Ecological assessment of selected alternative sanitation concepts via Life Cycle Assessment

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ABSTRACT

Conventional and alternative sanitation concepts are compared in terms of their ecological performance via the methodology of LCA. Alternative scenarios include urine separation, faeces composting and digestion, and greywater treatment in a soil filter or technical plant. Urine and faeces are used as secondary fertilizers in agriculture after adequate treatment. Data for Life Cycle Inventory is compiled from pilot projects, literature and databases. Results of normalized ecological indicators show that alternative scenarios can offer substantial advantages over the conventional system, especially in the categories of eutrophication and terrestrial ecotoxicity. Energy-related indicators also show less energy demand for the alternative scenarios, although their contribution to the overall eco-profiles is relatively small. The construction phase can be neglected in simplified LCA studies of sanitation systems.

Introduction

In conventional wastewater treatment, different wastewater fractions such as toilet wastewater and wastewater from kitchen, laundry, and personal hygiene (="greywater") are mixed and transported to a wastewater treatment plant in a sewer system. Here, the mixed wastewater is treated with mechanical, biological, and physicochemical processes to eliminate biodegradable organic carbon and the plant nutrients nitrogen and phosphorus. Besides the high energy demand which is necessary for the aeration of the activated sludge, this approach suffers from the waste of nutrients contained in anthropogenic excretions. Dissolved nitrogen is converted into nitrogen gas via nitrification and denitrification, while phosphorus is incorporated into the sewage sludge by chemical precipitation or biological phosphorus elimination. Residual nutrients in the wastewater treatment plant effluent can trigger excessive growth of phytoplankton in the receiving waters and lead to oxygen depletion and eutrophication.

In recent years, alternative sanitation concepts have been developed which are based on separate collection and treatment of the different wastewater flows. The distribution of nutrients and organic carbon (measured as chemical oxygen demand, COD) between greywater, human urine and faeces shows that these partial flows are highly different in quantity and quality (**Table 1**). The greywater flow has a high volume and relatively small loads of COD and nutrients, while urine and faeces are low in volume but contain the majority of nutrients N and P. Pathogenic microorganisms mainly derive from the faeces fraction, while undiluted urine is basically sterile when leaving the human body. The distribution of nutrients led to the idea of nutrient recycling via the use of human excreta for agricultural fertilizing. Industrially produced mineral fertilizer could be substituted with these fertilizers from secondary resources. Thus, the energy-intensive production of nitrogen fertilizer (fixation of atmospheric nitrogen via the Haber-Bosch process) and the import of raw phosphate rock potentially contaminated with toxic heavy metals such as cadmium (Cd), chromium (Cr), and uranium (U) could be avoided. Additionally, the separation of the nutrient-rich fractions from the remaining wastewater leads to a significant reduction of the nutrient loads entering the wastewater treatment plant and hence to a reduction in effluent loads to surface waters.

Table 1: Composition of different wastewater flows (average values from literature)

		Greywater	Urine	Faeces
Specific flux	[kg/(pe*d)]	29200	548	51
Nitrogen load	[g/(pe*a)]	1.3	10	1.5
Phosphorus load	[g/(pe*a)]	0.5	1	0.5
Potassium load	[g/(pe*a)]	2	2.6	0.55
COD load	[g/(pe*a)]	60	15	35
Pathogenic germs		++	–	++++++

The present work deals with an ecological assessment of these alternative sanitation concepts and their comparison with the conventional system. Ecological advantages of the new conceptual approach should be quantified with an integrated evaluation method together with potential hotspots of the alternative systems. Therefore, the methodology of Life Cycle Assessment as defined in [1] is adopted for this work. A detailed substance flow model is set up which describes all relevant flows of materials and emissions. Beside the operational processes (wastewater treatment, energy production, transport etc), this LCA also includes the expenditures for the construction of the necessary infrastructure. The resulting flows of materials and emissions are evaluated with a set of environmental indicators based on the LCA guide of CML [2].

Methodology

The framework of this LCA study is outlined roughly in **Figure 1**. The primary function of the investigated systems is the drainage and treatment of human urine, faeces, greywater, and biowaste. Preceding processes like the supply of energy, drinking water for flushing or the production of auxiliary chemicals are included into the system boundary as well as subsequent processes like the treatment of solid or liquid wastes. The functional unit of this LCA is the performance of the above mentioned primary function for one person during one year.

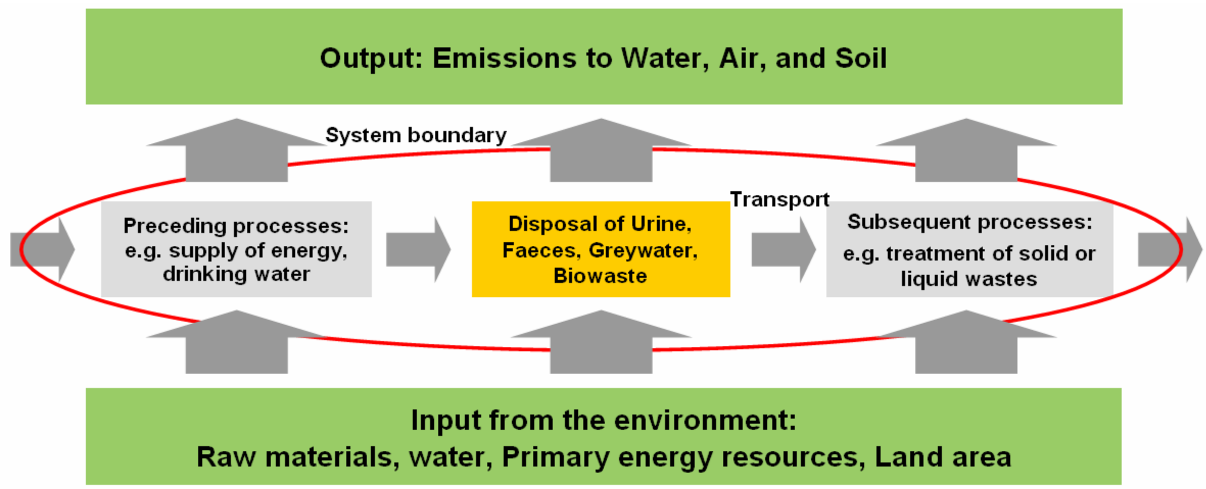

Figure 1: Simplified LCA framework of this study

The different sanitation scenarios for the conventional and the selected alternative sanitation concepts are listed in **Table 2**. The reference scenario consists of the drainage of the mixed wastewater and its treatment in an activated sludge plant with anaerobic sludge digestion and sewage gas usage for energy production. Biowaste is collected and transported to a composting plant prior to application as agricultural fertilizer. Two of the alternative scenarios use gravity separation toilets, where the undiluted urine is separated from the faeces and the flush water. While the urine is directly applied as a fertilizer in agriculture after a certain storage period (six months), faeces are separated from the flush water and stabilized aerobically in a composting process together with the biowaste before application as a fertilizer. The remaining greywater and the faeces filtrate are treated either in a soil filter or in an activated sluge plant (sequencing batch reactor, SBR). The other two alternative scenarios rely on vacuum separation toilets, where the faeces are drained in a vacuum system together with a small volume of flush water. They are treated in an anaerobic digestion process together with the collected biowaste to produce biogas which can be used for energy production. The digester residual can also be applied as an agricultural fertilizer after an aerobic stabilization. The separated urine and the greywater are treated in the same way as in the composting scenarios.

For proper system comparison, the reference scenario has to be expanded with the functions of industrial fertilizer production and energy production to account for the secondary functions of the alternative systems. The respective amounts of fertilizer equivalents to human urine and faeces are produced industrially as nitrogen and phosphorus fertilizer in the reference scenario. Thus, the corresponding resource usage and emissions are imputed to the conventional sanitation scenario. A similar procedure is adopted for the additional energy which is produced from the biogas during faeces digestion.

Table 2: Reference scenario and alternative sanitation scenarios

Scenario	Faeces	Urine	Greywater	Biowaste	System expansion
Reference	Conventional activated sludge plant with sludge digestion and use of sewage gas			Composting → Fertilizer	Mineral fertilizer + energy
Comp_Nat	Gravity separation toilets + composting → fertilizer	Separation → fertilizer	Soil filter	Composting → Fertilizer	Energy
Comp_Tech			SBR		
Vac_Nat	Vacuum separation toilets + digestion → fertilizer + energy	Separation → fertilizer	Soil filter	Digestion → Fertilizer	-
Vac_Tech			SBR		

Life Cycle Inventory (LCI)

The required data for the LCI is derived from pilot projects, literature and LCA databases (**Table 3**). The composition of the different wastewater flows is assumed via average values from literature. The global system parameters are taken from pilot projects of alternative sanitation systems or based on reasonable assumptions. The LCA model for the conventional activated sludge plant has been previously developed at TU Berlin. The different system modules for the alternative sanitation systems are based on literature data or (if available) data from pilot projects. LCI data for basic processes such as transport or the supply of energy and construction materials are adopted from an established database. The required infrastructure for the different sanitation systems has been estimated by a consulting engineer company experienced in the design of alternative concepts. A detailed documentation of the LCI is available on the website of this project.

Table 4 lists some important system parameters of the investigated sanitation scenarios. In the reference scenario, the conventional wastewater treatment plant is assumed to provide enhanced nutrient removal via denitrification and chemical phosphorus elimination. The soil filter is characterized by a low energy demand and limited denitrification, while phosphorus is eliminated in an additional precipitation stage. In the digestion scenarios, the use of vacuum separation toilets saves around 16 L/(pe*d) of flush water. The efficiency of the urine separation toilets is assumed to be 75% in volume, so that this amount of urine is applied as secondary fertilizer, while the remaining urine is treated together with the faeces stream. In all, the alternative sanitation systems can provide an amount of 2.6 kg nitrogen and 0.4 kg phosphorus fertilizer per person and year with secondary fertilizers, which have to be industrially produced in the reference scenario.

Table 3: Overview of data origin for Life Cycle Inventory

Process/Substance flow	**Data origin**	**Main sources**
Composition of wastewater flows	Literature	[3]; [4] et al
Global system parameters	Pilot projects, assumptions	[5]; [6]
Activated sludge plant	LCA model by TU Berlin	[7]; [8] et al
Soil filter	Literature, pilot projects	[5]; [6]
Composting	Literature	[9]
Digestion	Literature, pilot projects	[9]; [5]
Fertilizer application	Literature	[10]; [5]
Industrial fertilizer production	Literature	[11]
Energy	Database	[12]
Truck transport	Database	[12]
Infrastructure	Consultants	[5]
Construction materials	Database, literature	[12] etc

Table 4: Important parameters for system operation

		Reference	Composting		Digestion	
			Soil filter	SBR	Soil filter	SBR
Water demand	[L/pe*d]	101	101	101	85	85
Elimination during wastewater treatment	[% C-elim]	95	90	93	90	93
	[% N-elim]	80	40	70	40	70
	[% P-elim]	95	86	84	86	84
Energy demand of wastewater treatment	[kWh/m³]	0.63	0.06	0.5	0.06	0.44
	[kWh/pe*a]	23.6	2.0	18.4	1.6	12.8
Urine separation	[%]	-	75	75	75	75
Industrial fertilizer production	[kg N/pe*a]	2.6	0	0	0	0
	[kg P/pe*a]	0.4	0	0	0	0

Life Cycle Impact Assessment (LCIA)

For Life Cycle Impact Assessment, a set of environmental indicators is adopted based on the methodology of the Institute of Environmental Sciences of Leiden ([2], see **Table 5**). It was decided to use a modified indicator for eutrophication which considers only chemical oxygen demand and phosphorus as relevant substances for eutrophication. This concept for P-limited watersheds is described in another LCIA method ([13]) and neglects the influence of nitrogen on eutrophication. The LCIA indicator set is complemented by two well-established energy-related indicators which have been defined by the German VDI ([14]).

Table 5: Ecological indicators for Life Cycle Impact Assessment

Category	Abbr.	Source
Cumulated energy demand fossil	CED fossil	[14]
Cumulated energy demand nuclear	CED nuclear	[14]
Abiotic resource depletion	ADP	CML ([2])
Global warming potential (100a)	GWP	CML ([2])
Acidification	AP	CML ([2])
Eutrophication (P-limited watershed)	EP	IMPACT 2002+ ([13])
Human toxicity (inf)	HTP	CML ([2])
Terrestrial ecotoxicity	TETP	CML ([2])
Aquatic ecotoxicity	FAETP	CML ([2])

Results

The resulting indicator values of LCIA have been normalized to German conditions and summarized into eco-profiles to allow an overall comparison of the different sanitation scenarios (**Figure 2**). The results show that the implementation of alternative sanitation systems has the potential to offer environmental benefits in comparison to the conventional sanitation system. The separation of nutrient-rich urine and faeces from remaining wastewater lowers the eutrophication potential substantially due to the reduced phosphorus loads to the treatment plant. The substitution of heavy metal contaminated mineral fertilizer by secondary fertilizers from urine and faeces decreases Cd and Cr loads on agricultural land and leads to a lower terrestrial ecotoxicity potential. Energy-related indicators are not decisive for the overall comparison, although especially the digestion scenarios offer advantages in cumulated energy demand and the related global warming potential. However, their contribution to the total eco-profiles of the respective scenarios is small. A possible drawback of the investigated alternative scenarios might be an enhanced acidification potential due to the ammonia emissions from urine application and composting.

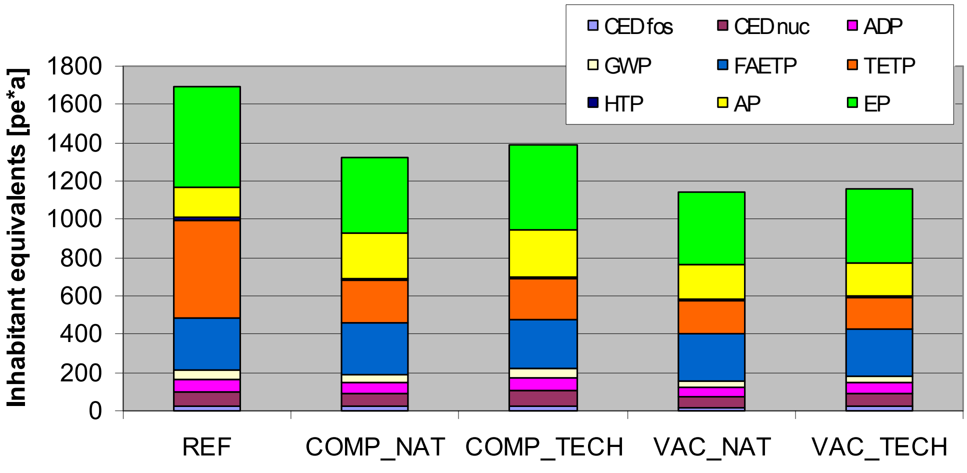

Figure 2: Normalized eco-profiles of conventional and selected alternative sanitation concepts

During the construction phase, alternative systems show a higher material demand due to the multiple pipe networks for the different wastewater streams. However, the contribution of the construction phase to the overall ecological comparison is relatively small (< 5%), so the influence of the construction phase is only marginal.

In general, the alternative sanitation scenarios offer environmental benefits in this LCA study. With vacuum separation toilets, the total environmental burden can be reduced by a maximum of 30% compared to the conventional wastewater treatment plant. However, the environmental advantages can only be realized if the secondary fertilizers from urine and faeces are efficiently used and can really substitute mineral fertilizer.

Conclusions

This LCA compares the conventional wastewater treatment system with several alternative sanitation scenarios. These scenarios comprise urine separation, faeces composting or digestion, and greywater treatment in a soil filter or technical plant (SBR). The separated urine and faeces are used as secondary fertilizers in agriculture. Data for the LCI is taken from pilot projects, literature, or databases and is complemented with reasonable assumptions. The impact assessment is mainly based on a set of indicators developed at CML. The normalized results for the different scenarios show that alternative sanitation systems can offer substantial environmental advantages in comparison to the conventional system. Especially the categories of eutrophication and terrestrial ecotoxicity play a major role in this comparison. Energy-related indicators are less relevant for the overall comparison, although alternative scenarios can offer substantial energetic benefits as well. The construction phase may be neglected in simplified LCA studies of sanitation systems, because its contribution to the overall eco-profiles is negligible.

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References

1. ISO 14040, *Environmental management - Life Cycle Assessment - Principles and framework*. 1997: International Standardisation Organisation.
2. Guinée, J.B., et al., *Handbook on Life Cycle Assessment - Operational Guide to the ISO Standards*, ed. J.B. Guinée. 2002, Dordrecht, Boston, London: Kluwer.
3. Ciba-Geigy, *Wissenschaftliche Tabellen Geigy, Teilband Körperflüssigkeiten (Scientific tables Geigy, Volume body fluids)*. Vol. 8. 1977, Basel: Ciba-Geigy AG.
4. Lange, J. and R. Otterpohl, *Abwasser - Handbuch zu einer zukunftsfähigen Wasserwirtschaft (Wastewater - handbook for a sustainable water management)*. 2. Auflage ed. 2000, Donaueschingen-Pfohren: MALLBETON GmbH. 301.
5. SCST, *Results of the KWB project SCST*. 2006, not published: Berlin.
6. Otterwasser, *Untersuchungen zur anaeroben Behandlung von Fäkalabwasser mit Bioabfällen und weiteren Cosubstraten sowie der Grauwasserreinigung am Pilotprojekt Lübeck-Flintenbreite - Abschlussbericht (Investigations of the anaerobic treatment of faecal wastewater with biowaste and other co-substrates and greywater treatment in the pilot project Lübeck-Flintenbreite)*. 2005, Otterwasser GmbH: Lübeck.
7. ATV, *A131 Bemessung von einstufigen Belebungsanlagen (A131: Dimensioning of single stage activated sludge plants)*. ATV-DVWK-Regelwerk. 2000, Hennef: Abwassertechnische Vereinigung e.V.
8. ATV-DVWK. *Leistungsvergleich kommunaler Kläranlagen (Performance comparison of municipal wastewater treatment plants)*. 2004 [cited.
9. Vogt, R., et al., *Ökobilanz Bioabfallverwertung (Life cycle assessment of biowaste treatment)*. Initiativen zum Umweltschutz. Vol. 52. 2002, Berlin: Erich Schmidt Verlag. 454.
10. Stockholm Vatten, *Urine Separation - Closing the Nutrient Cycle. Final Report on the R&D Project Source-Separated Human Urine - A Future Source of Fertilizer for Agriculture in the Stockholm Region?* 2000: Stockholm (Schweden). p. 44.
11. Patyk, A. and G.A. Reinhardt, *Düngemittel - Energie- und Stoffstrombilanzen (Fertilizers: energy and sustance flow balances)*. 1997, Braunschweig/Wiesbaden: Vieweg. 223.
12. IFU and IFEU, *Umberto - Software für das betriebliche Stoffstrommanagement, Version Umberto 4.3 (Umberto - software for operational substance flow management, version Umberto 4.3)*. 2004, Institut für Umweltinformatik GmbH und Institut für Energie- und Umweltforschung Heidelberg GmbH: Heidelberg, Hamburg.
13. Jolliet, O., et al., *IMPACT 2002+: A New Life Cycle Impact Assessment Methodology.* Int. J. LCA, 2003. **8**(6): p. 324-330.
14. VDI, *VDI-Richtlinie 4600: 1997-06: Kumulierter Energieaufwand - Begriffe, Definitionen, Berechnungsmethoden (VDI guideline 4600: 1997-06: Cumulated energy demand - Terms, definitions, calculation methods)*. 1997, VDI Verlag: Düsseldorf.