Nutrients in urine: energetic aspects of removal and recovery

M. Maurer*, P. Schwegler and T.A. Larsen

EAWAG, Environmental Engineering, Überlandstrasse 133, CH-8600 Dübendorf, Switzerland

* Author to whom all correspondence should be addressed

Abstract The analysis of different removal and recovery techniques for nutrients in urine shows that in many cases recovery is energetically more efficient than removal and new-production from natural resources. Considering only the running electricity and fossil energy requirements for the traditional way of wastewater treatment and fertiliser production, the following specific energy requirements can be calculated: 45 MJ kg^{-1}_N for denitrification in a WWTP, 49 MJ kg^{-1}_P for P-precipitation in a WWTP, 45 MJ kg^{-1}_P for N-fertiliser and 29 MJ kg^{-1}_P for P-fertiliser production. These numbers are higher than the values derived for thermal volume reduction of urine (35 MJ kg^{-1}_N for eliminating 90% water) or production of struvite (102 MJ kg^{-1}_N, including 2.2 kg P). Considering only the electricity and fossil energy for the traditional way of wastewater treatment and fertiliser production, the energy value of 1 PE urine is 0.87 MJ $PE^{-1}d^{-1}$ (fertiliser value: 0.44, wastewater treatment: 0.43 MJ $PE^{-1}d^{-1}$).

A more detailed life cycle assessment (LCA) of the entire urine collection system, including the required materials and the environmental burden, support the energy analysis. The LCA compares conventional denitrification in a wastewater treatment plant with collecting urine in households, reducing the volume by evaporation and using it as a multi-nutrient fertiliser. The primary energy consumption for recovery and reuse of urine, including the nutrients N, P and K, is calculated with 65 MJ kg^{-1}_N, compared with 153 MJ kg^{-1}_N derived for the conventional 'recycling over the atmosphere'.

Keywords Energy requirements; LCA; nitrogen; phosphorus; urine source separation

Introduction

In regions with sensitive surface waters, the costs for wastewater treatment are dominated by the conversion and elimination of nitrogen and phosphorus. The introduction of nitrification, a prerequisite for enhanced nitrogen elimination, into an activated sludge plant increases the reactor volume significantly and leads to higher energy consumption of approximately 60 to 80%. The elimination of phosphorus requires either the addition of chemicals and subsequent disposal of inorganic sludge or an increase of reactor volume for enhanced biological phosphorus removal (EBPR). At the same time, the elements N and P are essential for agriculture and have to be produced technically from natural resources. Phosphorus is gained from rock phosphates, which deplete in quantity and quality (USGS, 2002). Nitrogen fixation is determined by the cost and availability of fossil fuels. The idea is compelling that by recovering the nutrients from wastewater streams and reusing it for agricultural purposes, the costs of extensive wastewater treatment could be avoided and resources saved.

Several removal and recovery techniques have been investigated (Brett *et al.*, 1997; Maurer *et al.*, 2002). However, currently only very limited information is available to decide which route, removal or recovery, should be taken. This article gives an overview over the possible technologies for nutrient recovery from liquid wastes, compares them with the current practice, and discusses the feasibility of recovery. Energy data for the various technologies are compiled and give an important decision guideline for removal or recovery.

Urine

In municipal wastewater, urine is the dominating source for the major agricultural nutrients nitrogen, phosphorus and potassium, and holds 50% to 90% of these essential elements (Larsen and Gujer, 1996). Urine is therefore a prime target, for achieving a more sustainable handling of nutrients from urban wastewater. Of the fertiliser consumption in the EU, 12 % of N, 6% of P and 10% of K could be recovered from urine maximally (EFMA, 1999). These relatively small amounts indicate that currently there is a substantial excess of nutrient supply in agriculture.

Nutrient loads in wastewater and their source are subject to uncertainty. For nitrogen, a load of 11 $g_N PE^{-1}d^{-1}$ seems well established (ATV, 2000). For P and K, we assume a load of 1.1, and 2.7 $gPE^{-1}d^{-1}$ respectively. In Table 1, we present the basic data for the calculations performed in this paper.

Nitrogen

In principle there are two ways to prevent the eutrophication of aquatic systems by wastewater and to make its nitrogen content available for farming:

1. Conversion of the nitrogen compounds into elemental nitrogen gas and technical production of ammonia by the Haber-Bosch process ('recycling over the atmosphere').
2. Direct recovery from liquid waste and conversion into a reusable form.

In western Europe, northern America and Japan, the first pathway is common practice in wastewater treatment, where microbial denitrification is used to convert nitrate into elemental nitrogen gas. For pathway 2, large-scale applications are scarce and many approaches are still under development.

Nitrogen recovery techniques

Except aquacultures, all recovery techniques require relatively concentrated solutions. Some of them have already been tested and used on a full-scale base, such as struvite formation or ammonia stripping. Others, such as volume reduction by evaporation, partial freezing or reverse osmosis have only been tested in laboratories (Maurer *et al.*, 2002). In municipal wastewater handling, the only liquid waste streams with high concentrations of nitrogen are sludge dewatering liquid (digester supernatant), containing about 15–20 % of the total nitrogen load in wastewater, and human urine, containing about 80 % of the total nitrogen load (Table 1).

Besides the costs for installation and operation, the main question remains whether direct recovery and reuse technologies are more sustainable than denitrification combined with technical fertiliser production. One important indicator is the running energy requirement of a specific process. Energy considerations do not replace a careful evaluation of all relevant environmental factors, e.g. with life cycle assessments. Nevertheless, consumption of energy in the form of electricity, fuel and chemicals is a very important guideline to compare two processes.

Table 1 Typical values for the major nutrients in urine. Based on numbers in text and Ciba Geigy (1977) with characteristic concentrations in urine from adult

Element	In urine %	In urine $g_X PE^{-1}d^{-1}$	Typical conc. $g_X m^{-3}$	Typical conc. mmol l^{-1}
N	80	8.8	8180	584
P	50–80	0.7	670	21.6
K	80–90	2.3	2160	55.2

Energy

Tables 2 and 3 summarise the energy requirements for the various techniques to remove, produce and recover nitrogen. The calculations do not represent a complete life cycle assessment (LCA), but focus only on the running energy consumption (electricity, fuel and chemicals); so called 'grey energy' contained in hardware such as reactors and pumps are not included. The values are mostly derived from the literature, except the data for thermal volume reduction of urine, which is based on a detailed feasibility study. In the following the underlying calculations are explained in detail.

Denitrification: Technically there are several ways to achieve denitrification. To get an idea about the energy requirements for denitrification we distinguished three principal types: i) Heterotrophic denitrification without the use of an external carbon source. ii) Heterotrophic denitrification with addition of an external carbon source (e.g. methanol). iii) Autotrophic denitrification (Sharon / Anammox). The calculations only consider nitrogen that is converted into N_2-gas. The N incorporated into biomass is regarded as an intermediate that still needs further treatment. The oxygenation efficiency (energy efficiency of the aeration process), where needed, was assumed to be $1.7\ kg_{O_2}\,kWh^{-1}$ ($= 2.2\ MJ\,kg^{-1}_{O_2}$).

i) A common way to eliminate nitrogen in a WWTP is pre-denitrification (Henze *et al.*, 2002). Typical for this process is that an excess of ammonium needs to be converted into nitrate (nitrified) to eliminate a specific amount of nitrogen. The calculations assume that from the nitrified ammonia 60% is finally converted to N_2 and the rest of the nitrate is 'lost' over the effluent. The electricity demand for the nitrification (aeration) is $17\ MJ\,kg^{-1}_{N,eliminated}$ and $3\ MJ\,kg^{-1}_{N,eliminated}$ is required for the internal recycling of water. However $6\ MJ\,kg^{-1}_{N,eliminated}$ is recovered in the form of oxidised COD in the denitrification process (Table 2).

ii) For denitrification with an external carbon source we assumed that typically methanol ($3.4\ kg_{Methanol}\,kg^{-1}_{N,eliminated}$, Purtschert *et al.*, 1996) is used. The calculations consider the thermal energy content of methanol ($77\ MJ\,kg^{-1}_{N,eliminated}$) and the electricity consumption for nitrification ($10\ MJ\,kg^{-1}_{N,eliminated}$ for aeration; Table 2).

iii) Autotrophic denitrification (Van Dongen *et al.*, 2001; Udert *et al.*, 2003) is only reasonably applicable in concentrated solutions. The aeration in the Sharon process requires $4\ MJ\,kg^{-1}_{N,eliminated}$ electricity and approximately $1\ MJ\,kg^{-1}_{N,eliminated}$ for pumping, mixing, etc. The elimination of $1\ kg_{COD}\,kg^{-1}_{N}$ COD from urine requires additional $1\ MJ\,kg^{-1}_{N}$ electricity. No heating for increased reaction temperature was considered (Table 2).

Table 2 Energy requirements for nitrification/denitrification and N-fixation with the Haber-Bosch process. Only running costs, e.g. for aeration, are considered (energy use for building materials and engines are neglected). The conversion of electricity into primary energy is based on an average European electricity mix (efficiency of 0.31) according to UCPTE (1994). See text for calculations and references

Process	Electricity MJ kg$^{-1}_N$	Other MJ kg$^{-1}_N$	Total UCPTE MJ kg$^{-1}_N$	Total UCPTE W PE^{-1}
Nitrification/pre-denitrification in WWTP	14	–	45	4.6
Nitrification/denitrification with methanol as substrate	10	77	109	11.1
Sharon/Anammox	5	–	16	1.6
Sharon/Anammox with urine (+COD removal)	6	–	19	1.9
Ammonia production (best available technology)	–	37	37	3.8
Average N-fertiliser production Europe	0.8	42	45	4.6
Average ammonia production Europe	–	43	43	4.4
Average urea production Europe	1	51	54	5.5

Table 3 Energy requirements for various urine treatment options to recover nitrogen. See also caption text in Table 2

Process	Electricity MJ kg^{-1}$_N$	Other MJ kg^{-1}$_N$	Total UCPTE MJ kg^{-1}$_N$	Total UCPTE W PE^{-1}
Thermal volume reduction of stabilised urine (10 fold concentration), one step distillation	–	389	389	39.6
Thermal volume reduction of stabilised urine (10 fold concentration) with vapour compression	7	11	34	3.5
Volume reduction of stabilised urine with reverse osmosis (5 fold concentration)	9	–	29	3.0
Struvite production (quantitative P-fixation)	6	6	25	2.5
Struvite production (quantitative N-fixation)	9	72	102	10.4
Stripping with air and $(NH_4)_2SO_4$ production	26	6	90	9.2

Fertiliser production: The best available technology for ammonia production requires 37 MJ kg^{-1}$_N$ with natural gas and 45 MJ kg^{-1}$_N$ with heavy oil (EFMA, 2000). Based on a careful investigation of the technologies actually used in Europe, Patyk and Reinhard (1997) reported 43 MJ kg^{-1}$_N$ for ammonium production and 54 MJ kg^{-1}$_N$ for urea production. In addition, they used fertiliser sales from the years 1993/94 to calculate the energy requirements of an 'average' fertiliser with 45 MJ kg^{-1}$_N$. Pimentel *et al.* (1990) used a value of 87.9 MJ kg^{-1}$_N$ for their estimation of energy use in agricultural production. However, it is not clear where they derived this value from (Table 2).

Volume reduction: Several techniques for volume reduction are described in the literature. For reverse osmosis of urine, Dalhammer (1997) reported an electricity demand of 5 to 10 kWh m^{-3} for a fivefold increase of concentration. At a nitrogen concentration of 3,100 g$_N$m^{-3} this gives a specific electricity consumption of 9 MJ kg^{-1}$_N$ (Table 3).

To estimate the cost and energy requirements for evaporation, a detailed feasibility study, based on experimental results, was performed (Mayer, 2002). Hydrolysis of the collected urine was inhibited by addition of sulphuric or acetic acid (Hellstrom *et al.*, 1999). Subsequently, urine was evaporated at 200 mbar and 78°C and neutralised. The nitrogen concentration increased from 9,606 to 96,522 g$_N$m^{-3} and the total solids from 43 to 445 kg$_{TS}$m^{-3}. The concentrated urine solution with a TS concentration of 573 kg$_{TS}$m^{-3} showed a viscosity of 6.42 mPa s (57 °C) and compared to pure water an increased boiling point of 10.1°C. Based on these data, a technical vapour condensation evaporation plant was laid out for a tenfold volume reduction of urine. The calculated energy requirements are: 7 MJ kg^{-1}$_N$ electricity and 11 MJ kg^{-1}$_N$ fuel for steam production (Table 3). This corresponds well with the values for seawater desalination given by Wood (1982), who reports 150–180 MJ m^{-3} distilled water (equivalent to 17–20 MJ kg^{-1}$_N$).

Another possibility is concentrating urine by partial freezing described by Lind *et al*. (2001), however no energy data are available for this technique.

Struvite production: In order to eliminate nitrogen quantitatively in the form of struvite ($NH_4MgPO_4 \cdot 6 H_2O$), 2.1 kg of magnesium and 2.1 kg of phosphorus need to be added. The energy requirements for the process itself are reported as 5.6 MJ kg^{-1}$_N$ (Siegrist, 1996). The following energy requirements were assumed (Patyk and Reinhard, 1997): magnesium oxide (MgO) 13.4 MJ kg^{-1}$_{Mg}$ and for phosphoric acid 21.1 MJ kg^{-1}$_P$ fossil fuel and 3.7 MJ kg^{-1}$_P$ electricity. No purification and granulising step was included in the calculation and it was assumed that no pH adjustments are needed (Table 3).

Stripping and production of ammonium sulfate: Air is used to strip out ammonia, which is thereafter absorbed in an acid solution. This process requires 2.4 kg kg$^{-1}_N$ calcium oxide for increasing the pH and 7.0 kg kg$^{-1}_N$ sulphuric acid for absorbing the gaseous ammonia (Siegrist, 1996). It produces a 40% ammonium sulfate solution. The electricity requirement for the aeration is an estimated 26.3 MJ kg$^{-1}_N$ and the following energy data are used for the calculations (Patyk and Reinhard, 1997): sulphuric acid (H_2SO_4) -1.1 MJ kg$^{-1}_{H2SO4}$ and calcium oxide (CaO) 5.8 MJ kg$^{-1}_{CaO}$ (Table 3).

Phosphorus

Recycling of phosphorus from conventional wastewater treatment plants is very limited. Although there are several ways to efficiently incorporate P into the excess sewage sludge, reuse of the latter is restricted. Reasons are the low plant availability of chemically precipitated phosphorus and the contamination of sludge with pollutants such as heavy metals and organic micropollutants (Renner, 2000). No energy data were found for the extraction of phosphorus from different sludge streams.

P-precipitation in WWTP: For chemical phosphorus elimination in WWTP we assumed that simultaneous precipitation with iron(II)-sulfate is performed. The stoichiometric ratio of iron to P-precipitated (β) is typically 1.8 and produces 6.8 kg$_{TS}$kg$^{-1}_P$ (Henze *et al.*, 2002). The energy requirements in total 49 MJ kg$^{-1}_P$ include the production of the precipitant (24 MJ kg$^{-1}_P$), the transport of the sludge to an incinerator (2 MJ kg$^{-1}_P$) and the energy loss for burning inorganic material in a modern incinerator with off-gas treatment (23 MJ kg$^{-1}_P$; Table 4).

Enhanced biological P elimination (EBPR): Under favourable conditions a WWTP can eliminate phosphorus biologically. It is assumed that the carbon substrate requirements can be covered by the wastewater and that the additional sludge production is 3.3 kg$_{TS}$kg$^{-1}_P$ (= 1 MJ kg$^{-1}_P$ for transport and 11 MJ kg$^{-1}_P$ for incineration and off-gas treatment). The electricity requirements for mixing and internal recycling is assumed to be 5 MJ kg$^{-1}_P$ (value depends strongly on the flow scheme; Table 4).

Struvite production. Focussing on P- instead of N-elimination, struvite production only requires the addition of magnesium, typically in the form of MgO. For details, see the same process described in the section 'Nitrogen' (Table 4).

Fertiliser production: For triple superphosphate production, based on a careful investigation of the technologies used in Europe, Patyk and Reinhard (1997) reported 3.6 MJ kg$^{-1}_P$

Table 4 Energy requirements for various urine treatment options to recover phosphorus. See also caption text in Table 2

	Electricity	Other	Total UCPTE	Total UCPTE
Process	MJ kg$^{-1}_P$	MJ kg$^{-1}_P$	MJ kg$^{-1}_P$	W PE^{-1}
P-precipitation in WWTP (with FeSO$_4$), incl. energy for sludge transport and incineration	–	49	49	0.4
EBPR in WWTP	5	12	28	0.2
Thermal volume reduction of stabilised urine (10 fold concentrated) with vapour compression (corresponding values from)	85	134	408	3.3
Struvite production (quantitative P-fixation)	3	13	21	0.2
Triple superphosphate fertiliser production	4	23	36	0.3
Average P-fertiliser production Europe	4	16	29	0.2

electricity and 22.7 MJ kg$^{-1}_P$ fossil energy consumption. Taking the fertiliser sales 1993/94 into account, the production of an 'average' P-fertiliser consumed 3.8 MJ kg$^{-1}_P$ electricity and 16.1 MJ kg$^{-1}_P$ fossil energy. These numbers correspond well with the value of 26.4 MJ kg$^{-1}_P$ used by Pimentel *et al.* (1990) for their estimation of energy use in agricultural production (Table 4).

LCA of denitrification and urine source separation

A more detailed analysis of the entire urine collection system, including the required materials and the environmental burden, was performed to verify the conclusions drawn from the comparison of the running energy requirements alone (Schwegler, 2002). The life cycle assessment (LCA) compared two alternatives for Switzerland to keep away nitrogen (functional unit: mass of nitrogen eliminated) from the river Rhine:

1. DENI: upgrade of existing wastewater treatment plants (WWTP) for nitrification and denitrification and use of artificial fertiliser in agriculture. Base-line for the upgrade of the WWTP is their technical status in Switzerland in 1993, with a high number of high loaded plants and only partial nitrification. To achieve nitrification and denitrification for the entire year, additional reactor volume (0.071 m^{3}kg$^{-1}_N$yr^{-1}) and electricity (20.4 MJ kg$^{-1}_{N,eliminated}$) for the higher oxygen consumption (11.3 kg$_{O2}$kg$^{-1}_{N,eliminated}$) is required. In addition, chemical fertiliser production and application in Swiss agriculture is also included into this scenario.

2. USS (Urine Source Separation): decentralised collection of urine, centralised thermal volume reduction and use as fertiliser in agriculture (recovery and recycling). The scenario assumes that slightly diluted urine is collected locally in the households, collected by a truck twice a year and delivered to a centralised evaporation plant, where the urine is concentrated by a factor 10. The decomposition of urea in the storage tanks is prevented by adding sulphuric or nitric acid. The concentrated urine is applied to agriculture mainly as a urea-fertiliser. It is assumed that per PE a total tank volume of 0.356 m^3 (= 0.11 m^{3}kg$^{-1}_N$, incl. storage volume in work areas) and about 11.7 m tubing (= 3.7 m kg$^{-1}_N$) are required, having a life span of 30 years (material: polyethylene). The average transport distance is assumed as following: consumer $\rightarrow$ evaporation plant: 60 km and evaporation plant $\rightarrow$ farmers: 100 km.

The calculations were done with the software EMIS (version 3.5, 2001), based on data sets from various environmental inventories. The main results of the study are (Table 5):

- The primary energy consumption for recovery and reuse of urine, including the nutrients N, P and K, is 65 MJ kg$^{-1}_N$, compared with 153 MJ kg$^{-1}_N$ derived from the conventional 'recycling over the atmosphere'.

- Regarding energy requirements and greenhouse effect, USS performs markedly better than denitrification. Although thermal volume reduction and extensive transport is included, USS only yields 42% of the energy consumption and 52% of the greenhouse potential, compared with the conventional way of handling nitrogen from liquid waste.

- The results for the potentials to form environmentally relevant acids and atmospheric ozone is less clear. Here, the outcome depended very strongly on the chosen technology for applying the concentrated urine in agriculture and how experts assess the environmental consequences (scenario 1 and 2). The values given in Table 5 represent the worst cases, using field sprayers for the application of concentrated urine (scenario 1). Another scenario assumed that the farmers dilute urine and use trailing hoses (scenario 2). Using data from Johansson *et al.* (2000), the estimation for the potential acid formation drops from 112 for scenario 1 to 25 g$_{SOx-equivalent}$kg$^{-1}_N$ for scenario 2. These uncertainties indicate that the field application of urine, even if N is stabilised as urea, requires specific attention in order to quantify any ecological benefit or drawback.

- The results also show that the household collection of urine contributes significantly to the energy balance. The calculation is based on a relatively conservative estimation of tank volume and pipe length in households and workplaces, but also assumes that it will be possible to collect urine almost undiluted (5% tap water). Figure 1 shows that 22 MJ kg^{-1}_N in the form of plastic are required, which is a third of the net energy consumption of the whole process.

Discussion

At present, nitrification/denitrification and the subsequent recovery of nitrogen by the Haber-Bosch process is the prevalent way of dealing with nitrogen. These processes together have typical operating energy demand of totally 90 MJ kg_N^{-1} (45+45, Table 2). The advantage of the nitrification/denitrification technology is that it can be implemented relatively easily into the existing system. Energetically more favourable is the elimination of nitrogen in a Sharon-Anammox process, combined with fertiliser production (19 + 45 = 64 MJ kg_N^{-1}, Table 2). This process requires concentrated N-solutions like digester supernatant or urine, and enables the elimination of nitrogen in large amounts.

The high energy requirements for the N-fixation by the Haber-Bosch pathway makes many recovery and reuse techniques interesting. From an energetic point of view, the evaporation of the water content of urine seems to be competitive. Although farmers are used to handling liquid fertilisers with a high water content (liquid manure), a recent survey shows that a solid product would be much preferred and would be more readily accepted (Lienert *et al.*, 2003). The elimination of water is one possibility to enable transportation and storage of nitrogen, hereby making it comparable with conventional N-fertiliser. Laboratory experiments with urine showed that a 90% elimination of water is relatively easy to achieve
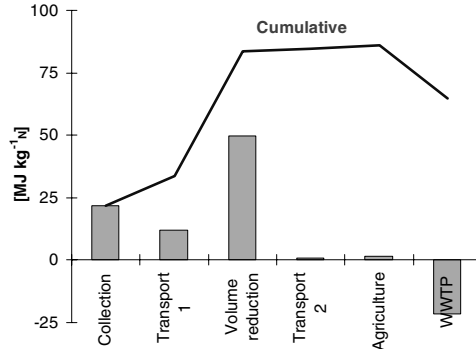

Figure 1 Energy consumption of the different units for recovery and reuse of urine in agriculture. 'Transport 1' is collecting and bringing the urine to the evaporation plant (60 km); 'Transport 2' is delivering the concentrated urine to the farmers (100 km). The energy savings in the WWTP includes the reduced oxygen consumption for nitrification and the decreased sludge

Table 5 Main results of the LCA to compare the two options to treat urine: USS – urine source separation, treatment and use as a fertiliser and DENI – denitrification in a WWTP and production of artificial fertiliser from elemental nitrogen (Schwegler, 2002)

Item	USS	DENI	Units
Energy consumption (primary resources)	65	153	MJ kg^{-1}_N
	7	16	W PE^{-1}
Ozone formation	15	12	$g_{ethen-equivalent} kg^{-1}_N$
greenhouse potential	4,093	7871	$g_{CO2-equivalent} kg^{-1}_N$
Formation of acids, scenario 1	112	39	$g_{SOx-equivalent} kg^{-1}_N$
Formation of acids, scenario 2	25	39	$g_{SOx-equivalent} kg^{-1}_N$

(Mayer, 2002). The last step towards a solid multi-nutrient fertiliser is technically possible, but seems to require specific know-how. Currently it is not clear whether this is feasible for small scale applications (less than 10^5 $kg_N d^{-1}$).

Another interesting product with similar properties as artificial fertiliser, is struvite recovered from urine (Lind *et al.*, 2000). Compared with the 90 MJ kg_N^{-1} for the conventional 'recycling over the atmosphere', the energy demand of 102 MJ kg^{-1}_N for the production of struvite seems high (Table 3). However, in struvite every kilogram nitrogen is accompanied by 2.2 kg phosphorus. The production of equivalent amounts of artificial P-fertiliser requires 64 MJ (Table 4), which totals (90 + 64 =) 154 MJ kg_N^{-1} for the corresponding conventional treatment route. Table 3 shows that only the stripping of ammonia and the evaporation of water without energy recovery seems to be less favourable.

A recent investigation by Richard and Johnston (2001) indicate that recycled struvite has a potential to substitute for current fertiliser on the market. Together with the potential benefits of urine source separation for urban water management (Larsen and Gujer, 1996), this recovery route looks like a prime candidate for a sustainable improvement of the current wastewater handling.

The conclusion that from an energy point of view recovery and reuse of nutrients from urine seems to be more favourable than removal is also supported by a live cycle evaluation. In addition, the more detailed LCA revealed two critical points in the recovery and reuse scenario:
- The urine collecting system on a household level can consume large energy resources in the form of tanks and piping and therefore deserves further attention.
- The environmental consequences of applying urine in agriculture were ambiguous. The impacts depended strongly on the application technology and on differing opinions of experts. Manure and artificial fertiliser are known to cause negative impacts depending on their application. However, urine as a fertiliser is scientifically not very well investigated and more experience needs to be compiled.

The conclusions for phosphorus are very similar to nitrogen. The elimination of phosphate and the new fertiliser production requires between 57 MJ kg^{-1}_P (EBPR, Table 4) and 78 MJ kg^{-1}_P (P-precipitation). Struvite production only consumes 21 MJ kg^{-1}_P. Table 4 also indicates that the P-content of urine is too small to make evaporation worthwhile for the recovery of phosphorus only.

The only way to recover potassium or sulfur is using concentrated or diluted urine directly as a fertiliser. For K-fertiliser production Patyk and Reinhardt (1997) reported 0.5 MJ kg^{-1}_K electricity and 9.6 MJ kg^{-1}_K fossil energy consumption (a total of 11 MJ kg^{-1}_K primary energy according to UCPTE, 1994).

By combining the electricity and fossil energy consumption for the main elements nitrogen, phosphorus and potassium, we can calculate an 'energy value' for collected and untreated urine. Per PE we get an intrinsic fertiliser value of 0.44 MJ $PE^{-1}d^{-1}$ (5.1 W PE^{-1}) and a wastewater treatment energy bonus of 0.43 MJ $PE^{-1}d^{-1}$ (5.0 W PE^{-1}). This means that the total energy value (= intrinsic energy content) of 1 PE urine is: 0.87 MJ $PE^{-1}d^{-1}$ (10.1 W PE^{-1}). A majority (91%) of this energy content is due to nitrogen, only 6% to phosphorus and the rest to potassium.

Conclusions
- The detailed analysis of different removal and recovery techniques shows that in many cases recovery is energetically more efficient than removal and new-production from natural resources. This is especially valid for recovery and recycling of P and N by using urine directly as a fertiliser or by producing struvite as an end-product.
- Pathways working with concentrated solutions, such as urine, are in general

energetically more favourable than conventional processes in wastewater treatment plants.

- Considering only the electricity and fossil energy consumption for the traditional way of wastewater treatment and fertiliser production, the energy value of 1 PE urine is: 0.9 MJ $PE^{-1}d^{-1}$ (fertiliser value: 0.44, wastewater treatment: 0.43 MJ $PE^{-1}d^{-1}$). 91% of this energy content is due to nitrogen, 6% due to phosphorus and the rest is in potassium.
- Additional purification steps (e.g. for elimination of micropollutants) could be integrated into a recovery and recycling application and could energetically still be more favourable than the current traditional pathway for nutrient elimination in wastewater treatment.

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