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LCA on wastewater and sludge management for local decision-making in Gothenburg – are new LCA method developments enough?

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Abstract: This paper describes an LCA study that was made to inform decision-makers in Gothenburg about two different sludge management options. Incineration of anaerobically digested sludge with recovery of a phosphorus fertiliser product seemed preferable to using pasteurised anaerobically digested sludge in agriculture. Aspects under the control of the decision-makers were important for overall results, and caused the main differences between the studied systems, indicating considerable potential for local improvement efforts. Applying a human toxicity characterisation method with a more sludge specific fate model were important, but not crucial, for the results. However, the results are connected to large uncertainties and remaining challenges are discussed in the paper.

Keywords: life cycle assessment; decision-making; sewage sludge; biosolids

Introduction

Life cycle assessment (LCA) has been used to inform decision-making over almost three decades, and for the wastewater treatment sector almost as long (Tillman, 1998). However, although considerable effort is put into performing LCA studies, Corominas *et al*. (2013) found that only 34% of LCAs on wastewater treatment adequately discuss the interpretation of the LCA results. This could lead users of the results to either over- or underestimate their usefulness as decision support on environmental consequences.

The aim of this study was to evaluate the potential for using LCA for strategic decision-making in a local context - to guide decisions on the sludge handling in the wastewater treatment plant (WWTP) Ryaverket in Gothenburg, Sweden. A special focus was put on the implementation of new developments in LCA methodology for increasing the relevance of the LCA for assessing sludge use in agriculture, e.g. through a more context specific human toxicity assessment. Awaiting new national sludge legislation (Swedish EPA, 2013), building knowledge and educating decision-makers were in focus, rather than establishing a decision basis for an actual pending decision. The study therefore needed to clearly communicate which perspectives the LCA could and could not bring, to enable the decision-makers to plan for complementary studies and perspectives.

Method

Svanström *et al.* (2017) compared several future alternatives for sludge treatment and handling from Ryaverket, using the LCA method, assessing climate impact (global warming potential, GWP), acidification (acidification potential, AP), eutrophication (freshwater, marine and terrestrial eutrophication potential, EP) and smog formation (photochemical oxidant formation potential, POFP). They concluded, however, that a more extensive LCA was needed, especially to also address human toxicity impacts in the assessment. Human toxicity potential (HTP) was not included in their initial study due to uncertainties regarding the appropriateness of available methodology for assigning this type of system. The current study further evaluated two of the sludge handling alternatives assessed by Svanström *et al*. (2017), by putting them in a larger studied system, together with the wastewater treatment processes generating the sludge at Ryaverket, and tested two new method developments for making LCA more context-specific, and thereby e.g. enable assessment of human toxicity. The new method SLAtox (Harder *et al.*, 2016), until now untested in a full LCA, improves the specificity of human toxicity impact assessments for the specific situation of sludge use on arable land. It uses effect factors from USEtox (Rosenbaum *et al*, 2008, Hauschild *et al*, 2008, Rosenbaum *et al*, 2011), the International Reference Life Cycle Data System (ILCD) Handbook's recommended LCA method for toxicity (EC-JRC, 2011), but employs a fate model which is more specific for human exposure resulting from sludge use on arable land compared to e.g. USEtox. New methods have also been developed by Heimersson *et al*. (2017), to consider other potentially beneficial additions to the soil (e.g. organic carbon and micronutrients) in the LCA, in addition to the nitrogen (N) and phosphorus (P) commonly accounted as resources from sludge in previous studies. Their new way of accounting for such benefits by accounting for replaced crop production were applied in this study as well.

The two studied routes are described in Figure 1. In the 'the incineration system' the wastewater is biologically treated in order to remove N, P is chemically precipitated, and the generated mixed primary and secondary sludge is pasteurised, anaerobically digested, dewatered and stored to obtain hygienisation, and finally applied to arable land. In 'the pasteurisation system' the digested sludge is instead incinerated before phosphorus is recovered and used as a fertiliser product. The operation of the plant was in focus (construction was not included).

Goal of the LCA: The goal of the LCA was to assess the environmental performance of the wastewater management in the Gothenburg region, with different sludge handling strategies. Treatment of 1 tonne of sludge (on a dry basis) delivered to the digester was chosen as the functional unit. The LCA was performed to inform local decision-makers in Gothenburg on the importance for the overall environmental impact from the wastewater management of having principally different options for sludge handling, in an early stage of a decision-making process.

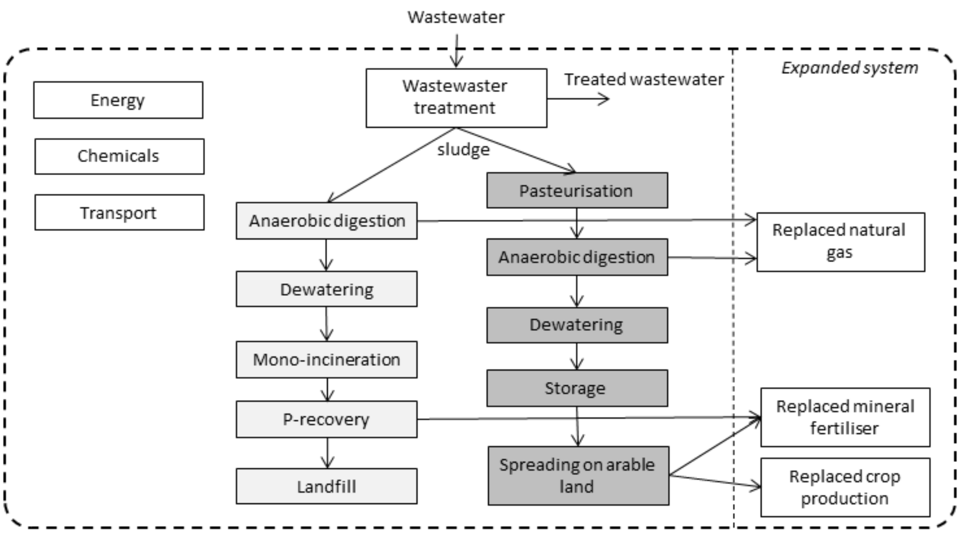

Figure 1 Schematic description of the studied systems. Light grey boxes belong to the incineration system and dark grey boxes belong to the pasteurisation system.

The two systems are studied at their current level of technological development, and with environmental impacts of the operation of the studied wastewater treatment and sludge handling in focus, rather than the effects of a change in sludge handling practice. It is made to inform decision-makers responsible for the specific studied treatment system and its environmental impact. In order to avoid introducing the large uncertainties of marginal modelling of background systems, an attributional LCA approach was chosen, in line with the argumentation by Heimersson *et al*. (2019). The choice of an attributional approach meant that average market production processes were considered rather than marginal ones for inputs like electricity and chemicals. However, for practical reasons, secondary functions of the system were accounted for by substituting average production and use of a conventional product.

Life cycle impact assessment (LCIA): GWP, AP, freshwater, marine and terrestrial EP, POFP and cancer and non-cancer HTP were assessed, using the midpoint indicators recommended by the ILCD Handbook (EC-JRC, 2011). The sensitivity of the HTP assessment to toxicity modelling was studied by evaluating the importance of choosing either USEtox or SLAtox for characterising emissions relating to sludge use in agriculture.

Life cycle inventory: In addition to the studied function (handling of the sludge from wastewater treatment), both studied systems generate digester biogas (assumed to replace natural gas in heavy vehicles) and deliver P to arable land, and the pasteurisation system also provides N to arable land (both assumed to replace mineral fertilisers), as well as organic material and micronutrients. The lower of the two estimates of replaced crop production by Heimersson *et al*. (2017) was used in the current study, as the organic content of soils within reasonable transport distance from Ryaverket was considered low enough for the addition of sludge to give an increase in soil organic carbon that potentially could result in increased crop yields.

Primary inventory data on the existing processes at Ryaverket were used as far as possible (Mattsson (2015), Swedish EPA (2015) or supplied by Gryaab). For the human toxicity assessment, data are from an inventory made by Harder *et al.* (2016) for the inventory on wastewater and sludge, Lederer & Rechberger (2010) for transfer coefficients for metals in the incineration system and Nielsen *et al*. (2013) for other substances formed during incineration. The characterisation of cancer and non-cancer HTP from the foreground system was based on 15 heavy metals (emitted through the WWTP effluent and from the sludge during incineration or after spreading on soil) and 106 organic micropollutants (from the sludge on arable land), which is beyond common practice. In this study, it is assumed that all the heavy metals detected in the sludge are bioavailable, which may be a pessimistic assumption. The importance of this assumption was therefore tested using sequential extraction data from Zufiaurre *et al*. (1998) (for anaerobically digested sludge). Other data on the studied sludge treatment systems were taken from the inventory by Svanström *et al*. (2017).

The Gabi Software was used for generating LCIA results. Background processes were mainly from the Gabi Professional database.

Results and Discussion

The LCA results, see Figure 2, can provide decision-makers in Gothenburg with some important insights, described in the following sections. The results in Figure 2 are normalised against the largest negative or positive impact within each impact category, in order to allow for displaying the results in one figure with as much detail as possible.

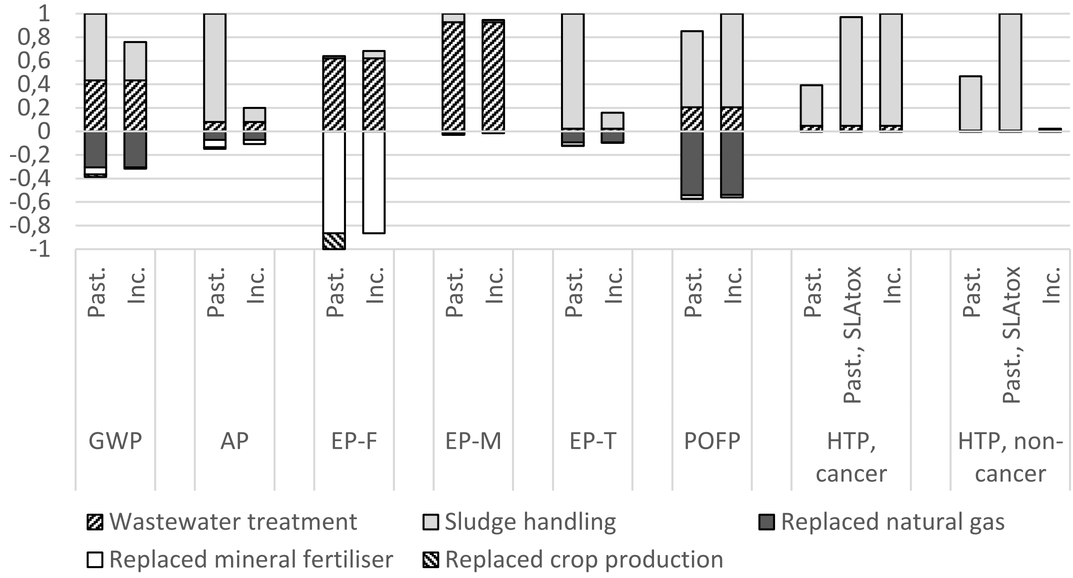

Figure 2 LCIA results for the pasteurisation (Past.) and incineration (Inc.) systems, for the assessed midpoint indicators. The results are normalised against the largest negative or positive bar for each impact category. Sludge handling corresponds to the grey boxes in Figure 1. 'Past., SLAtox' implies that SLAtox is used for emissions through sludge on soil (USEtox 2.0 is still used for the remaining system), as a sensitivity analysis.

The decision-makers have the power to influence the environmental impact from the systems. Figure 2 shows that the choice of sludge handling route has large impact on the LCA results, as has the resource utilisation of energy and nutrients.

Emissions originating from the sludge, during storage and after application on land, are important contributors to AP, terrestrial EP and HTP results, and are the main reason to the differences between the systems. AP and terrestrial EP results for the pasteurisation system are strongly affected by ammonia emissions from sludge during storage and after spreading on land; such emissions are low in the incineration system. Human toxicity results were dependent on heavy metal emissions. The toxicity results, and uncertainties in the assessment, are further discussed later in this chapter.

Resource utilisation, as a consequence of the choice to upgrade the biogas and use it as vehicle fuel and to use the sludge as organic fertiliser, make important contributions, most notably for the GWP, freshwater EP and POCP results, by replacing conventional natural gas, mineral fertiliser (in particular N) and crop production. However, it should be kept in mind that accounting for the benefits in terms of the substitution for additional crop production has only recently been suggested for LCA (Heimersson *et al*. 2017). The quantification is based on a limited amount of data and the assumption that the local conditions provide such opportunities; there is access to arable land at farms without manure production within reasonable transport distance, and with soils with relatively low SOC. This opportunity to make an LCA specific for the decision context is one of the method's major benefits, but also limits the usefulness of the study beyond the intended context and audience. Freshwater EP results depend on P-containing emissions, but since the effluent is considered to be released to the sea in our case, the applied method does not assign a large impact to the emissions through the WWTP effluent.

All of the above can be influenced by the targeted decision-makers, e.g. by source reduction efforts for wastewater pollution (see e.g. the Swedish industry initiative Revaq (2016)), modified treatment processes (see e.g. Svanström *et al*. (2017)) or modified practices for storing and land-applying sludge (see e.g. Willén *et al.* (2017) or Yoshida *et al*. (2015b) for the potential impact from storage under different conditions).

Results are uncertain. The HTPs for the pasteurisation system is dominated by heavy metal emissions through the sludge use on arable land. The major contribution to the cancer HTP comes from chromium (Cr), mainly Cr(VI), which has been assumed to constitute only 2% of the total Cr, in accordance with assumptions on Cr speciation in wastewater (Yoshida *et al*. 2015a). The dominating contribution to non-cancer HTP comes from zinc (Zn). For the incineration system, Cr(VI) emissions constituted the major cancer HTP contribution (15% of the Cr in the incineration flue gas is assumed to be Cr(VI) (Environment Australia, 1999), the same fractions were also assumed in the ash granules, an uncertain assumption which showed to be important for the results), and Zn the major non-cancer HTP contribution. The HTPs was dependent on a few substances (in particular Zn and Cr), but not necessarily the ones of primary concern in local quantitative risk assessments (see discussion in Harder *et al*. (2016)) or of major concern to Swedish stakeholders (Bengtsson & Tillman, 2004). A similar dependence on Zn were found also in other studies on wastewater systems (Heimersson *et al*, 2016, Yoshida *et al*, 2015a) and in other contexts (Nordborg *et al*, 2017, Sörme *et al*, 2016).

The sensitivity analysis showed that the human toxicity results were sensitive to the fate modelling done in the characterisation method, as can be seen in Figure 2, when comparing the human toxicity results using USEtox (the system denoted Past. in the figure) to results when using SLAtox. Despite only accounting for exposure through ingestion of above ground and below ground produce (but with a fate model developed to be more specific to sludge application to arable land than USEtox) SLAtox exhibits higher HTP, due to higher intake fractions. Varying the bioavailability of the heavy metals had, however, limited impact on the results.

As pointed out by Harder *et al*. (2016), sludge contains a large number of chemicals. Many of these are not included in the current LCA due to limited data availability. Although all the metals of principal concern to stakeholders are included here, there is thus a possibility that the LCA results may underestimate the toxicity-related risk. On the other hand, long-term field studies in the south of Sweden regarding sludge application on arable land (Andersson, 2012) point towards a lower plant uptake of metals than currently modelled in LCIA, and since the impact calculated in this LCA is dominated by metals, this suggests that the results shown here could be overestimated. The modelling of metals in USEtox is discussed further by e.g. Jolliet & Fantke (2015). A need for toxicity assessments beyond LCA is highlighted, especially since human toxicity related to exposure through the use of sludge as organic fertiliser on arable land is an issue of great concern to many stakeholders.

Other types of uncertainties, such as uncertainty in inventory data, have not been quantified, but should be taken into account qualitatively when interpreting the results in Figure 2. A review by Heimersson *et al.* (2019) showed that the majority of LCAs on wastewater treatment systems do not quantify uncertainties, however such information could, in many cases, improve the interpretation of the results.

The incineration system generally performed equal or better than the pasteurisation system. Compared to the study by Svanström *et al*. (2017) the studied system is, in the current study, enlarged to include the wastewater treatment, in addition to the sludge treatment. This resulted, for example, in that the difference in marine EP between the systems decreased in importance, due to the marine EP result's heavy dependence on the N emissions through the effluent (which was earlier outside of the studied system).

The incineration system showed lower AP, terrestrial EP and non-cancer HTP impacts than the pasteurisation system, see Figure 2. For the remaining assessed impact categories the results showed no large differences between the systems. The contributions of this study beyond common LCA practice, i.e., consideration of replaced crop production and the HTP assessment, proved important for the results, but were not crucial for the overall comparison between systems. Overall, the conclusions on the comparison between systems drawn by Svanström *et al*. 2017 were not changed by this more extensive assessment. However, as discussed above, there are still large uncertainties in important parts of the inventory data and the impact assessment.

Not all environmental and human health aspects relevant for a decision on future sludge strategy in Gothenburg could be satisfactorily covered in the LCA. Some possibly relevant impact categories have been left out of this study. LCIA methods exist for assessing e.g. abiotic resource depletion (ARD), ecotoxicity potential and energy consumption. ARD could have contributed to broadening the perspective on the value of the mineral P fertiliser replacement, but the exclusion of production capital in the inventory reduces the meaningfulness of ARD results. Emerging LCA characterisation methods for risks connected to odour or pathogens may be useful, when inventory data can be found. The impact of odour from wastewater or sludge management has never been quantified in an LCA case study, but recent work on manure odours could prove useful (Peters *et al*., 2014). Harder *et al*. (2014) used QRA-inspired calculations for pathogens in LCIA to provide a rough estimate of the pathogen risks of a general wastewater treatment scenario where sludge was applied to arable land.

For several reasons, LCA alone does not provide enough information to evaluate if the impact on human health and the environment from an activity, such as sludge use on agricultural fields in a particular region, is to be considered as safe, due to a number of inherent characteristics of LCA; 1) it usually only addresses normal operating conditions, 2) it does not compare impact results to threshold limits, and 3) the HTP assessment does not differentiate between one person being exposed to large amounts of a substance, and many people being exposed to smaller amounts (Harder *et al*., 2015) To inform decision makers regarding the local risks of sludge use in agriculture, the decision basis needs to be complemented with, e.g., a QRA or direct field studies. Similarly, LCA disregards the sensitivity of the local environment, e.g. in the Gothenburg water recipient, in favour of a more general assessment.

The fact that LCA cannot serve as the exclusive basis for the assessment of consequences to human health and the environment, of the studied sludge management options, needs to be stressed as people are prone to perceive impacts that we can quantify as more certain than those that we cannot; the latter may even be completely disregarded. The purpose of assessing e.g. toxicity in the LCA framework is not to replace other local quantitative risk assessments. However, LCA is a method that, with a reasonable effort from the analyst, enables a generalised assessment of different types of impacts in different types of systems. The life cycle perspective and the assessment of several types of impacts under the same system boundaries do bring important perspectives to strategic planning of the sludge handling in Gothenburg.

Conclusions

The LCA could provide decision-makers in Gothenburg with some important insights. Aspects that they can control, such as how digested sludge is further treated and used, proved to be important. The main differences between the two studied systems were an effect of emissions originating from the sludge, again highlighting the potential for the decision-makers to affect the environmental performance of their systems by active management. It can be concluded that the incineration system in general performed better than the pasteurisation system, but that this result is connected to large uncertainties. Applying a human toxicity characterisation method with a more sludge specific fate model did not alter the results. However, a need for toxicity assessments beyond LCA was highlighted.

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