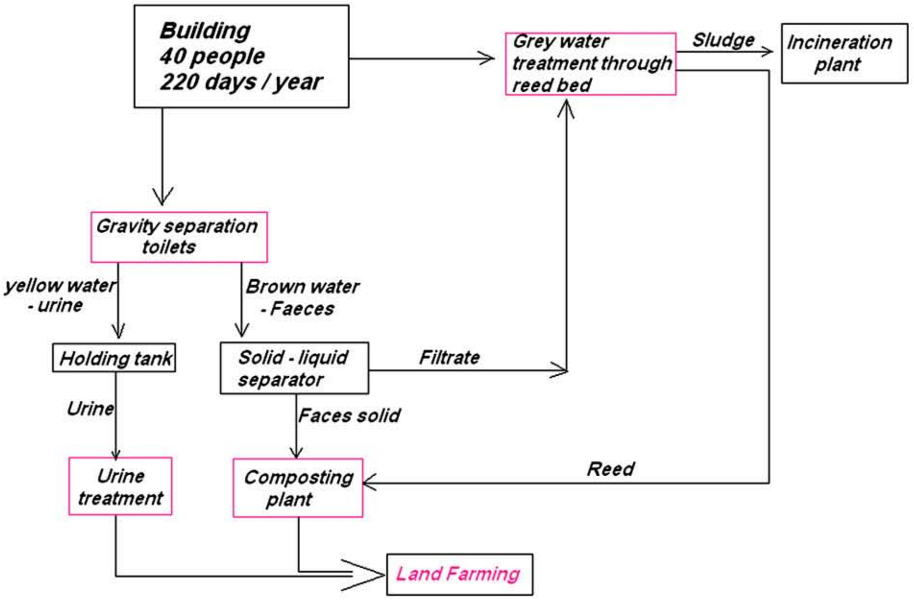
(a) Treatment processes



(b) Nutrients' flows calculated in the Umberto network

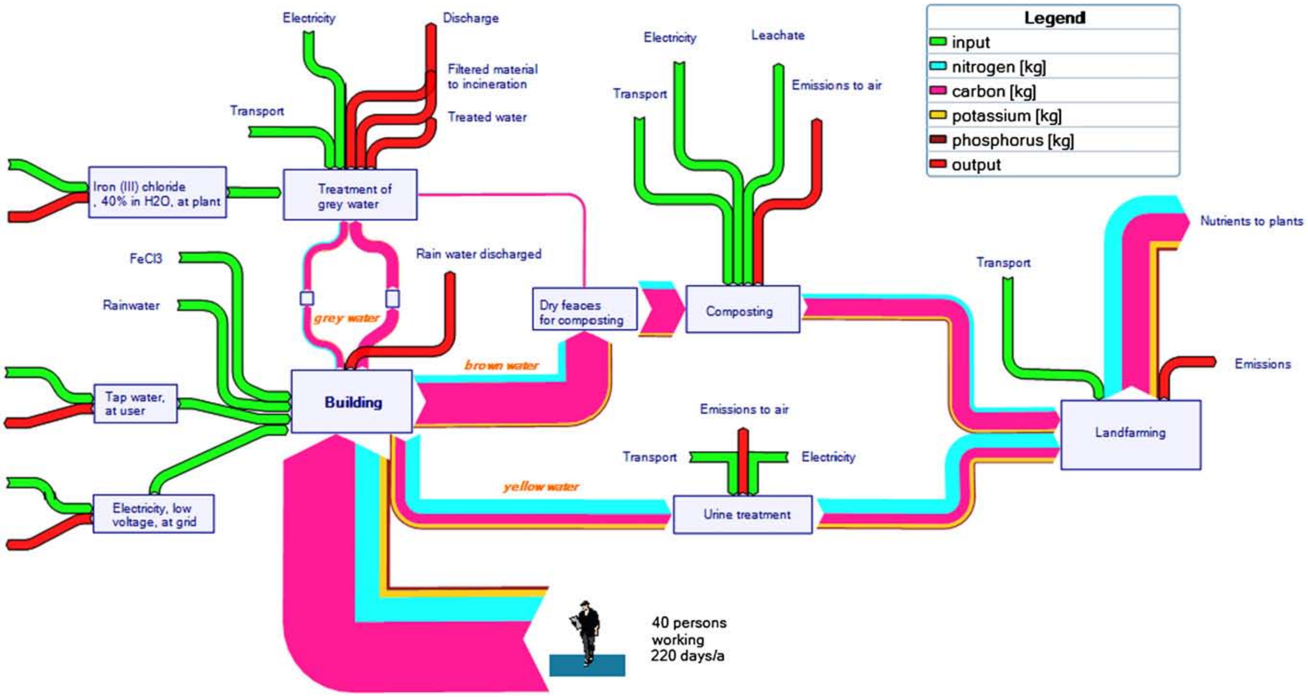


Fig. 1 – scheme of ecological sanitation scenario (EcoSan).

the building and the composting plant, as well as the working distance for tractors at landfarming plant, are set to 50 km.

The infrastructures (mainly sanitation equipments and sewer network) are excluded from the scope of the present study because their contribution to environmental impacts has been proven to be negligible (Remy et al., 2006). The use of toilet paper and soaps was neglected too because they basically do not depend on the type of sanitation systems considered.

3. Life cycle inventory analysis (LCI)

The software Umberto 5.5 (www.umberto.de) was used for the LCI. The methodology is compliant with the ISO 14040–14044 standards and follows the current state of the art of attributional (descriptive) LCA (Lundie et al., 2007; Rebitzer et al., 2004; Pennington et al., 2004, Guinée, 2002). Fig. 1b shows the flows of nutrients as calculated with Umberto 5.5·

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It can be observed that the loss of nutrients through grey water is negligible and most of N, P and K are carried by yellow water.

3.1. *Inventory data of the EcoSan system*

Background data are issued from the Ecoinvent 2.0 database. Foreground data are based on literature values from reliable sources, which have been checked and reviewed as detailed hereafter.

3.1.1. *Gravity separation toilet*

The efficiency of the separation is set to 80%. Experiences from Swedish pilot plants indicate that 60 to 90% of total urine flow could be separated depending on the motivation of the tenant (Jönsson et al., 1997). The influence of this parameter is studied in sensitivity analysis.

3.1.2. *Solid–liquid separation*

A sedimentation stage followed by a mechanical thickening device is considered. Ferric chloride (10 g/kg dry matter) is added for coagulation and residual sludge production. Electrical energy consumptions are: 0.03 kWh/kg dry matter for thickening device, 0.025 kWh/m^3 for pumping the faeces with flush water, 0.14 kWh/m^3 for pumping the filtrate to grey water treatment and 0.03 kWh/m^3 for pumping sludge (Remy et al., 2006). Through the filtrate, 100% of phosphorus and 84% of nitrogen of misdirected urine are lost together with organic carbon load from faeces. The filtrate is pumped to the grey water treatment plant, and the residual sludge from faeces is temporarily stored in dewatering container and transported to the composting plant.

3.1.3. *Composting of faeces*

Composting faeces for the production of organic fertilizers was proven to effectively reduce pathogens and odour problems, producing a stabilized soil conditioner with some nutrients (Remy et al., 2006). The composting process includes two steps: intensive and open composting. Intensive composting is conducted in closed boxes with heat insulation. Due to the lack of specific data, the inventory is based on the data from a study on bio-waste (Vogt et al., 2002), providing estimates of the amounts of resources and emissions involved in the process. The leachate is pumped together with the sludge from grey water treatment to the incineration plant (Renou et al., 2008). The exhausted air is cleaned in biofilter to prevent odorous and ammonia emissions. The biofilter can be a source of CH_4 and N_2O emissions (Remy et al., 2006; Renou et al., 2008). Open composting is finally necessary in order to have good quality compost for landfarming. Data for open composting are issued from Vogt et al. (2002) as well.

3.1.4. *Treatment of yellow water*

The yellow water is pumped to the holding tank which is designed for a maximum holding time of 14 days. Then the yellow water is transported along 50 km to the storage tank, where it stays for 6 months in order to meet hygienic requirements. Prior to the application as fertilizer, the yellow water is diluted with rainwater (1:1). The energy demands for pumping and for dilution are estimated to respectively 0.08 and 0.1 kWh/m^3 of yellow water (Remy et al., 2006). Nitrogen losses through ammonia evaporation are estimated to 0.01 and 0.003% N respectively in piping and storage tanks (Sirkka, 1999; Remy et al., 2006).

3.1.5. *Treatment of grey water*

The treatment is achieved by means of a reed bed, based on the elimination of COD, N, and P from wastewater during the passage through a soil filter. Most of the COD and nitrogen content is removed by microbial activity in the soil filter, while phosphorus is mainly retained by adsorption onto soil particles. Sludge is then co-incinerated in municipal waste incineration plant because of the elevate content of heavy metals which is not allowed for digestion or composting. The incineration process is quite difficult to be modelled, because of the nature of the waste co-incinerated, the repartition of pollutants between air and ashes and the need for extra fuel to maintain the combustion. Very poor information about these issues is available in literature. For sake of simplicity, the release to air of the main components of sludge as elements or in their oxidized form is considered. For example, zinc is considered to move from water to air and phosphates to be released as phosphoric acid. Prior to the soil filter particulate matter is removed by a sedimentation stage, in order to reduce the pollutant load on the filter and to prevent clogging by particle aggregation on the filter surface. 15% C, 11% N, 10% P and 70% dry matter are removed in this stage. The filter is operated as vertical flow and the faeces filtrate is added to the particle free grey water coming from the sedimentation stage. The surface of filter needed is estimated to 2 m^2 per person and the filter produces an average amount of 2.44 kg reed/m^2/a at 41% dry matter. The energy demand is 0.005 kWh/m^3 of grey water. The elimination of other heavy metals has been estimated to be equivalent to the one achieved by conventional wastewater treatment. Due to the insufficient removal of phosphorus of the filter, post precipitation is provided to remove the retained phosphorus by precipitation with $FeCl_3$. The efficiency is estimated to 80% (Remy et al., 2006). The sludge from sedimentation, precipitation and the reeds moved is transported to the composting plant.

3.2. *Multi-functionality: landfarming of natural fertilizers*

EcoSan allows recovering nutrients from wastewater, which are then distributed into the soil through landfarming of urine and compost. These natural fertilizers may represent a co-function of the EcoSan system in addition to the main function which is the treatment of wastewater. The environmental burdens of the EcoSan system should then be split between the two functions. The way to address multi-functionality depends on the type of LCA (attributional or consequential) and on the economic value of natural fertilizers, i.e. on the market, which is rather unpredictable. Several approaches are highly debated in the LCA community: no unique solution does exist (see e.g. Lundie et al., 2007). Based on the attributional perspective, in this study multi-functionality is addressed by considering

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three different cases (Lundie et al., 2007; Rebitzer et al., 2004; Guinée, 2002): case 1) “Cut off”: urine and compost are given free of charge to farmers; this is the most likely case because farmers would probably accept to use these natural fertilizers, despite their heavy metals content, mainly because of cost saving. In this case the environmental burdens of transport and landfarming are cut-off, i.e. not allocated to the EcoSan system. Case 2) “Waste”: urine and compost have negative economic value and are therefore considered as waste. Landfarming is a waste treatment process and the environmental burdens related are allocated to the EcoSan system. The nutrients which are fed to the plants are not considered in the assessment because they are part of the receiving agricultural system and therefore their fate has to be allocated to this system. Case 3) urine and compost are sold as natural fertilizers, i.e. have positive economic value, and displace the production and delivery of chemical fertilizers. On one hand, the “system expansion” approach is suggested by the ISO standards and often considered in the practice (Rebitzer et al., 2004; Ekvall and Finnveden, 2001), despite some authors advise restricting its applicability to consequential LCAs (see e.g. Weidema, 2003; Lundie et al., 2007). Using this approach, the credit generated through the displacement could be fully allocated to the EcoSan system. This is a rather arbitrary choice indeed because the credit could be split up between EcoSan (donor system) and the agricultural system using the fertilizer (receiver system) as well. However it is not straightforward to identify pertinent criteria for that subdivision and it is often advocated to allocate the whole credit to the donor system. On the other hand, economic allocation instead of system expansion could an alternative solution to multi-functionality (Guinée et al., 2004). Nevertheless, economic allocation is rather infeasible in this case because of the lack of information about the market value of natural fertilizer. The “system expansion” approach was considered for the case 3), due to the easiness of application and popularity. However, it should be noted that this approach is likely to give EcoSan a significant advantage and is not consensual in the LCA community.

The “waste” approach (case 2) is considered by default for sake of coherence with the approach used by Ecoinvent in the modelling of conventional treatment systems (see Section 3.3). The other approaches (cases 1 and 3) are studied in the sensitivity analysis.

During landfarming, emissions arise from both fertilizers themselves and the operation of the tractor. Compost from faeces plays a minor role in the NPK input into agricultural soil (see also Fig. 1b). Furthermore, the total mass flow of compost represents only a minor fraction of the flow of diluted urine. NH_3 emissions of urine application are based on results from various pilots studied (Heinonen-Tanski and van Wijk-Sijbesma, 2005; Remy et al., 2006), while NO_x and N_2O emissions factors are the same than for mineral fertilizer (Table 2). CO_2 emissions from urea hydrolysis of urine and from carbon degradation of compost are not included in the inventory because of lack of information about the differences between the studied scenarios.

Table 2 – Emission factors for urine and compost during landfarming

	g NH_3–N/g N	g N_2O–N/g N	g NO–N/g N
Urine	0.06	0.0125	0.007
Compost from faeces	0.05	0.0125	0.007

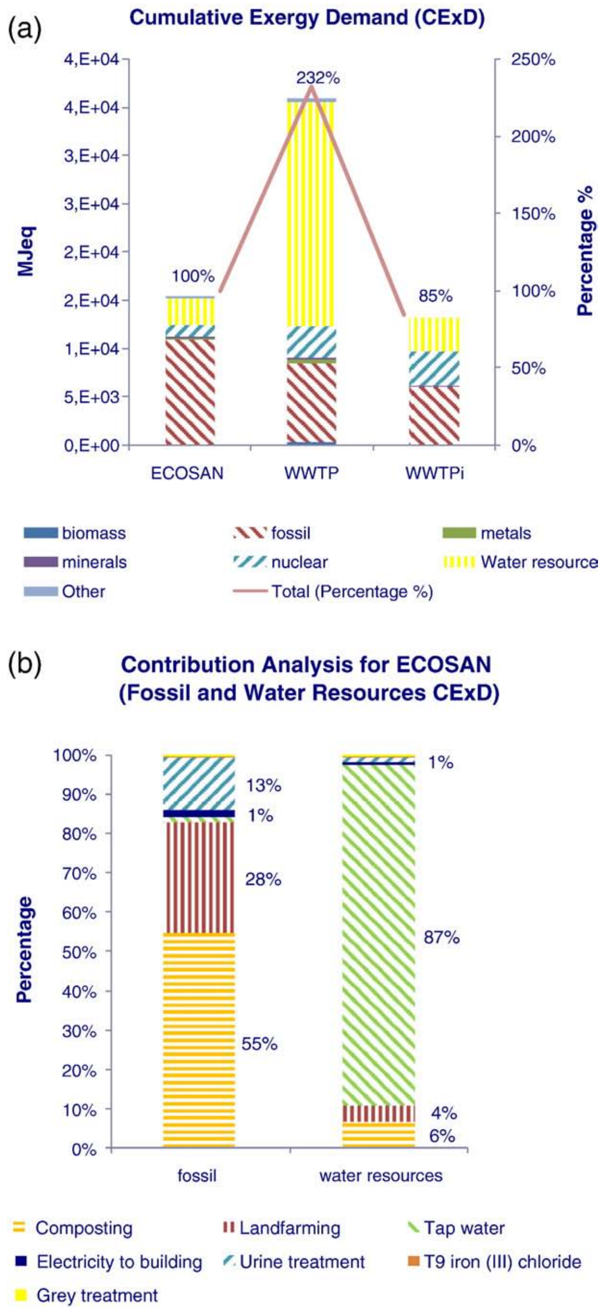

Fig. 2 – Cumulative Exergy Demand (CExD).

3.3. *Inventory data of the conventional (reference) wastewater treatment systems*

In the baseline reference system (*WWTP*), standard sanitation systems are considered, leading to a tap water

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consumption of 392 m^3/a. Wastewater outputs from the building, including rainwater collected from the roof, are treated in wastewater treatment plant, as it is the case for a mixed sewer system (sewer overflows are not considered). Wastewater treatment is modelled using the excel tool from the Ecoinvent database. Within this tool the contents of the raw sewage are physically and chemically altered in three treatment steps. Phosphorus is removed as far as possible and ammonium (NH_4) is converted to elemental nitrogen N_2 and NO_3. Transfer coefficients are based on the average operation in Swiss wastewater treatment plants. Average transfer coefficients are used to calculate the outputs of a plant for specific, user-defined wastewater composition from the building studied. A plant having a capacity range from 30 to 2000 per-capita equivalents (class 5) is considered. The office building is situated in a rural area and this is the typical capacity of plants in these areas of Luxembourg. System boundary includes the plant itself and the digester sludge waste treatment through landfarming, which is considered to be a "waste treatment" system. The emissions from landfarming are therefore fully allocated to the WWTP scenario. The second reference scenario (*WWTPi*) is based on an improved version of the baseline, including the use of waterless urinals, WC separation toilet and of part of rainwater collected. These improvements lower the tap water demand to 55 m^3/a. The excel tool considers by default the addition of iron chloride ($FeCl_3$ 40% in water) and aluminium sulphate ($Al_2(SO_4)_3$ powder) to tertiary treatment in order to precipitate dissolved phosphate. In Luxembourg, however, aluminium sulphate is often replaced by iron chloride. This replacement can be considered by assuming the demand of iron chloride to be equivalent to the demand for aluminium sulphate (Mouchet, 2000). Emissions of Al to agricultural soil and LCI data for $Al_2(SO_4)_3$ are replaced with

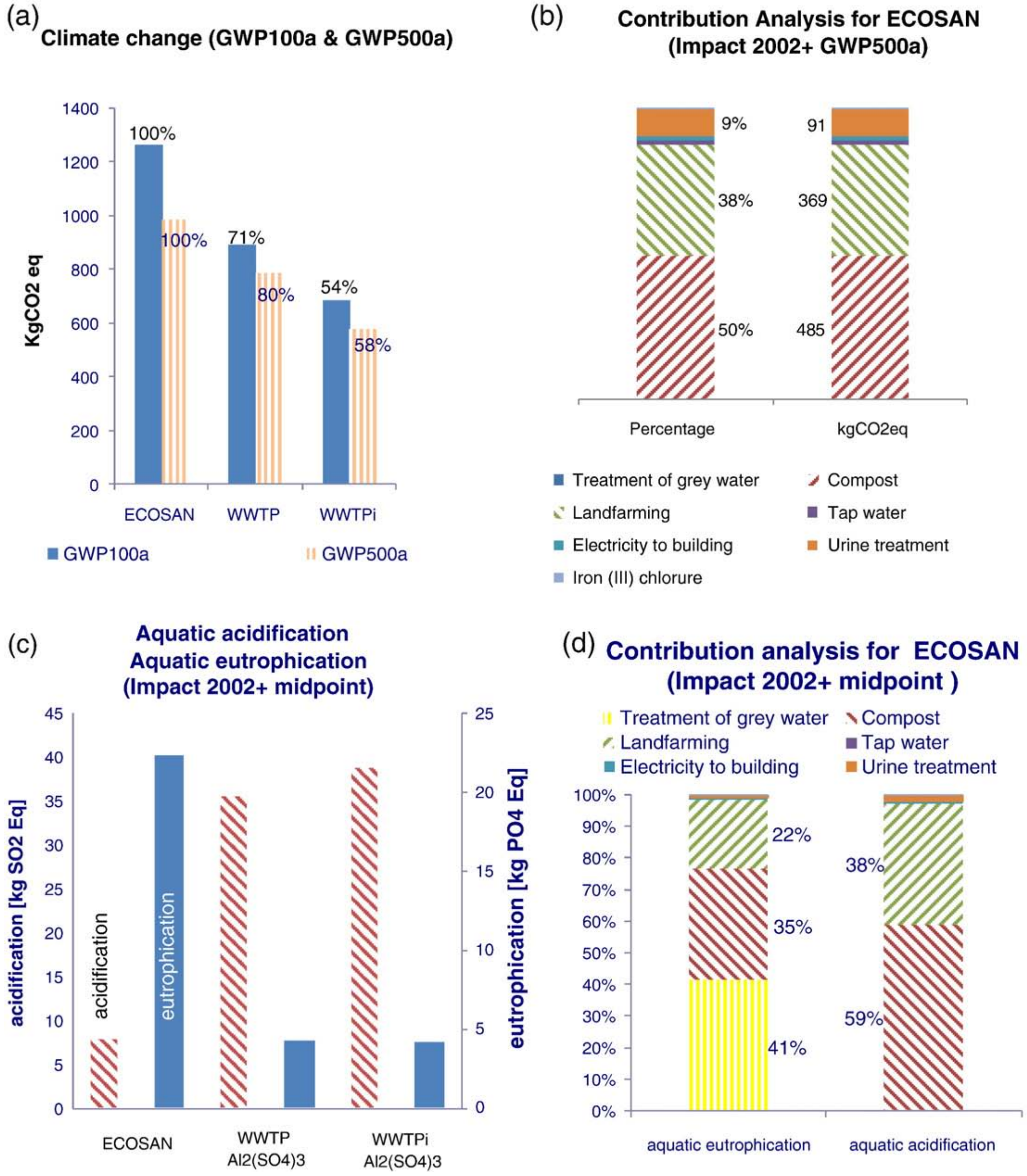

Fig. 3 – Climate change (a,b) and midpoint impact categories (c).

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Fe emissions to agricultural soil and LCI data for $FeCl_3$ as well. Both cases are considered in calculations and the results from the combined use of iron chloride and aluminium sulphate are presented by default.

4. Life cycle impact assessment

The assessment is threefold. Cumulative Exergy Demand (CExD) provides a valuable evaluation of the depletion of natural resources from the point of view of the users, i.e. the mankind (Boesch et al., 2007). The evaluation of midpoint impact together with endpoint damages provides a complementary and comprehensive evaluation of the environmental burdens associated with the studied scenarios. Midpoint impacts describe well known environmental problems, whereas endpoint damages provide a consistent and concise view of the effects of the studied scenarios on the final targets.

4.1. *Cumulative Exergy Demand (CExD)*

For all the scenarios, the main contributions to CExD are mainly due to the demand for water, fossil and nuclear resources (Fig. 2a). The production of tap water used in the building is mainly responsible for water resource exergy consumption. The latter is especially relevant for WWTP. This effect would have been underestimated without the CExD valuation. Fossil exergy is mainly consumed by composting followed by land farming due to transportation activities (Fig. 2b). Nuclear exergy demand arises from the electricity production. These results for the conventional treatment scenarios are quite in line with the expectations. On the contrary, the fossil energy demand of EcoSan is rather high as compared to the concurrent systems and is responsible for 70% of the total CExD, whereas water energy and nuclear energy account just for 18% and 8% respectively. This result already shows that the use of fossil resources for transportation and electricity consumption is a key point to be addressed for the improvement of EcoSan.

4.2. *Midpoint impacts*

The contribution to climate change (i.e. greenhouse effect) is evaluated at the midpoint level and further normalized at the endpoint level. EcoSan shows the highest contribution to climate change, almost twice the contribution of WWTPi (Fig. 3a). This is coherent with the fossil CExD results. The main responsible is transportation involved in composting and landfarming (Fig. 3b). As a result, the transport distance in EcoSan is definitively a key parameter which is further investigated in sensitivity analysis.

Aquatic acidification and aquatic eutrophication are assessed at the midpoint level as well, because of the uncertainties affecting their assessment at the endpoint level (Jolliet et al., 2003). In the case of aquatic eutrophication, the characterisation factors of the "undefined watershed" case instead of the default case ("P-limited watershed") are used in order to consider the contribution of nitrogen emissions that are likely to be significant and would be neglected otherwise. EcoSan shows the lowest contribution because of the reduced amount of N, P and COD emissions to water and soil during landfarming as compared to the emissions generated by conventional plants following partial treatment (Fig. 3c and d). Furthermore, part of the nitrogen originally in water is emitted to air during grey, brown and yellow water treatment. This is also proven by the results of aquatic acidification,

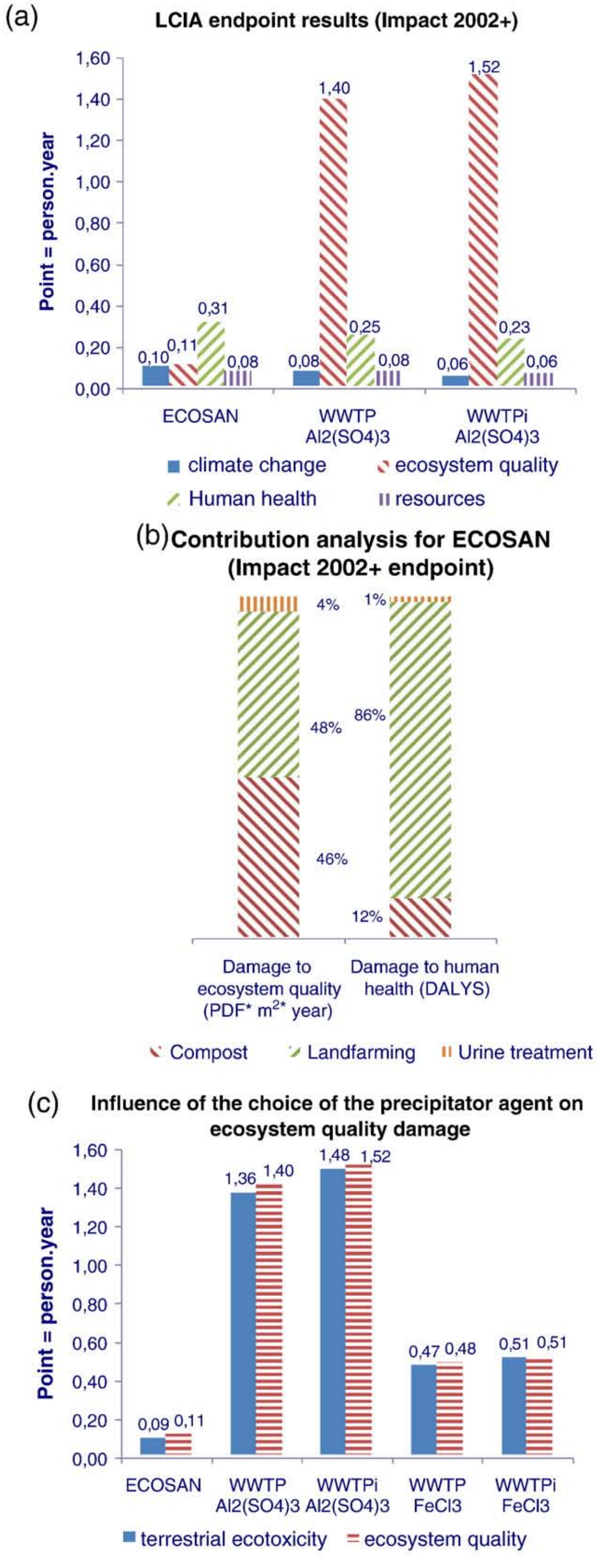

Fig. 4 – Endpoint damage categories.

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where EcoSan has the highest contribution because of ammonia emissions, especially during grey treatment and composting. Although the results for eutrophication and acidification cannot be compared, it is evident that EcoSan does not effectively reduce these impacts but displaces the environmental problem from eutrophication to acidification as compared to conventional treatment systems.

4.3. *Endpoint damages*

The damages generated by EcoSan are always higher than the corresponding damages generated by the conventional treatment systems, except for damage on ecosystem quality (Fig. 4a). For the latter, the differential between EcoSan and conventional systems is very important and represents a clear advantage for EcoSan. The damage on ecosystem quality is led by terrestrial ecotoxicity related to emissions of Al from aluminium sulphates during landfarming (Fig. 4b). The use of only iron chloride ($FeCl_3$ case) would reduce the contribution by more than 50% compared to the combined use of iron chloride and aluminium sulphate ($Al_2(SO_4)_3$ case). The damage remains, however, more than four times higher than the damage generated by EcoSan (Fig. 4c).

5. Life cycle interpretation

5.1. *Gravity analysis*

The main contributors to the impact and damage categories are listed in Table 3. CO_2 is the main contributor (70% to 90%) to climate change for all the scenarios. Emissions arise mainly from the transportation of compost to landfarming and to a less extent from composting activities. Uranium, coal, oil and natural gas generate 97–98% of the total damage on resources. In EcoSan, these resources are used for transportation purposes (60%) and electricity and tap water production (40%). In WWTP and WWTPi, 60% of the resources are used for electricity production while the remaining part is used for the production of chemicals, such as iron chloride and aluminium sulphate, and for tap water production.

The main contributors to human health damage in EcoSan are ammonia and nitrogen oxides. 80% of ammonia emissions are from open composting. Nitrogen oxides emissions are mainly from the biofilter used in composting and from transport processes. The results for WWTP and WWTPi are quite similar for this damage category. Zinc emissions onto agricultural soil from landfarming of sludge dominate terrestrial ecotoxicity effects. Although the huge number of substances potentially contributing to human health damage, it is worth noticing that the five substances listed in Table 3 contribute to more than 92% (99% in the case of EcoSan) of the damage. Therefore, these are the emissions that have to be reduced.

Concerning ecosystem quality, zinc and aluminium emissions have an utmost contribution. In EcoSan, zinc emission comes directly from the input wastewater stream to be treated, as well as copper. This means that the treatment scenario does not add other principal substances contributing to ecosystem quality damage. When both aluminium sulphate and iron chloride are used in conventional treatment plants, the main contributor is aluminium, which comes entirely from the aluminium sulphate. If only iron chloride is used, zinc and copper emissions onto agricultural soil lead to

Table 3 – Gravity analysis

		ECOSAN	WWTP	WWTPi
			$Al_2(SO_4)_3$	
Climate change	Carbon dioxide	71%	88%	83%
	Nitrogen dioxide	25%	9%	14%
	Methane	1%	1%	1%
	Total	97%	98%	98%
Resources	Uranium	11%	28%	38%
	Coal	11%	33%	38%
	Oil crude	67%	13%	8%
	Natural gas	9%	25%	15%
	Total	98%	99%	99%
Human health	Zinc	6%	46%	54%
	Nitrogen oxides	33%	15%	14%
	Sulfur dioxide	2%	5%	4%
	Particulates	14%	16%	8%
	Ammonia	43%	10%	12%
	Total	98%	92%	93%

			$Al_2(SO_4)_3$		$FeCl_3$	
		ECOSAN	WWTP	WWTPi	WWTP	WWTPi
Ecosystem quality	Nitrogen oxides	3%	0%	0%	0%	0%
	Aluminum	3%	66%	66%	2%	0%
	Zinc	66%	23%	23%	66%	68%
	Copper	12%	9%	9%	28%	28%
	Ammonia	12%	0%	0%	0%	0%
	Total	96%	98%	99%	96%	96%

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ecosystem quality damage still higher than the damage of EcoSan. The origin of these emissions cannot be identified because of the "black box" modelling of wastewater treatment step through the excel tool. However, in EcoSan the precipitation is replaced by reed bed technology for grey water treatment, and therefore the amount of agent needed is certainly lower. This already explains the advantage of EcoSan for this damage category. The magnitude of these results does rely on the evaluation of the damage on ecosystems quality of aluminium, zinc and copper as well. The damage has been re-evaluated using another valuation system (Ecoindicator99, Goedkoop and Spriensma, 2000), which does not consider toxicity effects of aluminium. In this case the damage of EcoSan is 4 to 5 times higher than the damage of conventional systems. Despite the evaluation provided within the Impact 2002+ methodology represents the current state of the art of LCIA, the effects of heavy metals on ecosystems are still widely debated in literature. Recent researches pointed out the weaknesses of the evaluation of hazardous concentration (HC50) for terrestrial ecotoxicity by equilibrium partitioning extrapolation of aquatic HC50 due to the variability of partition coefficient for metals in soil (Haye et al., 2007). This could lead to the over-estimation of effects. Unfortunately the results provided by Haye et al. (2007) are not readily comparable with the one provided by Impact 2002+ and thus this issues could not be cleared in this study.

5.2. *Sensitivity analysis*

5.2.1. *Multi-functionality and allocation*

The damage results obtained for the cases discussed are represented in Fig. 5a. The "avoided burden" case shows the best result, with a reduction up to 57% in damages on climate change, 10% in damages on human health and 30% in damages on resources. This scenario is rather optimistic because the credit gathered from the avoided production of fertilizers is fully assigned to the EcoSan scenario (donor system) instead of being partially split up between this system and the agricultural system (receiver) which takes benefit of the nutrients provided by EcoSan. Exception given for climate change, the difference between the "cut off" and "waste" cases is negligible. Concerning ecosystem quality, the differential between EcoSan and conventional plants is too important and it is not affected by allocation choices, whatever is the choice of the precipitator agent used. As a conclusion, the "cut off" approach "avoided burden" approach provides significant advantages to EcoSan and the choice of the allocation method mainly affects climate change.

5.2.2. *Transport distance*

The transportation distance of dry faeces from the building to the composting plant, of urine from the building to the storage and of compost to landfarming has a significant influence on climate change (Fig. 5b). If the distance was reduced to 40 km, the EcoSan scenario would show lower damages on resources than WWTP and WWTPi (Fig. 5c). Concerning the damages on human health and climate change, the distance has to be reduced to 20 km in order to obtain the same result.

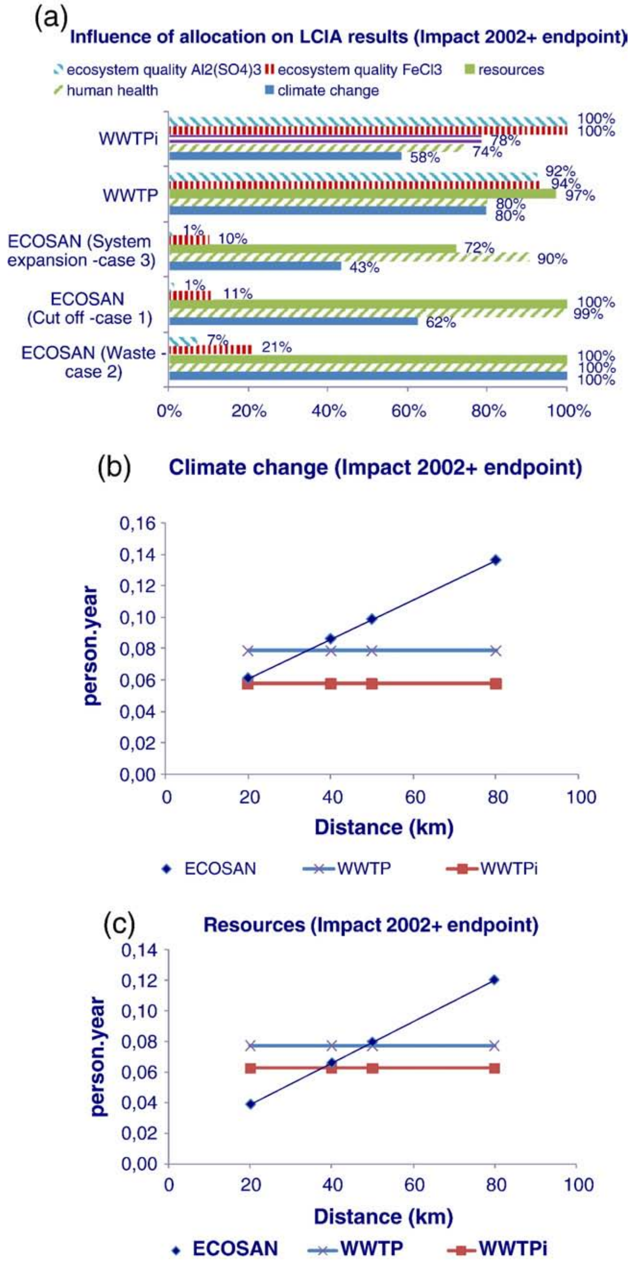

Fig. 5 – Sensitivity analysis.

5.2.3. *Efficiency of urine separation*

It determines the amount of urine that is misdirected with brown water from separation toilets. In the pilot plant in Berlin–Stahnsdorf, the results of experiences have indicated that a considerable fraction of nutrient (essentially nitrogen) in urine cannot be separated from brown water and thus is lost for fertilizing purposes (Remy et al., 2006). Hence the urine separation efficiency could be an important parameter because it affects the amount of nutrients in fertilizer. The increase of misdirected urine from 15% to 30% leads to a negligible reduction of climate change impact as well as of ecosystem quality and resources damages. Concerning human health, damage increases because the

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more urine is misdirected with faeces to brown water, the more ammonia and nitrogen oxides are released to air during open composting.

6. Conclusion and overview

The ecological sanitation scenario (EcoSan) has a significant advantage compared to conventional centralized wastewater treatment system concerning the reduced contribution to ecosystem quality damage. This result relies mainly on the evaluation of terrestrial ecotoxicity of aluminium, zinc and copper. The evaluation methods still have important shortcomings for heavy metals and are currently not consensual yet. Working groups are operating at the European level (UNEP Life Cycle Initiative and European LCA platform) to build consensus and to give a best practice for the evaluation of (eco)toxicity effects. In future studies, it is recommended to use this best practice approach, as soon as available, in order to clarify these issues.

Grey water treatment in reed bed has lower requirements than the conventional treatment processes. Furthermore, the treatment of faeces filtrate together with the grey water can increase the nutrient loads considerably. This natural process is definitively appropriate to the purification of the nutrient-depleted greywater. The urine separation efficiency does not affect significantly the environmental performances, but affects the amount of nutrient recovered. The efficiency should therefore be maximized.

Apart from these advantages and positive points, EcoSan generates higher impact on climate change and aquatic acidification and higher damage on human health than an optimized conventional system (WWTPi). At the design of an EcoSan system, transport distances of urine and compost should be maintained between 20 and 40 km in order to reduce human health and resources damages and climate change impact to the level of conventional scenarios. As shown in the LCIA, the increased emission of acidifying gases (mostly ammonia) represents a considerable drawback compared to conventional systems as well. During the treatment of faeces, the emissions of nitrogen gases from composting processes should be carefully monitored because of the significant contribution to acidification and global warming.

Future studies could also investigate the possibilities of further treatment of urine to reduce transport volume and inactive potentially harmful pharmaceuticals and other trace organic substances. These improvements could contribute to reduce climate change and toxicity related impacts. Despite in literature the expenditures for system construction are claimed to have a minor significance for LCA results, the increased demands of energy and related emissions for construction of pipes, the production and end life management of some devices (biofilter, separation toilets) in EcoSan shall be evaluated. Indeed, the EcoSan scenario studied is still quite theoretical: many assumptions are involved in calculation, which need to be validated through field investigations and measurements. Improvement of data quality concerning landfarming and composting emissions and update of important system variables (separation efficiencies, transport distances and destination of use of compost) with results from e.g. pilot studies and field applications would strengthen the results highlighted throughout this study and give further design recommendations.

In the meanwhile, ecological sanitation is a promising alternative to small-scale wastewater treatment. At this scale, nutrients flows and losses can be better managed, secondary fertilizer can be easily used by interested farmers and (hopefully) have an economic value, with the related advantages on the environmental performances highlighted in the study of allocation choices. At higher scales, improved conventional systems (such as WWTPi) show better performances and are not likely to be replaced by EcoSan systems in the short term. Conventional systems (such as WWTP) show very poor performances and should be avoided as far as possible.

These results have already provided insights into the sustainability of innovative water management practices in the urban water context in Luxembourg. They have been widely disseminated to the stakeholders of the water sector and have found their entrance into water policy in Luxembourg, e.g. through the elaboration of a guideline on sustainable rainwater management in collaboration with the Water Agency and the adoption of water saving equipments, such as waterless urinals, in public buildings. Whether the potential benefits of alternative sanitation concepts can be realized ultimately depends on the respective boundary conditions within a settlement and technical implementation of the system's devices.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.scitotenv.2008.11.016.

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