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Improved life cycle modelling of benefits from sewage sludge anaerobic digestion and land application

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ABSTRACT

Nitrogen, phosphorus and organic matter are valuable resources in sewage sludge. Life cycle assessment (LCA) can be useful for comparing the potential environmental risks of sludge management strategies to their potential environmental benefits. With growing interest in resource recovery from sludge, there is an increasing need to properly account for the benefits that can be achieved, and to handle the multi-functionality issues that then arise in LCAs. So far, both of these aspects have often been handled in a generic and seemingly arbitrary way.

The study identified and explored several alternative approaches to handle the multi-functionality in the LCA of a sludge handling system that generates both biogas and a sludge that is used on arable land; either through avoiding allocation by substituting for avoided products or services (e.g. fertilisers and natural gas), or by allocating the impact from the studied system between its functions based on economic terms. The choice of approach strongly influenced the overall LCA-result for the studied system, in particular for some of the studied impact categories. Although an attempt was made to apply economic allocation in this article, it can be concluded that no coherent basis for applying allocation was identified. Substitution was more easily applied, however, the results were highly dependent on the product assumed to be replaced by biogas and the modelling of avoided mineral fertiliser use. The previously neglected benefits related to organic matter provided by the sludge to arable land were potentially as important as the benefits of the nitrogen and phosphorus, although the quantification of such effects will need further refinement, and are only relevant for certain soil conditions.

1. Introduction

In the EU-27 states alone, about 10 million tonnes (metric tons) of dry solids of sewage sludge (in this paper "sludge") is generated yearly (Milieu Ltd et al., 2010). As sludge in general has a heating value of 21 MJ/kg dry matter (for activated sludge) and contains 1.5–5% nitrogen (N) and 0.8–1.1% phosphorus (P) (Metcalf & Eddy Inc et al., 2004) and large amounts of carbon (C), previous disposal methods such as landfilling of sludge are increasingly seen as a loss of potential resources, and focus is gradually shifting towards utilisation of these resources, for example through recovery of energy, materials or nutrients (in the future, even other types of resources, such as trace amounts of metals, could become worth recovering (Westerhoff et al., 2015)).

Sludge treatment through anaerobic digestion followed by spreading on arable land is today a common way to deal with sludge and it enables use of resources in sludge in two ways, through the digester biogas and through the valorisation of the nutrients and organic matter in the digester sludge. Biogas can e.g. be combusted to generate electricity and/or heat that can be utilised internally in the wastewater treatment plant (WWTP) or be sold, or be used as a vehicle fuel. Utilisation of sludge as an organic fertiliser on arable land has been shown to increase agricultural productivity in numerous studies (see Singh and Agrawal (2008) for a review). Use of sludge on arable land can provide both N, P and other nutrients and thereby recycle nutrients in society, which is consistent with the aim of developing a circular economy, and can also contribute to maintaining the concentration of soil organic carbon (SOC) (Brady et al., 2012). However, the use of sludge in food production is also associated with risks due to the heavy metals, organic micropollutants and pathogenic microorganisms in sludge (VKM, 2009), and

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Abbreviations: C, carbon; K, potassium; LCA, life cycle assessment; N, nitrogen; P, phosphorus; WWTP, wastewater treatment plant.

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whether these risks are acceptable is debated. Generally, to fulfil national legislative requirements, the sludge needs to be hygienised before it can be applied to arable land, and there are also threshold limit values describing how much heavy metals and nutrients that can be applied to land (see e.g. EU Directive 86/278/EEC).

1.1. Modelling of agricultural sludge use in LCA

Life Cycle Assessment (LCA) is an assessment tool that can be used to quantitatively assess and compare the environmental performance of different products or services. It has been frequently applied in the context of wastewater treatment (Corominas et al., 2013). LCA can be used to compare environmental impacts of different types of sludge handling and can, together with other types of information such as from quantitative risk assessments, support decisions on the environmentally preferable way of handling sludge. But to provide valuable decision support, LCA methodology needs to be able to both assess negative impacts of the sludge management and account for potential resource recovery. The environmental impacts of sludge use in agriculture have recently attracted attention in several modelling studies, e.g. for toxicity assessments (Harder et al., 2016) and pathogen risk (Harder et al., 2014). Heimersson et al. (2016) showed that the modelling of N, P and major C flows originating from the wastewater is very important in LCA, since the type of wastewater treatment process determines whether they end up as an emission, contributing to environmental impacts, or as a resource flow and thereby possibly lowering or counteracting environmental impacts from the assessed system.

1.2. Accounting for secondary functions during sludge treatment

The increased focus on resource recovery from wastewater and sludge during recent years results in the fact that a wastewater and sludge management system is increasingly multifunctional. A system in which sludge treatment and end-use is the main function, and with secondary functions such as production of biogas and a soil fertiliser and conditioner, is an example of such a multi-functional system. When such systems are assessed, estimates need to be made on how much environmental burden that is to be attributed to the main studied function; this depends on how the multifunctionality is handled and how large the benefits from the resource recovery are considered to be. According to ISO 14044:2006 the preferred analytical approach is to inventory the studied system in enough detail that each flow can be connected to a particular function. However, if any of the processes in a studied system delivers several functions, such subdivision is not possible. For the multifunctional system described above, the digestion can be considered to occur in order to (1) reduce the mass of sludge, (2) generate biogas for use as an energy carrier and (3) stabilise the sludge before agricultural use. Further, the application of sludge on arable land occurs in order to (1) dispose of the sludge, (2) provide nutrients and organic matter to the soil and (3) handle by-products from the biogas production. It is thus impossible to subdivide the system in order to solve the multi-functionality problem. In such cases, ISO14044:2006 recommends to expand the studied system to also include the functions provided by the co-products. This may be interpreted as expanding the functional unit to account for all functions (sometimes referred to as system expansion) (Heijungs, 2014) or to give the system a credit for the secondary functions by awarding the system negative emissions or avoided resource use corresponding to the avoided product or service that the secondary functions replace (e.g. the avoided production and use of mineral fertilisers replaced by sludge) (Koffler, 2014). The latter is referred to as substitution, and is a very common way to handle multifunctionality in LCAs on wastewater and sludge management. The least preferred option, according to ISO 14044:2006, is to allocate the burden between the different products or services. One of the products can then be considered to be responsible for the entire burden, or the burden can be allocated between the functions based on some relevant and comparable physical attribute, for example weight or energy content, or if that is not possible, on economic value. Allocation (partitioning) has not been tested earlier for a system like the one discussed above, as far as available literature reveals.

Other examples of guiding documents on multifunctionality issues are the ILCD Handbook (EC-JRC, 2010) and PAS 2050 (BSI, 2011). For a review on guidelines on how to treat multifunctionality related to co-production, recycling and energy-recovery see Schrijvers et al. (2016).

1.2.1. The benefits of digester biogas generation

If all the biogas is assumed to be consumed internally in the studied system, no multi-functionality issue will arise (e.g. if the biogas is used to heat the digesters). However, from a life cycle perspective, this may not be the environmentally preferable option, and depends on e.g. what other heating sources may be employed and the alternative use of the biogas. It is expected that biogas will increasingly be seen as a resource for which optimal use has to be decided on a case-by-case basis, and when biogas (or products from its combustion – heat and possibly also electricity) is used outside of the studied system, the multi-functionality that arises will have to be managed.

Heimersson et al. (2016) showed in a literature review that digester biogas is commonly accounted for assuming on-site combustion of the biogas that generates heat and possibly also electricity that is used internally at the WWTP as a first choice, but potential excess energy is often considered to be sold and to replace other means of heat and electricity production. Some exceptions are that Cao and Pawłowski (2013) assumed that biogas replaced diesel as a vehicle fuel while a few others (e.g. Mills et al. (2014)) assumed that it replaced natural gas production.

1.2.2. The benefits of sludge use on arable land

Heimersson et al. (2016) showed that a majority of reviewed LCA studies on wastewater and sludge management with agricultural sludge use accounted for the benefits of N and P on arable land, by crediting the studied system for the avoided production, and sometimes also the use, of mineral fertilisers. The remaining studies used EcoInvent datasets, in which the sludge management function is considered as waste treatment function that is allocated the full burden of the sludge treatment and land application processes, and no additional functions are accounted for. Heimersson et al. (2016) showed that the modelling of the amount of fertiliser that could be replaced by the sludge in a substitution approach is generally based on generic sludge-mineral fertiliser replacement ratios (the rate at which nutrients in the sludge is considered to replace mineral fertiliser nutrients, this can be on the basis of e.g. assumptions on plant availabilities) that are not specific for the conditions in the studied system.

In addition to accounting for the benefits that N and P can provide, a few studies also accounted for the value of potassium (K) or for the carbon sequestration in soil (carbon capture in soil is then assumed to contribute to reduced climate impact). One Australian study suggested a method to account for the increased water retention capacity that could result from sludge spreading, when assessing the impact category of water use (Peters and Rowley, 2009).

Increased SOC can increase crop yields, e.g. as it potentially increases soils' N mineralisation capacity (Hedlund, 2012) and it improves the soil structure and increases the cation exchange capacity which is important for the soils ability to hold nutrients