Assessing the environmental sustainability of agricultural reuse of WWTP effluent and biosolids in Braunschweig/Germany with Life Cycle Assessment

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Abstract

This paper presents an analysis of the environmental footprint of the Braunschweig wastewater reuse scheme with Life Cycle Assessment. All relevant inputs and outputs of the system are quantified in a substance flow model and evaluated with a set of environmental indicators for cumulative energy demand, carbon footprint, acidification, eutrophication, and human and ecotoxicity. The analysis shows that energy demand and carbon footprint of the Braunschweig system are to a large extent offset by credits accounted for valuable products such as electricity from biogas production, nutrients and irrigation water. The eutrophication of surface waters via nutrient emissions is reduced in comparison to a conventional system discharging all effluent directly into the river, because some nutrients are diverted to agriculture. Normalised indicators indicate the importance of the primary function of the wastewater system (= protection of surface waters) before optimisation of secondary environmental impacts such as energy demand and carbon footprint. A further decrease of the energy-related environmental footprint can be reached by applying optimisation measures such as the addition of grass as co-substrate into the digestor, thermal hydrolysis of excess sludge, or nutrient recovery from sludge liquor.

Introduction

Municipal wastewater contains valuable resources such as plant nutrients, energy-rich organic substances and the water itself, which all can be reclaimed via direct or indirect recovery or reuse. Thus, energy and resource demand of wastewater treatment and corresponding emission of greenhouse gases can be partially or completely offset by recovered products, substituting industrial products (e.g. mineral fertilizer) or easing the pressure on natural resources on a local (e.g. water resources) or global scale (e.g. fossil fuels). However, recovery or reuse of wastewater and associated products may cause additional environmental burden in other areas (e.g. transport, chemical production, process emissions), leading only to a shift in environmental impacts but not to an overall improvement. Hence, a holistic and comprehensive analysis of the environmental impacts is necessary to detect and prevent such environmental trade-offs in the complex system of a wastewater treatment scheme. Such an assessment should include all relevant parts of the system under study as well as all impact categories of environmental relevance.

The present study uses the method of Life Cycle Assessment (LCA) (ISO 14040 2006; ISO 14044 2006) for a holistic and comprehensive analysis of the environmental benefits and drawbacks of agricultural reuse of purified effluent and biosolids in the wastewater treatment scheme of Braunschweig (Germany) serving 350,000 population equivalents (Eggers 2008). In

the Braunschweig system, municipal wastewater is treated in a conventional activated sludge plant with nutrient removal, and the purified effluent is reused in agricultural irrigation (3000ha) or discharged to surface waters after polishing in natural infiltration fields. Primary and excess sludge of the WWTP are stabilized via anaerobic digestion and spread on agricultural fields for nutrient recovery, either mixed with effluent (summer operation) or after dewatering (winter).
In the present study, LCA is used to analyse the environmental footprint of the current system and practice, to identify potentials for optimisation, and to assess specific measures for increased recovery of energy and nutrients in their effect on the environmental profile, e.g. the addition of co-substrates or the pre-treatment of sewage sludge by thermal hydrolysis.

Methods

This study closely follows the framework of Life Cycle Assessment as it is defined in the standard ISO 14040/44. It consists of important methodological definitions of the study ("goal and scope"), the collection of process data ("inventory") and setup of a substance flow model, the calculation of environmental impacts ("impact assessment"), and the final interpretation and discussion of the results. The methodology has been critically reviewed by an external expert (Prof. Finkbeiner, TU Berlin) and complies with ISO 14040/44 standards.

Goal and scope of Life Cycle Assessment

The primary function of this system is the treatment and disposal of municipal wastewater (350000 population equivalents). The functional unit of this LCA is defined as *the treatment of municipal wastewater per population equivalent and year*, related to the influent load of chemical oxygen demand (COD) (120 g COD/(PE*a)). The reference flow of wastewater is defined according to the measured influent volume and concentrations at the Braunschweig WWTP.
The present study focuses on the operation of the wastewater treatment scheme and excludes the infrastructure. This cut-off is reasonable as previous studies have shown a negligible influence of the infrastructure on the environmental footprint, especially if sewer systems are not within the scope of the study (Remy 2010). Hence, the system boundaries include the operation of the WWTP process, anaerobic sludge digestion and biogas usage in combined heat and power (CHP) plants, sludge dewatering (only in winter) and the infiltration fields (Figure 1). A small amount of external co-substrates (grease) is added into the digestion process as waste disposal (= no environmental burden for grease production accounted). For the agricultural reuse, the system boundaries are defined at the delivery of the effluent to the sprinkling devices (= the atmospheric emissions during application are not included in this assessment). Likewise, the disposal of the dewatered sludge from the winter operation is accounted up to the transport to the agricultural fields, without emissions during application. However, the input of nutrients and pollutants from sludge and effluent into soil is included as environmental impact.

Recovered or reused products from wastewater treatment are accounted via substitution of equivalent products (Table 1), crediting the related environmental impacts as "avoided burden":

- Electricity from biogas combustion in CHP plants amounts to 10300 MWh/a and substitutes electricity from the grid

- Excess heat of CHP plants which is not used on-site (e.g. for heating of digestors) is not accounted as credit
- Nitrogen in effluent and sludge is accounted for substituting mineral N fertilizer, assuming 100% plant availability of the nitrogen. However, only a fraction of the delivered nitrogen (40%) in wastewater reuse can effectively substitute mineral fertilizer due to the seasonal demand for nitrogen by the plants.
- For phosphorus, plant availability of the sludge-bound fraction is assumed to be limited (80%) due to the use of ferric coagulants in the WWTP process. As phosphorus can accumulate in the soil, the substitution potential is assumed to 100%.
- For the water itself, an amount of only 100 mm/a (on 3000ha = 3 Mio m³/a) is accounted as substituting irrigation with groundwater (= pumping energy). This amount represents the average of required irrigation in agriculture in the Braunschweig region and climate. Water that is applied in agriculture >100 mm/a is not directly required in irrigation and thus does not substitute groundwater pumping.

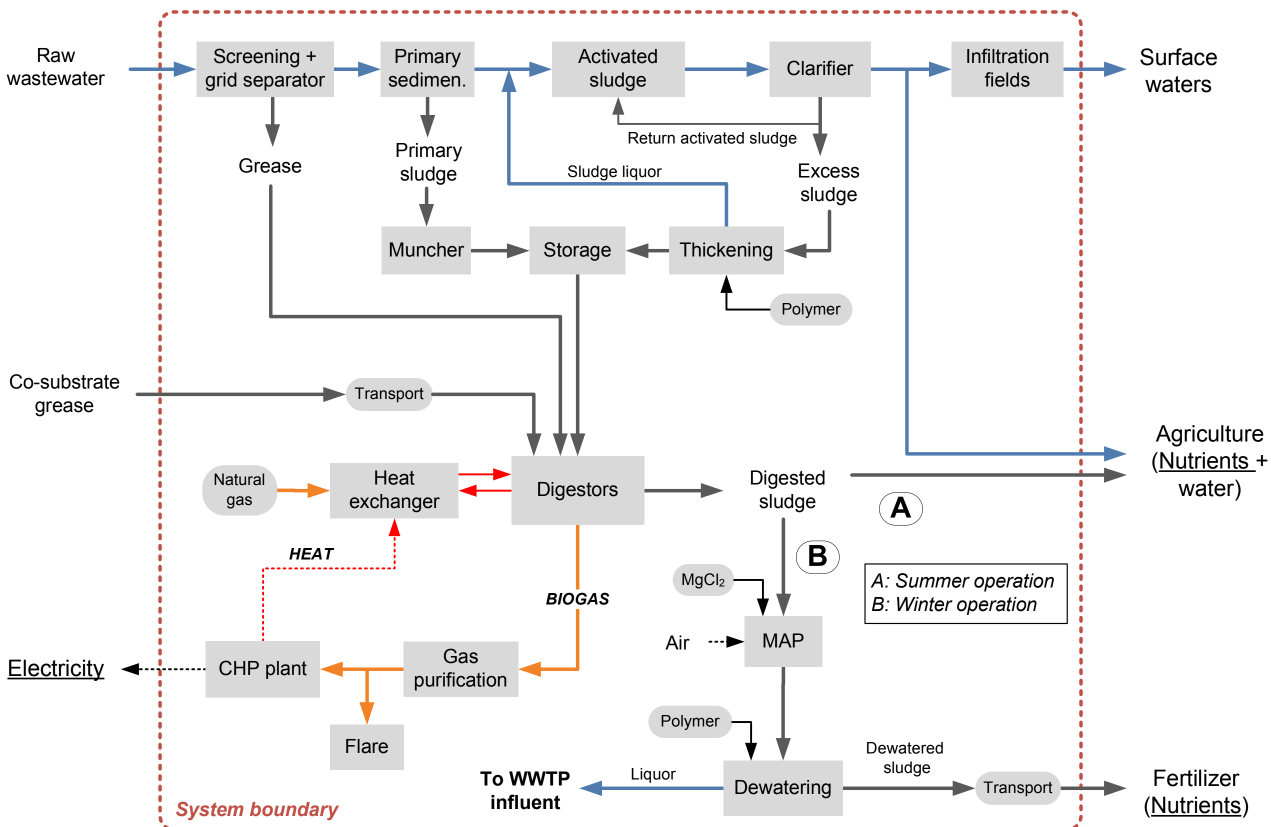


Figure 1: System boundaries of Life Cycle Assessment for Braunschweig wastewater scheme (products are underlined)

Process inventory

Process data is collected from the regular operation of the Braunschweig WWTP in the year 2010, compiled as annual mean data. This paper only gives an overview of the quality of inventory data, detailed information can be found elsewhere (KWB 2012). The process inventory is used to set up a substance flow model of the Braunschweig wastewater scheme with the LCA software UMBERTO® (IFU and IFEU 2009).

For the wastewater treatment process, mean influent and effluent quality of the WWTP as well as sludge quality and quantity is compiled from regular sampling. The demand for electricity and chemicals ($FeCl_2$) is quantified from information of the operators, while on-site emissions (N_2O, CH_4) are estimated based on literature data. Excess sludge is thickened in centrifuges (addition of polymer) and mixed with primary sludge. Mixed sludge is digested anerobically in mesophilic conditions (38°C) during the study (usually thermophilic at 55°C), and digestors are heated with off-heat from CHP plants. During winter months, a small additional amount of natural gas is used for digestor heating. Gas yields (~ 425 L/kg organic dry matter) of the digestors and CH_4 content (63%) of the biogas is monitored regularly. Biogas is scrubbed from H_2S and combusted in CHP plants with an electrical and thermal efficiency of 40 and 38%, respectively.

For agricultural reuse, 55% of annual effluent of the WWTP is pumped to agriculture (0.37 kWh/m³), whereas the remaining effluent is discharged into infiltration fields for polishing. After passing through infiltration fields, water is discharged to receiving surface waters. Quantity and quality of this discharge is measured and accounted as emissions into the environment. Digested sludge is simply added to irrigation water in summer to recover the nutrient content as fertilizer. In winter, digested sludge is dewatered after struvite precipitation (addition of $MgCl_2$) in centrifuges with the addition of polymer. After lime addition, dewatered sludge is stored on-site and disposed in agriculture in late summer (truck transport: 15 km).

Table 1: Products of the wastewater scheme and equivalent products accounted in this LCA

Product			Equivalent product	Remarks
Electricity	*MWh/a*	10300	Grid electricity	from biogas combustion in CHP plants
Heat	*MWh/a*	6752	Utilized heat	used on-site
			Excess heat	not accounted
N in effluent	*t/a*	123	Mineral N fertilizer	100% plant available, 40% substitution
sludge*	*t/a*	552		
P in effluent	*t/a*	12	Mineral P fertilizer	80% plant available (100% in effluent)
sludge*	*t/a*	318		
Water	*Mio m³/a*	12.4	Groundwater pumping	credits for 3 Mio m³/a (= 100mm/ha*a)

*** direct application in summer, dewatering in winter**

Background processes for electricity supply, chemicals production, transports, natural gas, and equivalent products (mineral N and P fertilizer) are modelled with datasets from the database ecoinvent (Ecoinvent 2007) (long-term emissions >100a not accounted). The electricity mix represents the effective power mix of Germany in 2010. Equivalent products such as electricity from the grid and mineral N and P fertilizer are credited as avoided (= negative) environmental impacts. Substitution of groundwater pumping for irrigation is assumed to save 0.48 kWh/m³.

Scenario analysis

The Braunschweig system is compared to a hypothetical conventional system without the reuse of effluent in agriculture. For this "conventional" system, WWTP effluent is directly discharged to surface waters, sludge is dewatered and applied in agriculture all year round, and energy demand for aeration is adjusted (+10%) due to increased nitrogen load in sludge liquor.

Additionally, different optimisation scenarios are evaluated in their effects on the environmental footprint:

- Addition of grass as co-substrate (+10% dry solids in digestor) with increasing gas yield (+23%) and quality (CH_4: 67%) (results of pilot trials (KWB 2012))
- Thermal hydrolysis of excess sludge with higher gas yield (+8%) and quality (CH_4: 64%) (KWB 2012), energy demand for hydrolysis is met to 100% by waste heat of CHP plant
- Nitrogen recovery from sludge liquor via NH_3 stripping (90% N removal, 1.6 kWh/m³ electricity + 5 kWh/m³ heat, 4 kg NaOH (50%) and 3.8 kg H_2SO_4 (78%) per kg N_{input})

Table 2: Environmental indicators for impact assessment

Indicator	*Unit*	*Accounted resources + emissions*	*Source*
Cumulative energy demand of non-renewable resources	*MJ*	Hard coal, lignite, oil, natural gas, uranium	*VDI 1997*
Global warming potential	*kg CO_2-eq*	Fossil CO_2, CH_4, N_2O	*Goedkoop et al. 2009*
Acidification	*kg SO_2-eq*	SO_2, NH_3, NO_x	*Goedkoop et al. 2009*
Eutrophication of freshwater	*kg P-eq*	P to water, soil	*Goedkoop et al. 2009*
Eutrophication of freshwater	*kg N-eq*	N to air, water, soil	*Goedkoop et al. 2009*
Human toxicity	*kg DCB-eq*	Organic pollutants and heavy metals to air, water, soil	*Goedkoop et al. 2009*
Aquatic ecotoxicity	*kg DCB-eq*		*Goedkoop et al. 2009*
Soil ecotoxicity	*kg DCB-eq*		*Goedkoop et al. 2009*

Impact assessment

Aggregated inputs and outputs (resources and emissions) calculated by the substance flow model are evaluated with a set of environmental indicators (Table 2). This study uses midpoint indicators based on widely accepted scientific models which express the potential environmental impacts in relation to a model substance (e.g. CO_2-equivalents for carbon footprint). Indicator results are normalised to the total environmental impact in each impact category (e.g. the total emission of greenhouse gases per person and year in Germany 2008).

Results

To illustrate the capabilities of the LCA approach, the results for the impact category of climate change (= global warming potential or “carbon footprint”) are shown here in a contribution analysis, revealing the decisive processes and assumptions for this category of environmental impact. The gross carbon footprint of the wastewater system in Braunschweig amounts to 43.2 kg CO_2-eq/(PE_{COD}*a). 55% of the carbon footprint is generated in the WWTP process, mostly due to electricity demand (42%) and on-site process emissions of N_2O and CH_4 from the biological process (Figure 2). Sludge treatment contributes 23% of the carbon footprint due to electricity and heat demand, chemicals and on-site emissions of CH_4 (from CHP plant) and fossil CO_2 (digestor heating with natural gas in cold winter months). Pumping to agricultural reuse and infiltration fields generates another 19% and 3%, respectively. Credits for secondary products add up to 33.6 kg CO_2-eq/(PE_{COD}*a), with contributions of 61%, 31%, and 8% for electricity and heat, nutrients, and groundwater pumping. For the carbon footprint, nutrient recovery plays a more important role than for the cumulative energy demand due to N_2O emissions during the production of nitrogen fertilizer. Hence, agricultural reuse is almost neutral in carbon footprint due to credits for fertilizer substitution.

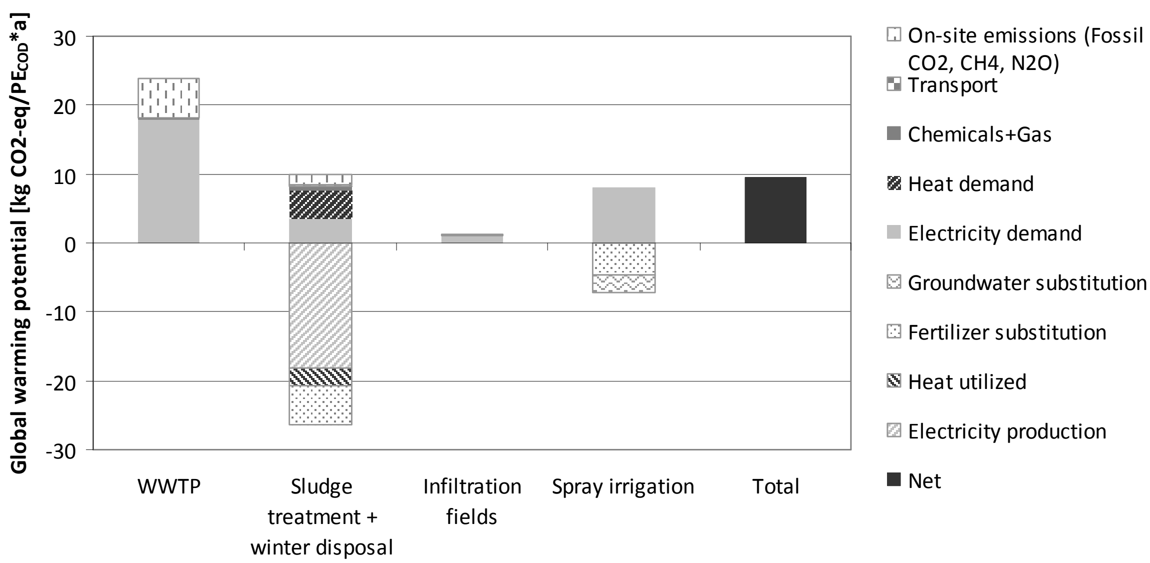


Figure 2: Contribution analysis of global warming potential of Braunschweig wastewater scheme

In total, the net carbon footprint of the Braunschweig system amounts to 9.6 kg CO_2-eq/(PE_{COD}*a), so that 78% of the initial carbon footprint can be compensated by secondary products. Besides the important influence of the energy-related emissions (burning of fossil fuels), direct emissions of the wastewater treatment plant in form of nitrous oxide (N_2O) in denitrification or methane (CH_4) from sludge treatment are responsible for 18% of the total carbon footprint. These emissions have been estimated by generic emission factors in this LCA and should be verified in on-site sampling.

However, normalization of all environmental indicators reveals that the quantitative contribution of wastewater treatment to the total environmental footprint is comparably low (<0.3%) for carbon footprint and cumulative energy demand (Figure 3). In contrast, the wastewater system has relatively high net contributions in eutrophication and ecotoxicity (0.8 – 11.8%). This relates to the primary function of wastewater treatment, which is defined as the protection of surface waters from excessive input of nutrients and pollutants. Consequently, it should be kept in mind that the optimization of energy demand and carbon footprint of a WWTP should never compromise its effluent quality, because the latter causes the largest contribution to the environmental impacts of a WWTP. In other words, the reduction of energy demand and carbon footprint can constitute an important target for reducing the environmental footprint of a WWTP, but not at the cost of impaired effluent quality.

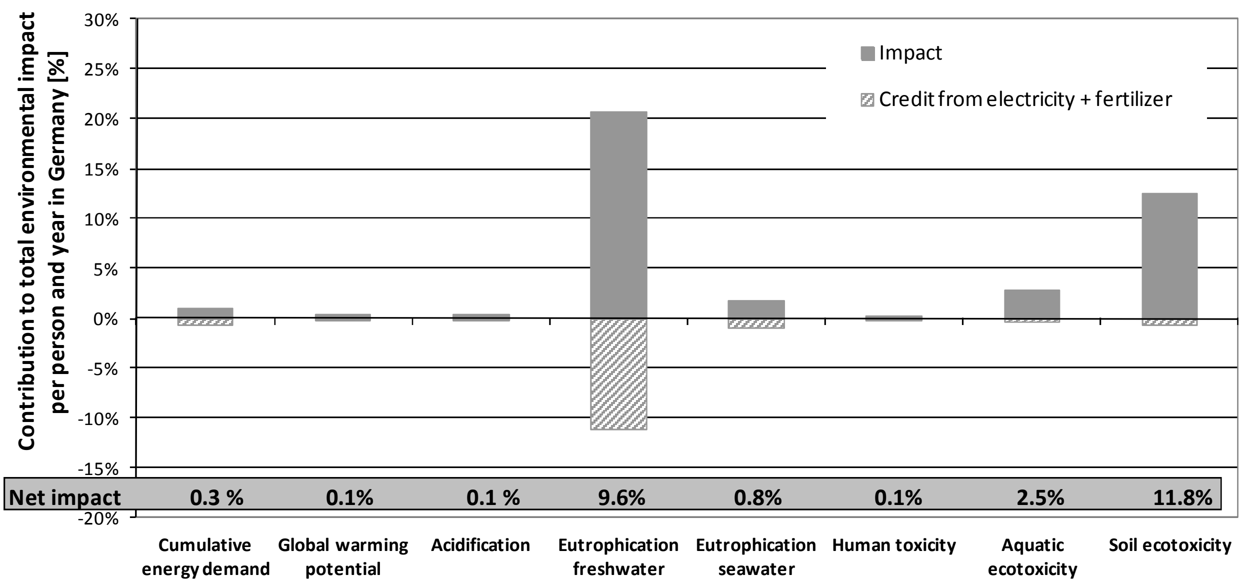
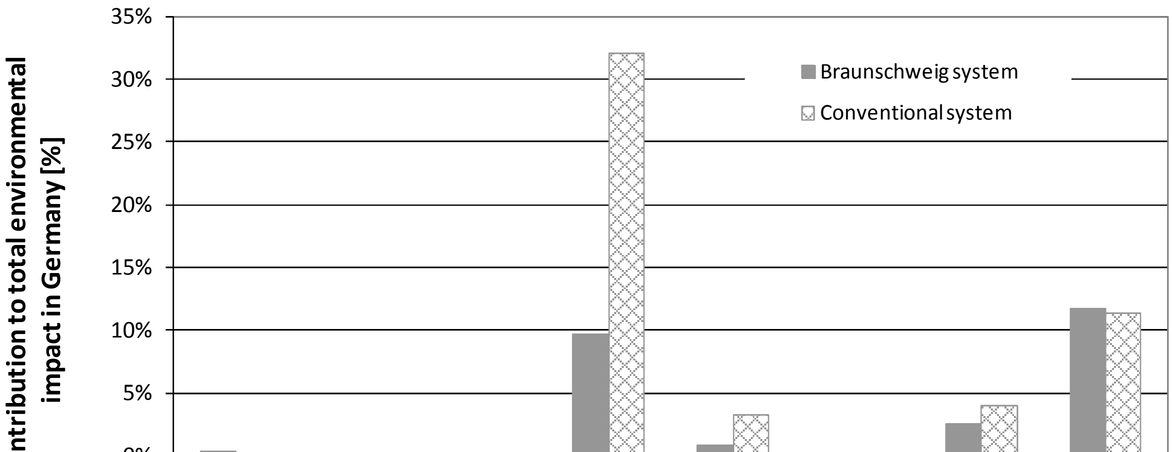


Figure 3: Normalised environmental impacts of Braunschweig wastewater scheme

If the Braunschweig wastewater scheme is compared to a hypothetical conventional wastewater system, the environmental impacts of direct reuse of effluent can be identified. The comparison reveals that the Braunschweig system is superior in the categories of eutrophication of freshwaters and seawaters and aquatic ecotoxicity (Figure 4). This effect is mainly caused by the diversion of nutrients N and P to agriculture via effluent reuse, so that the direct nutrient load to surface waters is decreased substantially. Another positive aspect is the polishing effect of the infiltration fields where effluent nitrogen is eliminated via denitrification. For the energy demand and related indicators such as carbon footprint or human toxicity, the Braunschweig system is inferior to a conventional system, mainly due to the higher electricity demand for pumping of effluent to agriculture. Hence, the Braunschweig system offers potentials for optimisation of energy demand and related emission of greenhouse gases. Options for increasing energy production include the addition of co-substrates into the digestors, the thermal hydrolysis of excess sludge to increase biogas production, or the recovery of nitrogenous fertilizer from sludge liquor to substitute mineral N fertilizer.



	Cumulative energy demand	Global warming potential	Acidification	Eutrophication freshwater	Eutrophication seawater	Human toxicity	Aquatic ecotoxicity	Soil ecotoxicity
Braunschweig system	0,29%	0,07%	0,08%	9,61%	0,83%	0,12%	2,47%	11,78%
Conventional system	0,17%	0,06%	0,11%	31,99%	3,23%	0,09%	3,88%	11,30%

Figure 4: Normalised net environmental impacts of Braunschweig system compared to hypothetical conventional system without agricultural reuse of WWTP effluent

The addition of grass as co-substrates in the digestor increases the amount and quality of biogas. Consequently, more credits are accounted for electricity production, leading to a substantial improvement in the energy-related environmental indicators (Figure 5). Potentially higher impacts from processing of increased amounts of sludge and biogas combustion are more than equalized by the benefits from generating more biogas. It has to be noted that the assumed gas yield of grass addition is estimated from pilot trials and has not yet been realized in full scale. The thermal hydrolysis of excess sludge can also increase biogas production, leading to a higher credit for electricity production (Figure 6). Gas yields are estimated based on pilot experiments and should be confirmed in full-scale testing together with assumptions for heat demand of the hydrolysis process (100% by off-gas heat from CHP plant).

For nitrogen recovery via NH_3 stripping, the substitution of mineral nitrogen fertilizer (72 t/a) leads to a reduced environmental footprint with regards to energy demand, carbon footprint and eutrophication of seawaters (Figure 7). However, the environmental profile reveals a negative impact for the categories of acidification and especially human toxicity, caused mainly by the production of chemicals (NaOH) for pH adjustment prior to stripping. This would be a typical shift of the environmental burden within the life cycle of the process towards chemicals production. Nevertheless, this option can be favourable in view of the low normalised impact of acidification and human toxicity within this LCA study.

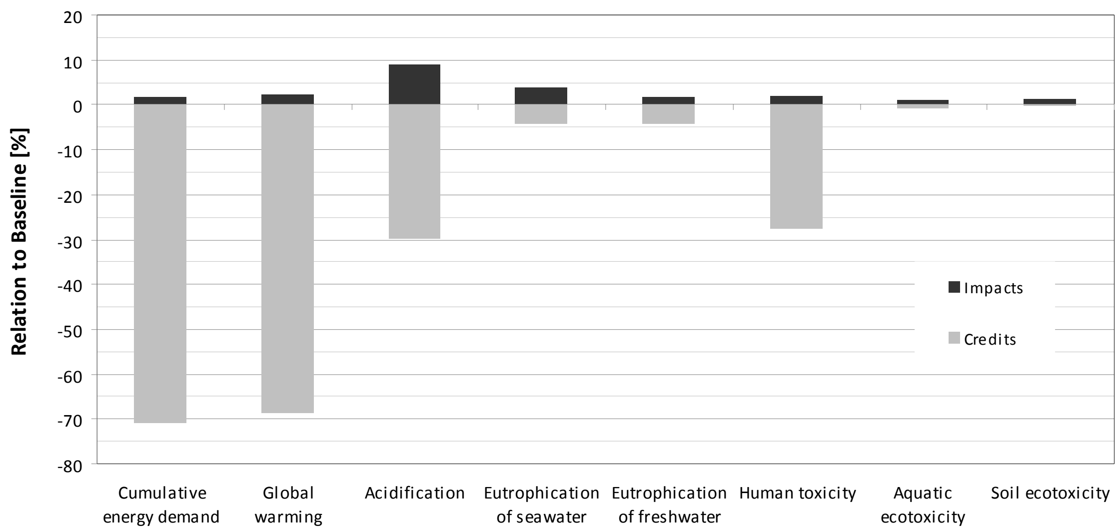


Figure 5: Change in environmental footprint with addition of grass as co-substrate in digestors (+10% TS)

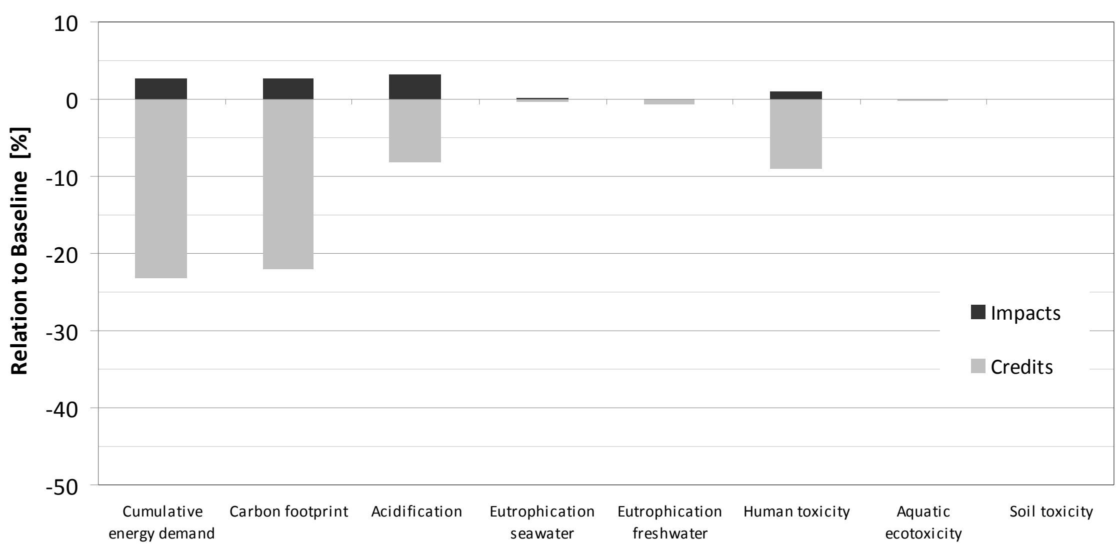


Figure 6: Change in environmental footprint with thermal hydrolysis of excess sludge

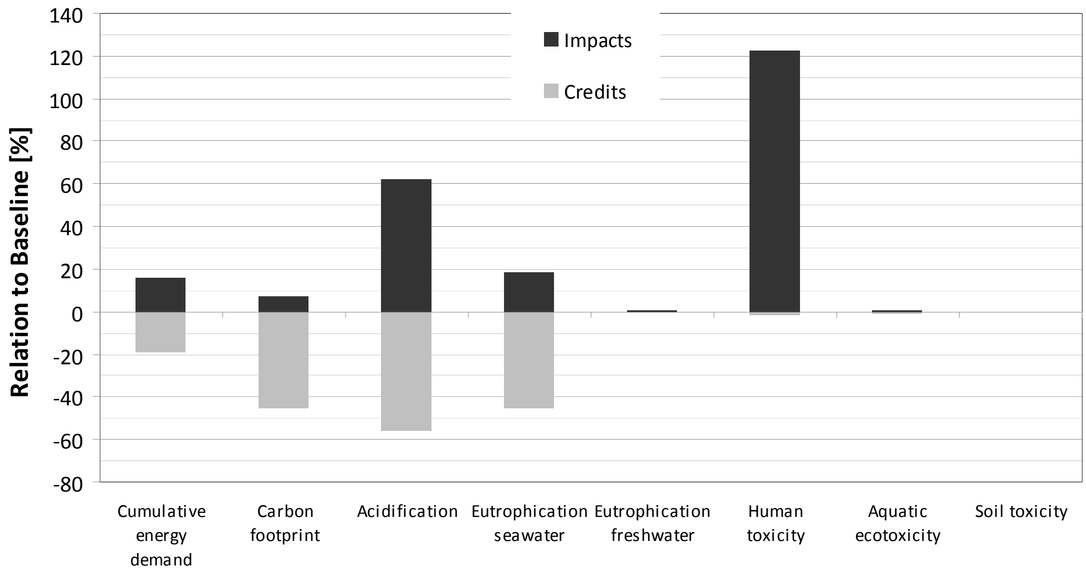


Figure 7: Change in environmental footprint with NH_3 stripping for sludge liquor

Discussion and conclusions

In this paper, the environmental footprint of the Braunschweig wastewater scheme is analysed with the methodology of Life Cycle Assessment. The analysis of the different environmental indicators reveals different groups of environmental impacts from the wastewater scheme and their main drivers:

- Energy demand and related environmental impacts such as carbon footprint and human toxicity are mainly determined by the demand for electricity. A substantial portion of the energy demand is offset by products from the wastewater scheme, i.e. electricity from biogas and substitution of mineral fertilizer. The pumping of effluent to agriculture beyond the amounts effectively required for irrigation impairs the energetic balance of the plant. However, the relative share of energy-related impacts is small after normalisation.
- Environmental impacts related to the protection of surface waters (eutrophication, aquatic ecotoxicity) are improved by the Braunschweig system due to the transfer of nutrients and associated pollutants to agriculture. This primary function of wastewater treatment is reflected by the high share of the respective indicators after normalisation. Hence, effluent reuse in agriculture can play a positive role for the quality of the receiving surface waters, because fewer nutrients are emitted directly in the river.

Finally, different measures for optimisation have been identified to decrease the environmental footprint without impairing other areas of environmental concern, e.g. the dosing of ensiled grass as co-substrate in anaerobic digestion, thermal hydrolysis of excess sludge, or nitrogen recovery from sludge liquor. Prospective benefits and possible drawbacks of the different options can thus be quantified and provide information for decision support towards future investments and operation strategies. Here, the method of LCA proves suitable for a holistic and comprehensive analysis of the environmental footprint of a wastewater treatment scheme, giving valuable information to support the optimisation of systems for wastewater management on the way to more sustainable solutions.

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