Sewage Sludge Utilisation Alternatives

– Comparative Analysis Using Life-Cycle Assessment –

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1. Abstract

In an overview of a variety of life-cycle assessments dealing with sewage sludge [1, 3, 4, 5] the trend showing that agricultural use is less favourable compared to incineration is reinforced. The principal disadvantages comprise a considerably higher contaminant input into the environmental medium soil, and higher acidification and eutrophication due to the increased ammonia release from agriculturally utilised sewage sludge compared to inorganic fertilisers. The various alternatives, the majority of which are based on incineration methods, in turn display numerous advantages and disadvantages compared to each other. Put simply, incineration method suitability is staggered, predominantly following the mercury content of the sewage sludge: for energy efficiency reasons (greenhouse effect), less contaminated sludges are better suited to co-incineration in coal-fired power stations and cement works. The optimal disposal of more heavily contaminated sludges is clearly by mono-incineration. The only disadvantage of all incineration methods when compared to agricultural use is related to phosphorus resource consumption. If phosphorus recovery processes are incorporated in the incineration options, the advantages can be combined, with comparatively small losses in the remaining environmental categories (e.g. greenhouse

effect) resulting from the more complex processes involved. Phosphorus recovery processes therefore represent an optimum combination of phosphorus resource conservation and minimisation of contaminant input into the soil. In the question of raw sludge incineration compared to digestion with efficient digester gas utilisation and digested sludge incineration, the second option displays considerable advantages in the life-cycle assessment.

2. Remit

The question of agricultural utilisation versus incineration has been the object of disputes among experts for more than twenty years. During this period IFEU has also compiled several life-cycle assessments and helped stimulate the discussion of the environmental assessment of alternative options [4, 5, 6, 7]. In 2009 IFEU cooperated in a *policy study on the state-of-the-art in sewage sludge treatment* on behalf of the municipal urban sewage system operators of the cities of Augsburg, Frankfurt, Karlsruhe, Mannheim, Munich, Stuttgart and Zurich [1, 2]. IFEU's task was to perform the ecological assessment for the various treatment techniques and technique combinations, and to incorporate the results into the overall assessment, applying technical, economical and operating criteria. The scarceness of the phosphorus resource has always been a point emphasised in the life-cycle assessments. Phosphorus recovery processes have thus formed a fixed component of many life-cycle-assessments since 2005. The life cycles of these processes were exhaustingly assessed as part of the BMBF/BMU-funded Phobe [3] projects.

This paper represents a summary of those studies. The primary aim is to provide an up-to-date environmental evaluation of the technical options for sewage sludge disposal compared to agricultural utilisation. In addition, a life-cycle assessment overview of phosphorus recovery processes is presented. This is closely linked to the core problem of whether the phosphorus recovery route can represent an ecologically optimised alternative to direct sewage sludge application to fields and to sewage sludge incineration.

3. Objective, investigation framework and life-cycle assessment methodology

3.1. Objective

The objective of the underlying studies is to enhance knowledge of the various environmentally relevant sewage sludge treatment options by providing a comparative overview. This knowledge will provide a contribution to the municipal wastewater treatment sector and to sewage sludge disposal, for operators, policy makers and the scientific community. It will also address questions posed with regard to the demands placed on the processes or the associated systems, in order to achieve optimum utilisation from an ecological perspective.

3.2. Investigation framework

The **reference variable** for this work is given by the annual disposable mass of municipal sewage sludge with a typical average composition.

The life-cycle assessment's **functional unit** is: disposal of a quantity of raw sludge of the appropriately defined composition. The system boundary (described in more detail below) comprises all directly associated environmental impacts, negative for consumptions and emissions, and positive for savings and substitutions of primary resources.

The life-cycle assessment's **system boundary** begins with raw sludge generation and includes its treatment and disposal. Any wastewater created and returned to the treatment plant (e.g. dewatering centrifugate) is also included, such that the municipal wastewater treatment process is also included within the system boundaries. This takes the interactions between sewage sludge treatment and sewage sludge generation into consideration. The endpoint of the disposal of sewage sludge is drawn at the disposal of wastes generated in the combustion process.

If different systems and their environmental impacts are compared, the systems involved must display a **benefit equivalence**. Because the disposal options considered here lead in varying degrees to energy recovery (e.g. utilisation of digester gas in CHPs, excess electricity from mono-incineration, fuel substitution by co-incineration) the replaced primary energy processes must be incorporated within the system boundaries. The saved primary processes are termed **equivalence processes**. The associated environmental impacts are credited to the corresponding disposal system. The same applies to the nutrients that substitute for primary fertilisers in the agricultural use of sewage sludge or when using products based on phosphorus recovery processes in agriculture.

The provision of capital goods (e.g. incinerator or incinerator conversion production) is not included in the balance.

Figure 1 shows a simplified schematic of the system boundaries, including the Pasch phosphorus recovery process.

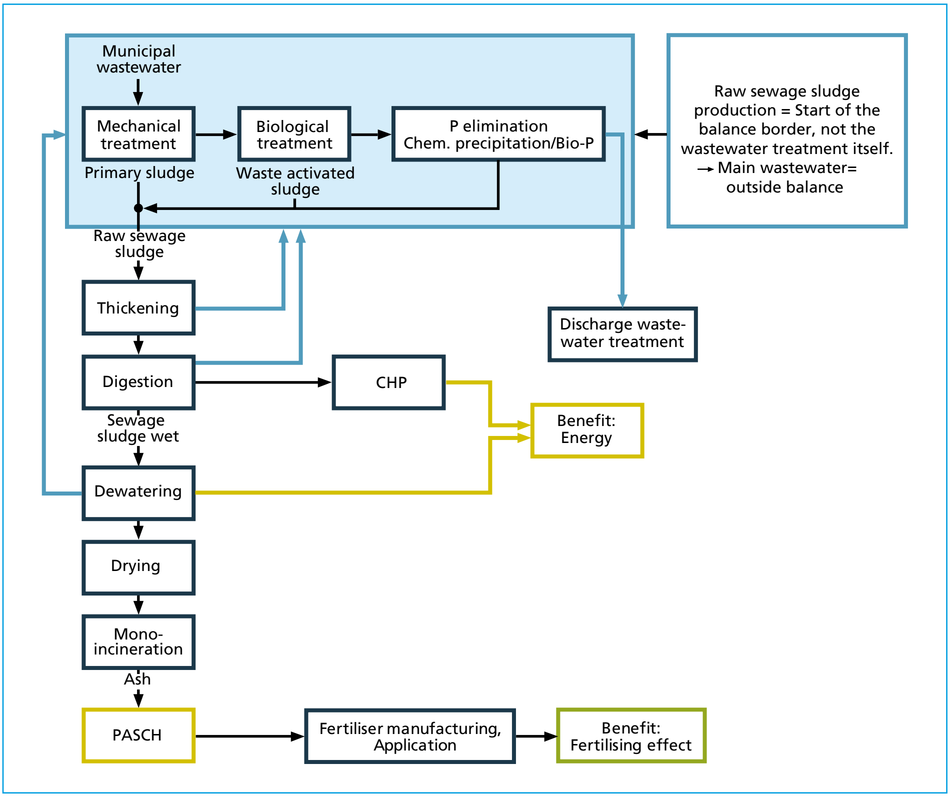


Figure 1: Greatly simplified schematic of the system boundaries

In the *policy study* [1] discussed above, a total of five mono-treatment and four co-incineration options were evaluated. Five options are adopted for analysis in this paper:

Mono-incineration

Mono-incineration 1	Dewatering and incineration in a fluidised bed.
Mono-incineration 2	Dewatering, drying and incineration in a fluidised bed.
Mono-incineration 3	Digestion, dewatering, drying and incineration in a fluidised bed.

Co-incineration

Co-incineration 1	Digestion, dewatering and incineration in a lignite-fired power station
Co-incineration 2	Digestion, dewatering, drying and incineration in a cement works/coal-fired power station.

Five phosphorus recovery processes were evaluated in the Phobe life-cycle assessment and compared to a reference mono-incineration (with phosphorus recovery) and agricultural use. Three processes are adopted for analysis in this paper:

- P-ROC: phosphorus recovery from bypass flow;
- Phoxnan: phosphorus recovery from raw sludge;
- Pasch: phosphorus recovery from ash.

3.3. Methodology

3.3.1. Modelling approach

A thermal facility is modelled by calculating incineration on the basis of the elementary composition of the applied sewage sludge (in terms of the equivalency process it is based on the composition of the substituted conventional fuel). In addition, the calculation is based on the average grade of release of the elements balanced as contaminants, as well as on the kind of incineration in case of the exhaust gas contents which are linked to the exhaust gas volume (e.g. NO_x). The facility specific reductions are then applied to the resulting raw gas in the respective flue gas cleaning cascade. In addition, the solid material flows (partly in form of wastes to disposal, partly to recycling) and the effluents, including their substances, are calculated. It is important in this context to take into account the typical N_2O emissions from the stationary fluidised bed incineration system. Considering the empirical data from different facilities, a figure of 180 mg/m^3 is applied here.

Energy use is designed to gain a maximum proportion of electrical energy following the withdrawal of low pressure steam for the drying process. The surplus of produced electrical energy is credited for substituting the average German fossil-based grid mix. The same holds true for the electrical energy produced in anaerobic digestion via micro CHP. Surplus heat partly substitutes for a conventional mix for the production of thermal energy.

The phosphorus recovery processes are modelled according to their energy and resource consumption, as well as their product yield. The phosphorus contained in the product is fully credited with the substitution of the respective amount of standard phosphorus fertiliser.

3.3.2. Impact assessment and valuation approach

In order to aggregate the generally very comprehensive inventory data into a rational quantity of evaluated data all substances emitted to, or withdrawn from, the environment with the same impact are combined (classification, e.g. carbon dioxide and methane contribute to global warming potential). If the extent to which the different substances contribute to the respective impact is known they can be aggregated, taking into account the respective equivalency factors (characterisation, 1 kg fossil methane causes the same impact as 27.8 kg fossil carbon dioxide).

The selection refers to comparable life-cycle assessments dealing with sewage sludge disposal. In addition to basic issues such as resources, global warming potential, acidification and eutrophication, the human toxicity category is also observed. This is represented by the mercury indicator in the studies shown here. The fossil resources in the resources group are quantified in study [1]. However, it should be noted that in the context of sewage sludge treatment the **phosphorus resources** indicator always plays an important role. In study [3] this indicator is examined as a function of the respective phosphorus recovery processes, while noting the changes in the other indicators.

The assessment approach applied here was developed at the German Federal Environment Agency [8]. It is based on two ISO 14042 elements:

Standardisation (specific contribution):
How significant are the differences between the systems when compared to the current total emissions and consumptions in Germany, respectively? This is expressed here by absolute numbers with the unit *resident equivalents* (REQ). The REQ reveals the average per-capita impacts caused by a citizen in Germany (e.g. 11.3 Mg CO_2 equivalents per year).

Ranking (ecological hazard and distance to protection target)
What is the significance of the individual criteria according to the state-of-the-science and public or political sensitivity – also considering political target achievement?

4. Results

4.1. Results of comparing incineration options

Due to the comprehensive system borders the results are analysed according to the respective processes and subsystems dominating the results. This is carried out using a sectoral analysis. Environmental impacts can thus be assigned, weak points can be recognised and optimisation potential easily developed.

Impact assessment

As an example, the global warming potential impact assessment results from the study [1] are shown below. In doing so the results from the system of sewage sludge disposal (comprising production of sewage sludge until disposal of the incineration ashes) and from the substituted equivalency processes (credits) are outlined separately. The numbers refer to a sewage sludge quantity of 30,000 Mg dry substance.

It is clear from Figure 2 that, with the exception of raw sewage sludge incineration, all options achieve a net reduction. The crucial point for the comparatively bad score for raw sludge incineration lies in the high proportion of back-up firing using fuel oil, a fossil fuel, the energetic use of which cannot be compensated by far by the electric efficiency factor of sewage sludge incineration and the associated grid electricity feed-in. The options utilising anaerobic digestion and efficient utilisation of digester gas show clearly better results.

Overall, mono-incineration falls behind slightly, because of the higher N_2O emissions compared to co-incineration. Furthermore, co-incineration scores better in the greenhouse gas balance due to the direct substitution of a CO_2 intensive primary fuel (lignite/anthracite), whereas here the options with drying and with substitution of anthracite perform best (co-incineration 2). Clearly less CO_2 is emitted by the input of fuel oil for the drying process to 85 % dry mass compared to the reductions by the substitution of CO_2 intensive anthracite thanks to the according rise in heat value.

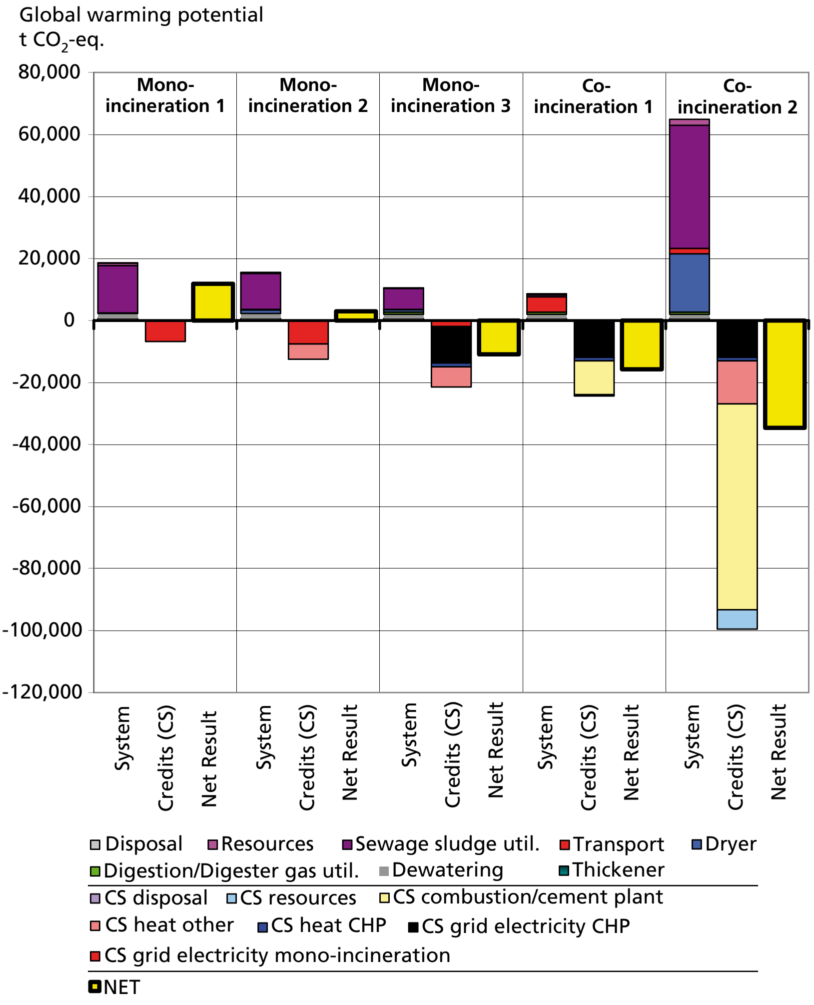


Figure 2: Results of the observed systems for the impact category global warming potential with regard to 30,000 Mg TR dry matter of sewage sludge

Standardisation and ranking

In Figure 3 the net results of the impact assessment are revealed as numbers normalised to specific contributions. Therefore the REQ unit is used. Example: the disposal of sewage sludge in the mono-incineration 1 option causes direct impacts amounting to 18,600 Mg CO_2-eq. for the entire system, but on the other hand saves 6,800 Mg CO_2-eq. via power and heat production. The net balance is thus 11,800 Mg CO_2-eq. Dividing this number by the average impact per inhabitant (11.3 Mg CO_2-eq./year) leads to impact per inhabitant 1,000 REQ.

From Figure 3 it becomes obvious to what extent the mercury toxicity indicator dominates the balance. While the differences between the options in all other categories range between 100 and 6,500 REQ, the differences between co-incineration in power stations or cement plants and mono-incineration are calculated to be around 200,000 REQ with regard to mercury.

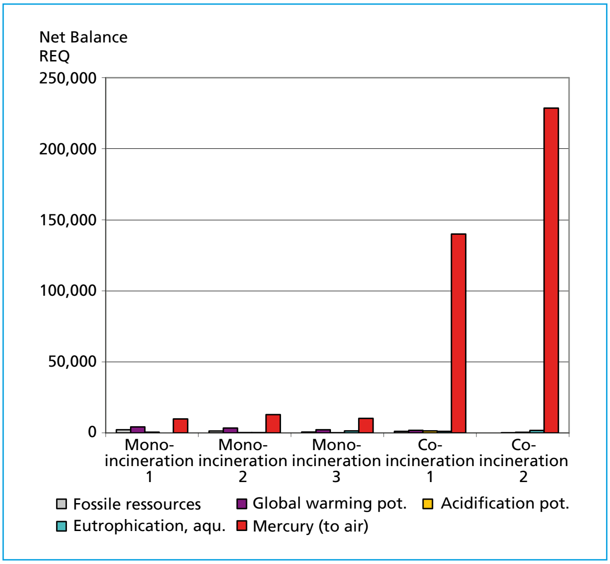


Figure 3:

Net standardised results of the impact assessment in resident equivalents (REQ) referring to the respective best system (= zero value) with regard to 30,000 Mg dry matter of sewage sludge

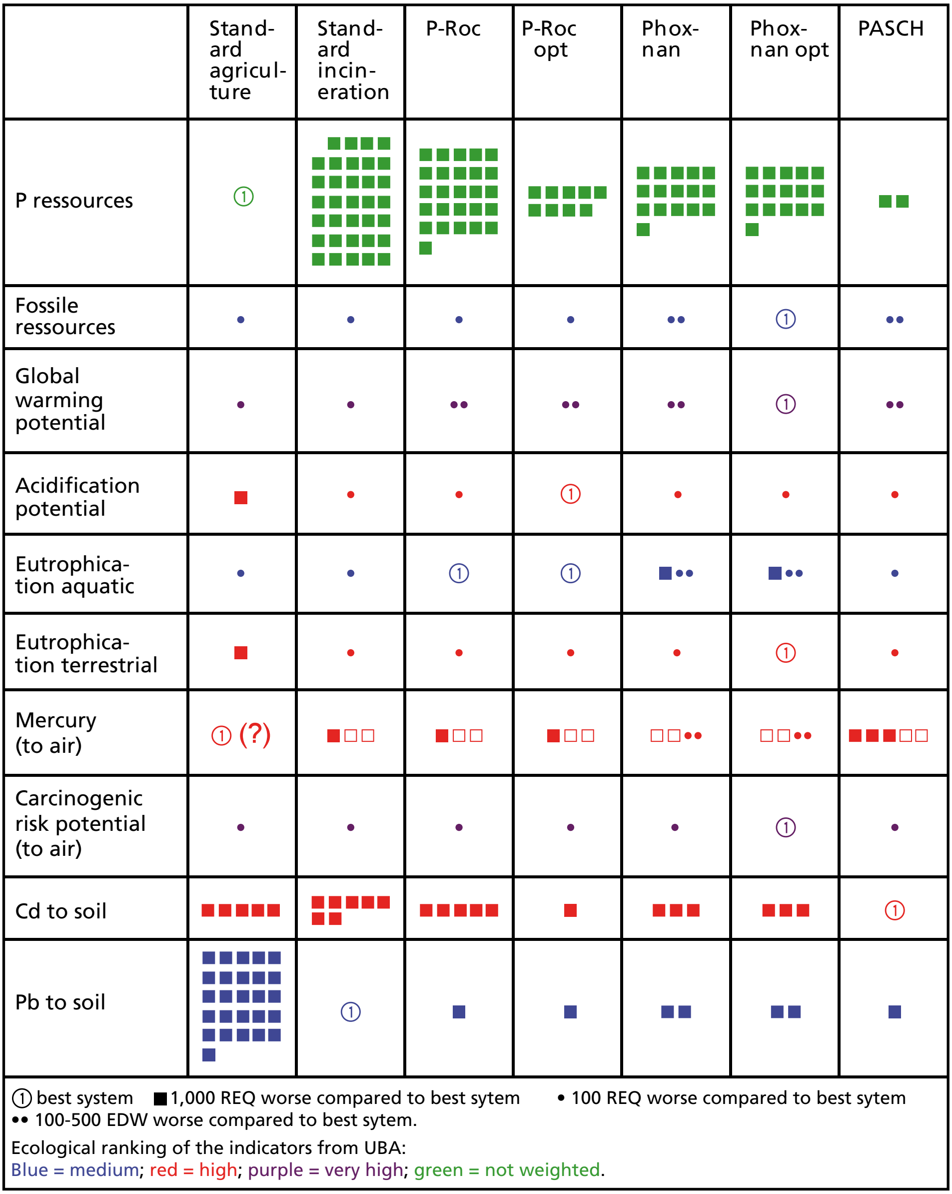
Compared to previous IFEU life-cycle assessments from, mercury thus increases greatly in significance in terms of the specific contribution. The reason for this is that the updated Federal Environment Agency inventory data [9] displaying 4.05 Mg Hg-total emissions in Germany in 2007 form a new basis, displacing old 1995 figure based on even older data, having amounted to 31 Mg/year Hg-total emissions.

In order to evaluate the results below mercury, only global warming, acidification, eutrophication potential and fossil resources are considered. On basis of these four categories alone and considering the great ecological significance of global warming potential, the following conclusions were drawn:

- Co-incineration 2 presents an overall advantage,
- Mono-incineration 3 follows up as next group,
- Co-incineration 1 follows closely,
- Mono-incineration 1 and 2 represent the final group.

4.2. Results of phosphorus recovery systems

The results of study [3] are presented below. This study is based on 2,920 Mg of sewage sludge in dry matter, correspondent to 100,000 population equivalents. In Figure 4 the normalised differences between the various systems are shown in a tile diagram. The more tiles a system has the worse it is compared to the best performing system with regard to the respective impact category, with one tile corresponding to 1,000 REQ. It is clear that the differences between the systems are mainly relevant in the phosphorus resources and lead input into soils categories, followed at a distance by cadmium input into soils and mercury emissions to atmosphere, as well as aquatic eutrophication potential and acidification potential. In



	Standard agriculture	Standard incineration	P-Roc	P-Roc opt	Phoxnan	Phoxnan opt	PASCH
P ressources	①	■■■■ ■■■■■ ■■■■■ ■■■■■ ■■■■■ ■■■■■ ■■■■■	■■■■■ ■■■■■ ■■■■■ ■■■■■ ■■■■■ ■	■■■■■ ■■■■	■■■■■ ■■■■■ ■■■■■ ■	■■■■■ ■■■■■ ■■■■■ ■	■■
Fossile ressources	•	•	•	•	••	①	••
Global warming potential	•	•	••	••	••	①	••
Acidification potential	■	•	•	①	•	•	•
Eutrophication aquatic	•	•	①	①	■••	■••	•
Eutrophication terrestrial	■	•	•	•	•	①	•
Mercury (to air)	① (?)	■□□	■□□	■□□	□□••	□□••	■■■□□
Carcinogenic risk potential (to air)	•	•	•	•	•	①	•
Cd to soil	■■■■■	■■■■■ ■■	■■■■■	■	■■■	■■■	①
Pb to soil	■■■■■ ■■■■■ ■■■■■ ■■■■■ ■■■■■ ■	①	■	■	■■	■■	■

① best system ■ 1,000 REQ worse compared to best sytem • 100 REQ worse compared to best sytem
•• 100-500 EDW worse compared to best sytem.

Ecological ranking of the indicators from UBA:
Blue = medium; red = high; purple = very high; green = not weighted.

Figure 4: Net standardised results of the impact assessment in resident equivalents (REQ) referring to the respective best system (= zero value) with regard to 30,000 Mg dry matter of sewage sludge

all further categories such as global warming potential, fossil resources and carcinogenic potential, the differences between the systems amount to less than an 200 REQ. Consequently, relevant amounts of phosphorus can be recycled by means of systems including phosphorus recovery in comparison to mono-incineration without phosphorus recovery efforts (standard incineration). The environmental impacts caused by the phosphorus recovery processes are low. Processes recovering phosphorus from ash tend to recover the largest amount of phosphorus. At the same time, the environmental impacts rise due to the greater effort required. Agricultural application of sewage sludge (standard agriculture) holds the biggest phosphorus recovery rate, where a relevant quantity of contaminants is simultaneously added to soils and ammonia emissions entail acidification potential.

5. Conclusions

The results can be sorted into two levels after analysing the life-cycle assessment results:

- In the mercury emissions toxicity indicator, **considerable advantages** of **mono-incineration** and co-incineration in a **MSWI** can be seen compared to co-incineration in coal-fired power stations and cement works. The normalised intervals are a hundred orders of magnitude greater than for the remaining impact categories.
- In the greenhouse effect, acidification and aquatic eutrophication categories, the **differences are comparatively small** for all options.

On this basis **the core result of mono-incineration is that it provides a considerable advantage**, compared to co-incineration in coal-fired power stations and cement works. In previous life-cycle assessments by IFEU on sewage sludge treatment the interval between these basic options was seen to be tighter, because the normalisation base for mercury at that time was based on out-of-date emissions inventories for calculating average impact per inhabitant.

Moreover, it can be seen from the results that systems utilising digestion instead of raw sludge incineration fare more favourably, in particular as a result of the greenhouse gas balance.

Relevant quantities of phosphorus can be extracted from sewage sludge using the phosphorus recovery processes described. Compared to the direct application of sewage sludge to fields, less phosphorus can be utilised using the described phosphorus recovery routes, but there is a relevant reduction in contaminant input into soils and atmospheric ammonia emissions. Compared to sewage sludge incineration without phosphorus recycling, no relevant, additional contamination occurs in the phosphorus recycling routes, with the exception of atmospheric Hg emissions and eutrophying water emissions. If conservation of the phosphorus resource is given a high ranking, processes and process combinations such as those described will very probably set ecologically compatible standards for the future management of phosphate sources such as sewage sludge.

6. Literature

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