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Life Cycle Assessment of Wastewater Systems: Influence of System Boundaries and Scale on Calculated Environmental Loads

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Life cycle assessment (LCA) methodology was used to compare the environmental loads from wastewater systems with different technical solutions. This study compared proposed conventional wastewater systems, both large and small scale, with separation systems: one in which urine is handled separately and one in which black water is treated in a liquid composting process. The study showed that large economies of scale, in environmental terms, could be gained both for the operation and for the construction phase. The separation systems outperformed the conventional systems by showing lower emissions to water and more efficient recycling of nutrients to agriculture, especially of nitrogen but also of phosphorus. This implies that the use of separation systems could significantly reduce the need for, and hence the production of, mineral fertilizers and thus reduce the overall use of energy and phosphate minerals. The combination of large-scale wastewater treatment and urine separation was found to be especially advantageous in these respects. It is concluded that some of the most important environmental advantages of separation systems emerge only when models of wastewater systems are expanded to also include potential effects on the production of fertilizers.

Introduction

Wastewater treatment has expanded quantitatively and qualitatively. Existing treatment systems often seem highly efficient when described in the traditional manner, focusing on specific water quality parameters. Present urban water systems in the developed world were also primarily designed for hygienic and drainage reasons. Given the long-term need for ecological sustainability, the goals for urban water systems need to move beyond the protection of human health and receiving waters to include minimizing loss of scarce resources, reducing the use of energy and water, reducing waste generation, and enabling the recycling of plant nutrients.

Improvements of current systems mainly aim at increasing the removal of environmentally disturbing substances. However, due to the mixing and dilution of different flows in these systems, there is little potential for the reuse of water or plant nutrients. In conventional systems, three fractions from households (urine, feces, and gray water) are mixed with industrial discharges and urban runoff. Separation of flows may improve the opportunities for recycling and reuse (*1*, *2*). If the nutrients in the wastewater were returned to agriculture, the demand for mineral fertilizer on which modern agriculture is heavily dependent would be reduced, and the substantial environmental loads imposed by the production and use of mineral fertilizer could be avoided.

Technical solutions that have been proposed involve separating flows containing plant nutrients from gray water and industrial wastewater. Systems such as urine separation and liquid composting have been designed and tested (*3*−*5*). Urine and sludge from these separation systems can be made available for agriculture. Urine contains by far the most nutrients and is in this respect the most valuable fraction (*3*). If urine is not fed into the sewage system, about half of the phosphorus and over 80% of the nitrogen in wastewater is taken care of at the source. Separation systems are, however, often regarded as consuming more resources than conventional systems due to greater transportation, spreading, and storage requirements. Increasing interest in these technologies has led to several studies of the environmental performance of separation systems, taking into account such aspects as pollutant loading, energy use, material, and chemical requirements (*5*, *6*).

Besides a short introductory literature review, this paper presents a study of the differences in the environmental loads imposed by conventional treatment processes and separation systems (one system combining urine separation and conventional treatment and one liquid composting system). The work reported here is based on the LCA modeling but is limited to a life cycle inventory (LCI); in other words, no impact assessment is carried out. The purpose is to illustrate the effects of expanded system boundaries and the physical scale of the systems.

LCA and Wastewater Systems

Several authors have used life cycle assessment (LCA) methodology to estimate the environmental loads from wastewater systems (*7*−*13*). In LCA, a model of the technical systems under study is constructed, and the flow of selected, environmentally relevant substances between the technical systems and the environment is calculated. Such a systems approach makes it possible to assess changes in wastewater treatment practices and to compare different technical solutions in terms of the estimated environmental loads they impose by emissions and resource use. For a general description of LCA, see the relevant ISO standard (*14*).

The majority of LCA studies of wastewater systems have compared different conventional treatment methods. In a Dutch study (*7*), an LCA was performed of different conventional wastewater systems in order to assess the total environmental burden of these systems on a national level in The Netherlands. The authors concluded that, to improve the sustainability of the systems, attention should focus on minimizing the discharge to water and minimizing the sludge production. Environmental burdens due to sludge handling were not assessed.

One study (*8*) focused more on the construction and demolition of wastewater treatment plants (WWTP) than their operation. In this study, attention was given to material and energy use, while emissions to water were limited to include only oxygen-demanding substances and suspended solids, neglecting emissions of phosphorus and nitrogen.

Other researchers have focused on parts of the wastewater system and have used LCA to study sludge treatment alternatives and different unit processes. An investigation compared different sludge treatment processes (*9*), consid-

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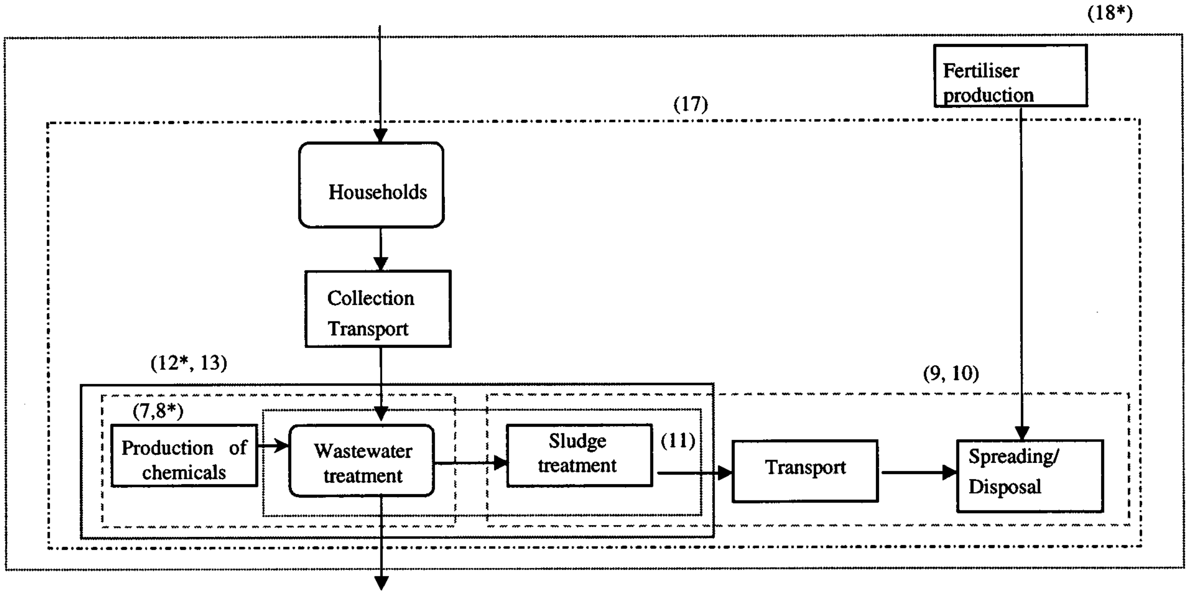

FIGURE 1. System boundaries used in different LCA studies for wastewater systems. The asterisk (*) indicates that the construction phase has been included.

ering sludge as a waste (landfilling, incineration, and ozonization) or as a resource (composting). One conclusion the authors drew was that when sludge is used as soil improvement the benefit should be compared with the production and use of chemical fertilizer. However, this was not done. In another study (*10*), six different sludge recycling strategies were compared. The main impacts associated with sewage sludge treatment were found to be energy use, diesel used in transportation, and direct emissions of ammonia from composting and dewatering.

In ref *11*, physical/chemical pretreatment steps were investigated and included the following environmental loads: energy balance, sludge (waste) production, effluent quality, use of chemicals, and space requirements. A similar investigation for different conventional WWTPs was made in a Norwegian study (*12*), which considered construction, chemical use, electrical energy, and emission of substances in the LCA. Chemical pretreatment was found favorable as compared to biological treatment. However, benefits from sludge use were not considered in these two studies.

In recent years and following the increasing interest for alternative sewage treatment technology, a few studies of the environmental performance of separation systems have been carried out. In the Swedish Orware simulation model, different systems for handling organic waste have been modeled (*17*). The sewage plant submodel includes mechanical, biological, and chemical treatment of wastewater as well as anaerobic digestion and dewatering of sewage sludge. The model has been used to compare conventional treatment with urine separation, and the environmental effects were evaluated through life cycle impact assessment (*23*). Recycling of nutrients to agriculture was considered in the model but not fertilizer production.

One extensive LCA study, including both construction and operation, compared the environmental load from alternative systems with the load from existing wastewater systems in two Swedish municipalities (*18*). Two alternatives were compared to the existing conventional systems: a local treatment in sand filter beds and a urine separation system. Changes in the wastewater system that might affect surrounding technical systems were approached through an expansion of the boundaries of the system model.

As can be seen in Figure 1, very different choices can be made for system boundaries in models of wastewater systems. These choices will inevitably affect the results. When carrying out an LCA, the choice of boundaries for the system under study and the set of parameters included in the inventory are important (*15*). The system boundaries should be chosen according to the purpose of the study (*16*). If the purpose is to compare a biological and a chemical unit process, the production of chemicals and energy should be included as well as the sludge treatment since it is likely that these will be affected. However, the collection and transportation of wastewater would be the same for the alternatives and could therefore be excluded. Most LCAs include only the operation of the studied technical systems and overlook the environmental load of the construction phase. Consequently, questions related to the scale and longevity of the systems are also overlooked.

An important distinction between different LCA studies of wastewater systems is whether sludge is regarded as a resource or a waste product. A few studies (e.g., refs *10* and *17*) consider the recycling of nutrients from sludge, but most other consider sludge as a waste problem. A more comprehensive grasp of the calculated environmental load caused by different wastewater treatment options requires that more than merely the wastewater systems themselves be included in the analysis. Attention should also be paid to the way such systems interact with surrounding technical systems, such as power generation, district heating, agriculture, fertilizer production, and other relevant material flows. Prior to the case studies reported in this paper, only one study had done this (*18*).

Case Descriptions. The two cases selected for study involved differently sized conventional wastewater systems, which were compared to different source separation systems. The studies are future-oriented evaluations of projected systems that have not yet been built (although some are under construction).

Luleå. In Luleå, a city in Northern Sweden, two treatment solutions were considered for a projected housing development (Figure 2). The area is planned to accommodate 2700 inhabitants and to provide workspace for 1000 people. The two options compared are a conventional large-scale wastewater treatment plant (WWTP) and a urine separation system. The comparison covers only the operation phase.

In the conventional system, all sewage from the housing area would be pumped to the existing WWTP, which currently

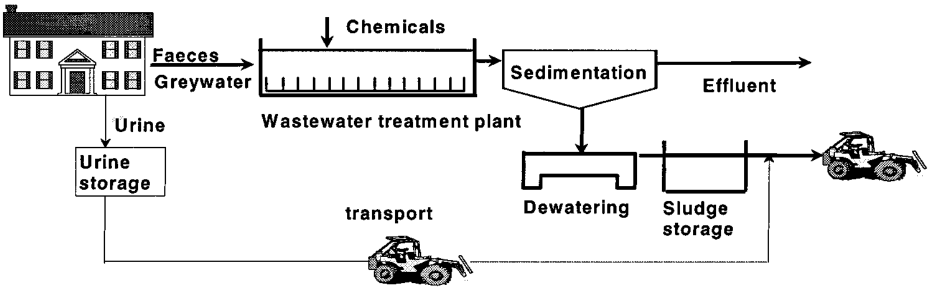

FIGURE 2. Flow chart for the large-scale systems in Luleå. The thin line is only valid for the urine separation alternative.

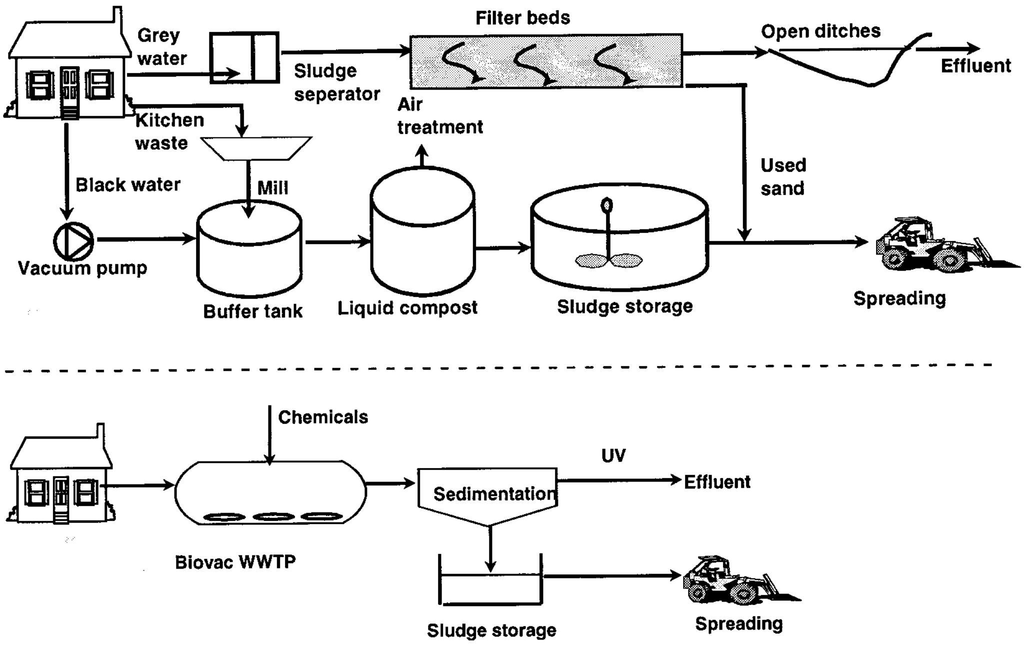

FIGURE 3. Flow chart for the small-scale systems in Horn, liquid compost (upper) and WWTP (lower).

serves 72 000 person equivalents (pe). The estimated reduction rates of a process including chemical precipitation with ferric chloride and a projected biological treatment step (without nitrification) were 95% for phosphorus and biological oxygen demand (BOD) and 30% for nitrogen. It was estimated that the sludge from the treatment plant would contain 95% of incoming phosphorus and 18% of the incoming nitrogen. The sludge would be stored 6−12 months before being transported by truck to farms on an average distance of 25 km from Luleå and applied as fertilizer.

In the urine separation alternative, separation toilets would be installed. After seasonal storage of 6 months, the urine would be transported approximately 8 km and spread as liquid fertilizer. Feces and gray water would undergo the same WWTP process as in the conventional alternative. Also in this case the sludge would be used for fertilization.

Horn. The second case involved Horn, a small, planned village of 200 inhabitants situated in a rural area in central Sweden. The study compared the environmental loads of both the construction and the operation phases of a conventional small-scale WWTP and a liquid composting process (Figure 3).

In the conventional system, water-saving toilets would be installed, and the wastewater led to a small batch-processing WWTP (Biovac), where it would be processed biologically and chemically with ferric chloride. The projected removal efficiency was 95% for phosphorus and BOD, respectively, and 25% for nitrogen. The treated water would undergo ultraviolet sterilisation. Sludge would be stored 6−12 months before being transported an average of 2 km and spread.

In the separation alternative, a vacuum system would be used to transport black water from toilets to a buffer tank, where it would be mixed with organic kitchen waste. The mixture would then be pumped to a reactor and aerated. Liquid composting is a thermophilic process in which a high temperature is reached through biological degradation. The air from the reactor would be treated in a peat filter. After treatment the sludge would be stored for 6−12 months before being transported 2 km and spread. Gray water would be treated in a septic tank, sand filters (with an area of approximately 350 m^2), and open ditches. Sand filters were estimated to remove 90 and 80% of the BOD and phosphorus, respectively, while nitrogen removal was set to 40% (*19*). The used filter sand containing adsorbed phosphorus would be spread on farmland. The septic tank sludge would be fed to the buffer tank of the liquid composting process.

System Modeling. The main purpose of the wastewater systems described above is to collect sewage and to reduce emissions of nutrients, BOD, and bacteria to acceptable levels. Apart from this, the systems also make nutrients in the sewage available for agriculture. To cover this double function, the LCA base model included the collection, treatment, and transportation of wastewater as well as the production of chemicals and other materials required to operate the systems. In an extended model, the production of electricity and mineral fertilizers was also included (Figure 4). The operation of the systems was analyzed for both case studies.

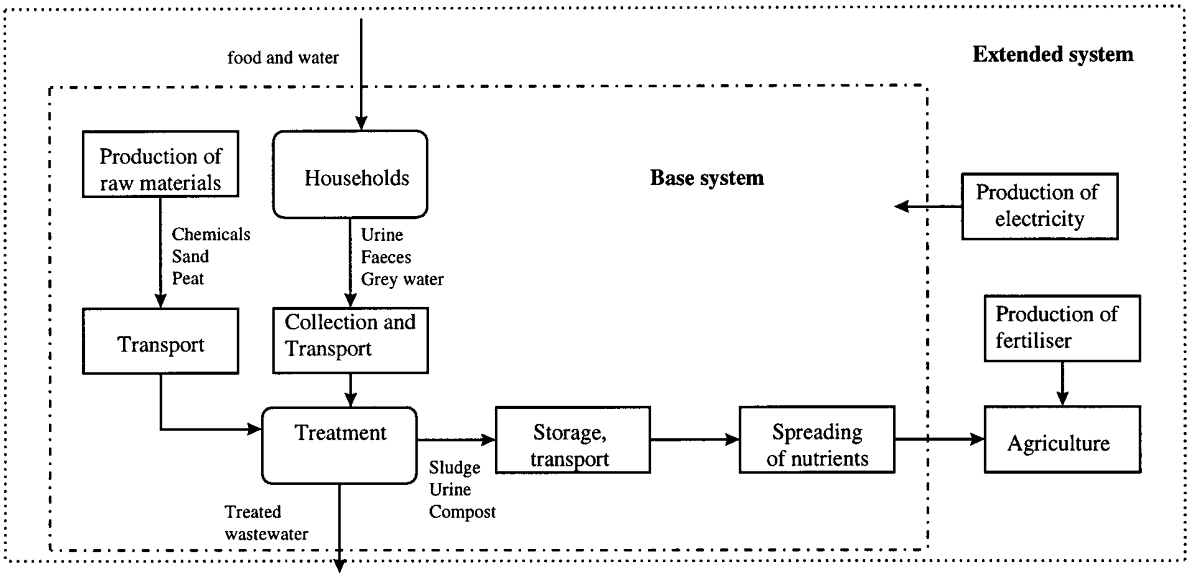

FIGURE 4. General overview of the material flows and system boundaries for the base model and the extended model of the operation of the wastewater systems.

The environmental burdens imposed by construction were modeled in the Horn study and covered the production of the equipment but not reuse or disposal. Pumps, tanks, and other technical parts were expected to last for 15 years; buildings, filter beds, and pipes were expected to last for 30 years; and toilets were expected to last for 25 years. The transportation of the material to the construction site was not included.

The production of drinking water and the collection of urban runoff were not included in the models. The treatment of kitchen waste was included in the analysis of the liquid composting system, but the benefits of reduced waste disposal were not accounted for. The nutrients in this waste were included but contribute only marginally.

The inventory analysis included parameters describing resource use (energy and raw materials) emissions to air, emissions to water, and waste generation. These flows were normalized to the functional unit *treatment of one yearly person equivalent of sewage* (pe•yr).

The electricity demand was calculated and is reported as kilowatt-hour of electricity in the base model and as the environmental loads related to the electricity production in the extended model. In calculating this, the present Swedish average electricity mix was used (nuclear energy 49%, hydropower 44%, combined power and heating plants 7%). In addition, a sensitivity analysis was performed using an European electricity mix with a larger part of fossil fuels.

Differences in the plant availability of nutrients in different kinds of residual products were taken into account. However, since the degree to which nutrients in sludge or urine can substitute for mineral fertilizer depends heavily on factors such as soil properties and spreading technique, data on substitutability are uncertain. The substitutability of phosphorus was assumed to be 100% in urine and compost and 70% for chemically treated sewage sludge. For nitrogen, the value of 50% was used, assuming a loss of 25% as ammonia emissions and 25% as nitrogen gas through denitrification in the soil. Other types of losses, such as nitrate leaching, were not included in the analysis.

The area of farmland needed for spreading was calculated by assuming that 22 kg of phosphorus would be spread per hectare and year. Liquid compost, urine, and unthickened sewage sludge have a dry solid content below 10%, which means that they can all be spread with the same type of equipment. Dewatered sludge needs another spreading equipment, with a smaller working width, which results in more tractor driving and greater diesel consumption.

Data Sources. Local authorities provided site-specific data, while data on equipment were provided by suppliers or estimated from existing systems. General data taken from the literature were used for nutrient content of sewage (*20*), the production of precipitation chemicals (*21*), fertilizers production (*22*), diesel consumption and emissions in the spreading of manure (*23*), and the production of different materials (*24*−*26*). Further background data on the case studies may be found in ref *27*.

Results

Base System. *Construction Phase (Horn Case).* More resources are required for the construction of the liquid composting alternative than for the small WWTP (Table 1). This is due to the higher demand for technical components, such as the buffer tank, vacuum unit, and two sets of pipes. The most common materials would be reinforced concrete, steel, and PVC. The resources used during construction are mostly non-renewable fossil resources: in the form of raw material in plastics (oil and gas), steel, and concrete (coal) and in the form of sources of thermal energy. Iron ore is used in steel components such as mixers and aerators, while chromium and nickel are used in stainless steel products such as the vacuum unit.

Emissions to air during construction are related to the quantity of resources used and are thus higher for the liquid compost than for the WWTP (Table 1). Most of the CO_2 originates from the production of iron, steel, and concrete. The largest emissions of NO_x are due to the production of PVC, followed by concrete, while the production of steel and iron is responsible for the major part of the emissions of SO_2.

Waste (Table 1) originates mainly from the production of concrete, iron, and steel; hazardous waste originates from the production of PVC. Emissions to water during the construction phase are small as compared to emissions during operation.

Operation Phase. The electricity demand per functional unit is about 4 times higher for the small-scale systems in Horn as compared to the large-scale systems in Luleå. Most of the electricity is used in the treatment processes, followed

TABLE 1. Inventory Results (Selected Parameters) for the Base Systems: Liquid Compost and Small-Scale WWTP (Horn), Urine Separation and Large-Scale WWTP (Luleå)[a]

	liquid composting		small-scale WWTP		urine separation	large-scale WWTP
	construction	operation	construction	operation	operation	operation
Resources						
fossil fuel, kWh	45	7	34	8.5	17.4	18.4
electricity, kWh	9.4	119	5	106	27	33
iron ore, g	5200		2000	5600	3700	7700
nickel, g	26		0.45			
chromium, g	58		1.0			
Emissions to Water						
BOD,[b] g	0.2	1000	0.1	900	900	900
total N, g	0.08	200	0.05	3700	600	3400
total P, g		40		40	20	40
Emissions to Air						
NH_3, g	0.06	1200	0.004	310	1000	220
CO_2, g	9300	1800	5200	1970	5900	6400
N_2O, g	0.002	0.07	0.003	0.06		
SO_2, g	27	0.79	17	2.2	10	11
CO, g	7.0	8.4	4.2	7.7	17	18
NO_x, g	36	30	26	30	87	88
Waste						
waste general, g	2400		1300	170	130	270
hazardous waste, g	6		4.2	5.5	4.2	8.7
Useful Flows to Agriculture						
total N, g		2500		610	2100	440
total P, g		830		730	690	680

[a] Expressed per functional unit (pe·yr). [b] BOD, biological oxygen demand.

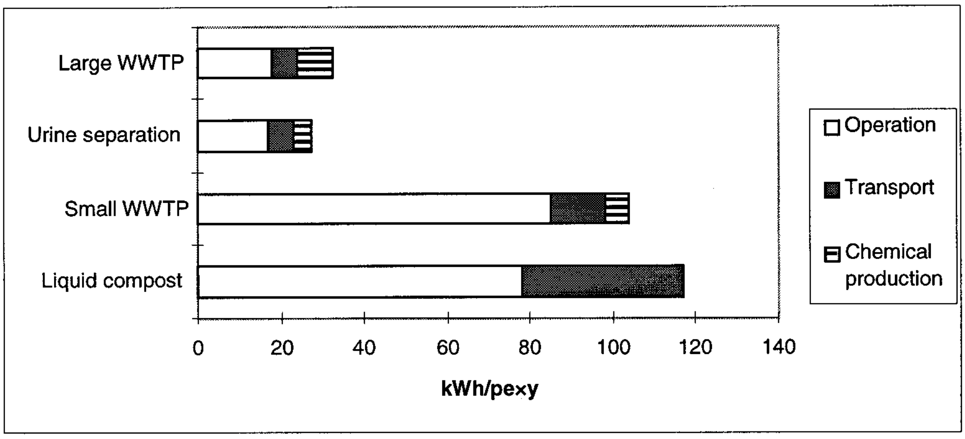

FIGURE 5. Electricity demand for different activities during operation of the base systems; liquid compost and small-scale WWTP (Horn), urine separation and large-scale WWTP (Luleå).

by the transportation of wastewater (Figure 5). The liquid composting process (Horn) has the highest electricity requirements, due to the aeration of the liquid and the vacuum transport. The urine separation system in Luleå uses the least electricity, illustrating the importance of the scale of the plant as well as of the technology used.

The fossil energy requirement arises from the production of treatment chemicals and the use of diesel to transport and spread residual products. In contrast to the electricity use, the large-scale systems have a higher demand for fossil energy than the small-scale ones (Table 1). This is mainly due to the longer distances to agricultural land and the more energy-intensive equipment used for the spreading of semisolid sludge. In some cases, transport distances are also longer for Luleå, as it is situated in the far north. The urine separation system in Luleå, in which both urine and sludge are handled, requires more energy for transports and spreading but less for the production and transport of chemicals.

The emissions of BOD vary between 0.9 and 1.0 kg/pe·yr. For phosphorus, they vary between 0.02 and 0.04 kg/pe·yr (Table 1). Large differences can be seen in the emissions of nitrogen to water, emissions from separation systems being much smaller than from conventional ones (Table 1). The liquid composting process emits about 0.2 kg/pe·yr nitrogen while the urine separation system emits about 0.6 kg/pe·yr. Both WWTPs emit much higher amounts: Horn, 3.7 kg/pe·yr, and Luleå, 3.4 kg/pe·yr. Even with nitrogen removal steps installed, emissions would still be considerably higher for conventional systems than for separation systems.

Calculated emissions to air from the operation are presented in Table 1. Emissions related to the burning of fossil fuels follow the same pattern as those from fossil energy use, with the large-scale systems emitting considerably more SO_2, NO_x, CO_2, and CO than the small-scale ones. Emissions of ammonia depend on how much nitrogen that is spread and

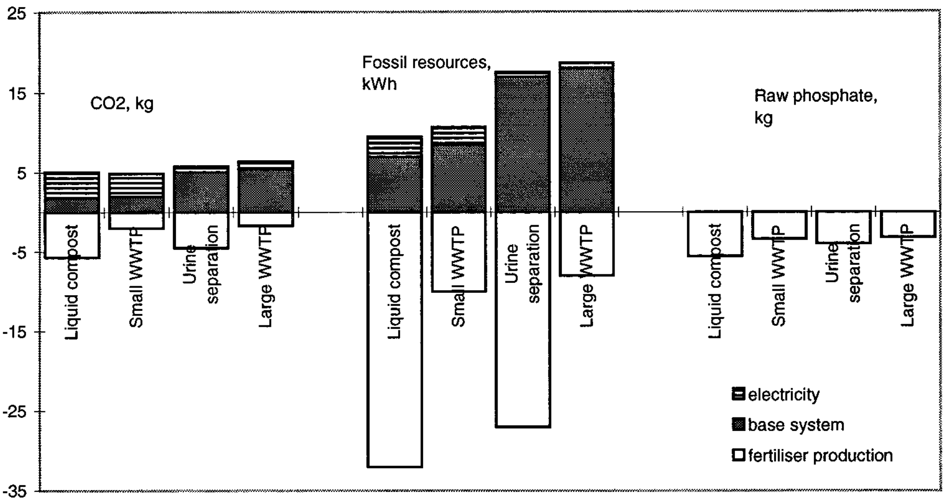

FIGURE 6. Use of fossil resources, raw phosphate, and emissions of CO_2 for the operation of the base system, electricity production, and fertilizer production; liquid compost and small-scale WWTP (Horn), urine separation and large-scale WWTP (Luleå). Note that, for the fertilizer production, the environmental loads are negative since it is the avoided need for fertilizers that is modeled. The overall load of the extended system is the sum of the three parts.

are higher for the separation systems than the conventional ones.

The use of precipitation chemicals is highest for the large-scale WWTP; consequently, this alternative also generates the largest amount of waste, which is related mainly to the production of chemicals. The small-scale WWTP and the urine separation system follow. Generation of toxic waste follows the same pattern. The liquid composting system generates no waste during operation.

Recycling efficiency for nitrogen varies significantly between the systems (Table 1). About 2.1−2.5 kg of N/pe•yr can be recycled from the separation systems even with the conservative assumption that 50% of the nitrogen in the urine and compost sludge is lost through ammonia emissions and denitrification. In the conventional systems only about 0.5 kg of N/pe•yr may be used as fertilizer. Recycling of phosphorus is high for all systems (Table 1).

Extended System. The substitutability of phosphorus is assumed to be higher for urine and compost sludge than for sewage sludge, which means that more mineral phosphate fertilizer can be avoided in the separation cases. For the separation systems, calculation shows that the mining of almost 4−6 kg of phosphate rock/pe•yr can be avoided if the urine or compost sludge is used (Figure 6). For the conventional systems, the amount is about 3.3 kg/pe•yr. The production of phosphoric acid from phosphate rock also generates large amounts of gypsum (a waste that includes heavy metals). The separation systems avoid some 7 kg of waste as compared to 5 kg for the conventional systems.

Among the most important benefits from nitrogen recycling is the saving of fossil energy and avoided emissions to air of substances such as CO_2, NO_x, and especially N_2O. In fact, the value of the nutrients in the separation systems, in terms of avoided fossil energy use, is substantially larger than what is needed for the operation of the systems and for the electricity production (Figure 6). This result, however, is partly a result of the choice to use average Swedish electricity data in the model. A sensitivity analysis with average electricity data from the European OECD countries showed how a different data set affected the results. In this case, the liquid compost alternative seems much less preferable than in the original calculations. The urine separation system was also affected, but it still seems to be a preferable solution compared to conventional technology.

Discussion

In this study, LCA was used to compare the environmental loads of conventional wastewater systems with those of separation systems. The choice of case studies made a comparison between large-scale and small-scale systems possible. The study showed that large economies of scale, in environmental terms, could be gained. The operational electricity requirements per pe were considerably lower for the large-scale systems than for the small-scale ones. No such benefits were found for fossil energy and related atmospheric emissions. The requirements for fossil energy depended not so much on size as on geographical location and access to suitable agricultural land. In fact, large cities may have difficulties finding land for spreading of residual products within reasonable distances. Our study showed that the urine separation solution in Luleå might be competitive to the conventional alternative, assuming transport distances shorter than about 60 km. Urine separation systems have however yet to be tested on a larger scale, and the effects of using human urine as fertilizer have not been fully evaluated, neither technically nor as regards the risks for infection.

In many long-lived installations, the construction phase is of less importance than the operation phase. However, the environment loads from the construction of smaller wastewater systems contribute a great deal to the total loads.

These findings are in agreement with the earlier LCA study of a small-scale system of 900 pe and a large-scale system of 550 000 pe (*18*). The authors of that study concluded that the environmental loads from construction are lower for large-scale than for small-scale systems (per unit of capacity), and those economies of scale can also be gained for the operation of the wastewater systems. Economies of scale have been the subject of other studies but mostly in terms of money, more seldom in terms of environmental burdens.

Emissions to water were less dependent on size and more on technical solution. In conventional systems, the nutrients are either removed from the wastewater (requiring chemicals and energy) or emitted to the receiving water (harming the aquatic ecosystems). Small-scale systems usually have similar conventional technology (mechanical, biological, and chemical treatment steps). Separation systems, on the contrary, limit nitrogen emissions to a considerably higher degree than can be achieved by WWTPs, regardless of size. Furthermore, in separation systems nitrogen is not lost to air or water but may be used as fertilizer.

One conclusion that might be drawn is that *scale* should not be mixed up with *type of technology*. Separation technologies have, as it has been shown, many positive features. These nonconventional technologies are however often thought of as small-scale inefficient solutions. In our view, this is a misunderstanding that comes from conflating scale and type of technology. If these two categories are not kept separate, the discussion will be confused and misleading. The results from the case studies show that the urine separation system combined with conventional treatment of feces and gray water in fact uses less energy than if all wastewater would be treated conventionally, even though the benefits from the nutrient recycling were not taken into account. It should be noticed, however, that the construction of these systems was not included.

The largest input of energy to a sewage system comes from the heating of household tap water (*28*). A larger WWTP may facilitate the recovery of energy from the wastewater by digestion of sewage sludge and using heat pumps to recover energy for district heating. A combination of such a WWTP with a separation system could give the advantages of nutrient recirculation, energy recovery, and efficient treatment.

We conclude that separation systems have clear environmental advantages as compared to conventional ones. These advantages become evident when the model of the wastewater system is enlarged to also include fertilizer production. We argue that, if the environmental consequences of changing conventional wastewater systems to separation technologies are assessed, system boundaries excluding fertilizer production and agricultural practice are not appropriate. Such narrow system boundaries favor existing technologies and systems since positive features of new solutions are not taken into account. Even though it is clear that the system boundaries must be related to the purpose of the LCA, there is an obvious risk that analyses, even very careful analyses, using narrow boundaries will conserve existing systems and make the introduction of new system solutions difficult.

In many cases, the positive features of new solutions will only become visible when changes in surrounding systems have also been modeled. In the case of wastewater systems, it might be argued that the use of sludge for fertilization is not feasible at present because of heavy metals and other kinds of contamination. If this argument is used, the advantages of returning nutrients to the soil will not be taken into account, and then there will be no incentives to make the sludge cleaner.

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