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Energy demand for phosphorus recovery from municipal wastewater

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Abstract

Phosphorus (P) is one of the essential nutrients for production of food. In modern agriculture, a large part of P comes from finite sources. There are several suggested processes for reuse of P from wastewater. In this paper, the energy use of direct reuse of sludge in agriculture is compared to the energy demand connected to use of mineral P and to reuse of P after thermal processing of sludge. The study is based on literature data from life cycle analysis (LCA). In the case of direct sludge reuse the sludge stabilization processes applied and the system boundaries of the LCA has a large impact on the calculated energy demand. The results though indicate that direct reuse of sludge in agriculture is the reuse scenario that potentially has the lowest energy demand (3-71 kWh/kg P), compared to incineration and extraction of P from sludge ashes (45-70 kWh/kg P) or pyrolysis of sludge (46-235 kWh/kg P). The competitiveness compared to mineral P (-4-22 kWh/kg P) depends on the mineral P source and production. For thermal processing, the energy demand derives mainly from energy needed to dry sludge and supplement fuel used during sludge incineration together with chemicals required to extract P. Local conditions, such as available waste heat for drying, can make one of these scenarios preferable.

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Keywords: incineration; combustion; pyrolysis; wastewater sludge; nutrient reuse.

1. Introduction

Phosphorus (P) is one of the essential nutrients for production of food. In modern agriculture, a large part of P comes from finite sources. The so-called mineral P is extracted from bedrock. Around two thirds of the mineral P in

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the world comes from mines in Morocco, China and the U.S. [1]. More than 80 % of the mineral P produced is used in agriculture [1]. In European agriculture, approximately 45 % of the nutrients comes from mineral fertilizers [2]. Other sources of P include manure, sewage sludge, food waste and slaughter waste. If all P contained in sewage sludge could be reused in agriculture, approximately 50 % of the mineral P could be replaced [3].

Many solutions for reuse of P from wastewater are emerging or implemented to different extent. The solutions include technologies that extract P from the produced sludge (e.g. extraction from ashes or wet extraction from sludge), technologies that capture P within the wastewater treatment process (e.g. struvite precipitation) and technologies that capture P "upstream" from the wastewater treatment plant (WWTP) (e.g. collection of P contained in urine). The potential of P reuse differs depending on where in the process the P is captured. The potential for recovery from ashes and sludge can be up to 90 %, while e.g. recovery potential from the liquid phase by precipitation of struvite or calcium monophosphide (CaP) is much lower (about 20%) [3, 4, 5].

Thermal processing of sludge is common in Europe. Reuse of the nutrients contained is though generally not established. Germany has required their 500 largest WWTPs to present a plan for P reuse by 2023, and the interest for thermal treatment is growing. In Sweden there is a similar trend and an investigation aiming at prohibition of sludge use in agriculture and demand for reuse of P was recently initiated. Implementation of thermal sludge processing is expected to have a large impact on the energy demand associated with nutrient reuse and wastewater treatment systems.

The aim of this paper is to investigate the energy demand of P recovery from municipal wastewater sludge, in the context of existing centralized advanced municipal wastewater treatment. The energy demand of direct sludge reuse is compared to the energy demand connected to use of mineral fertilizer P and to methods of P reuse from sludge incorporating thermal processing.

Several previous reviews on the resource recovery potential of municipal wastewater treatment have been made, e.g. Mo and Zhang [5] who considered energy recovery, water reuse and nutrient reuse. However, they did not include technologies based on thermal processing of sludge and they did not make a detailed comparison of energy demands. Reijnders [1] and Roy [6] reviewed P resources and recycling strategies, with wastewater considered as one important P source. A detailed review of the overall energy performance and appropriate energy measures for WWTPs was made by Longo et al. [7], who found that "the energy consumed at different stages of treatment and final disposal of sludge may represent a major fraction of the overall electricity balance for a plant". Syed-Hassan et al. [8] reviewed thermochemical processing (incineration, pyrolysis and gasification) as a disposal method for sewage sludge, but did not consider reuse of nutrients.

2. Method and material

Three different scenarios were compared from an energy perspective:

- scenario1: direct use of sludge in agriculture after stabilization, through e.g. composting, drying, or addition of alkaline material or other chemicals;
- scenario 2: use of fertilizer in agriculture produced from P extracted from ashes after drying and mono-incineration of sludge and
- scenario 3: use of biochar, produced from drying and pyrolysis of sludge, in agriculture.

Incineration and extraction of P from sludge ashes has the potential to produce a P-fertilizer product with very low contamination. Pyrolysis could remove parts of both organic pollutants and heavy metals contained in sludge, but also has the benefit that some of the organic matter is retained - a potential added value when the produced biochar is used in agriculture.

The study is based on literature data from studies made through life cycle analysis (LCA). To enable a comparison between previously performed studies, the data has been recalculated in units of kWh/kg P recovered/produced. Some studies for scenario 1 did not give the P-content of stabilized sludge. In those cases, sludge dry matter was assumed to contain 3 % P, as given by Turunen et al. [9]. In one study [10], the fuel used in the process was given in kg. This has been recalculated to kWh by using a heating value for heavy fuel oil of 11.61 kWh/kg oil [11] and for meat and bone meal 2.01 kWh/kg [12] assuming the latter to have similar heating value as biological industrial waste.

Besides comparing the energy demand of different P reuse options, the results allowed identifying key parameters of importance in comparison of the scenarios included.

3. Results and discussion

The results for scenario 1 are summarized in Fig. 1. There is a large variation in the energy demand according to the different studies. It is of importance which processes in the WWTP and which sludge-handling steps are included within the system boundaries for the investigations. The studied cases by Sablayrolles et al. [13], Amann et al. [4], Hospido et al. [10], Mininni et al. [14], von Bahr [15], Peters and Lundie [16] and Houillon et al. [17] all include biological and/or mechanical treatment (thickening, dewatering, composting, aerobic/anaerobic digestion and/or lime stabilization) of the sludge. Linderholm et al. [18] and Johansson [19] do not include the sludge treatment process, but consider the sludge as an existing, available resource (by-product from wastewater treatment), which only required transport and spreading. Amann et al. [4] and Minnini et al. [14] include energy demand for the whole WWTP in their investigations, which contributes to higher energy demand in those studies. As for Sablayrolles [13], Lundin et al. [20] and Houillon et al. [17] the energy demand is to a high proportion originating from the sludge stabilization (composting, pasteurization and liming respectively). If local legislation allows it, these could be possible to replace by more energy efficient stabilization options. Linderholm et al. [18] also calculated the possible energy credit from replacement of mineral nitrogen fertilizer (figures not presented here), which resulted in a net negative energy use for direct sludge reuse.

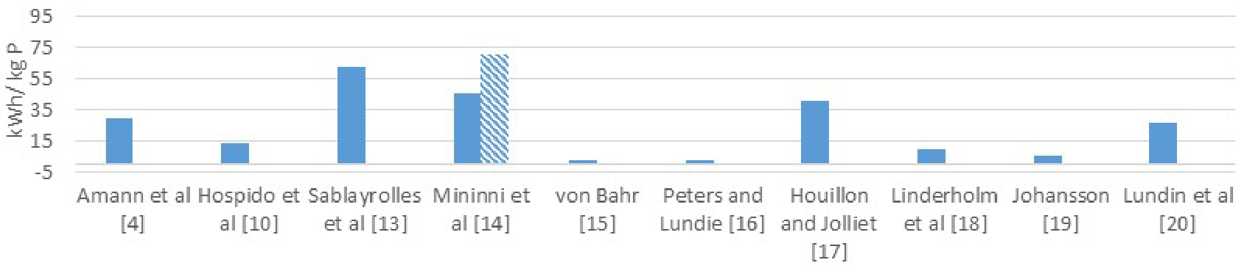

Fig. 1. Results for scenario 1 - direct use of sludge in agriculture. For Minni et al. [14] the filled column represents the case with the lowest energy demand and the dashed column represents the case with the highest energy demand. The results from Sablayrolles et al. [13] includes energy for additional fertilizers due to losses in the composting process. Hospido et al. [10] only consider the electrical energy demand.

Figure 2 show results for scenario 2. The studies Amann et al., Hospido et al. and Linderholm et al. [4, 10, 18] show similar results. Amann et al. [4] have included several possible extraction processes giving a range in the energy demand. A large part of the energy demand for incineration and extraction of P is connected to increased use of energy and chemicals compared to scenario 1, which gives results of similar order of magnitude in the different studies. The result according to [20] deviates from the other studies. The reason seems to be that they did not consider supply of support fuel for incineration and energy demand for production of chemicals used for extraction of P. In scenario 2 no credit for supply of nitrogen fertilizer, as Linderholm et al. [18] included in scenario 1, is possible.

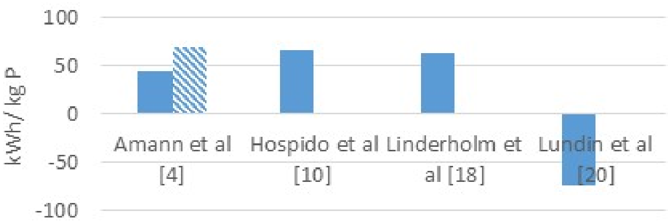

Fig. 2. Results for scenario 2 – use of fertilizer in agriculture produced from P extracted from ashes after drying and mono-incineration of sludge. For Amann et al. [4] the filled column represents the case with the lowest energy demand and the dashed column represents the case with the highest energy demand.

For scenario 3, Fig. 3, the main energy use originates from drying, which is required before pyrolysis. If waste heat from other processes could be utilized the energy demand could be drastically lowered [15]. In [10] and [17] the sludge is assumed to be disposed through pyrolysis at the WWTP, while [15] considers transport of sludge to a pyrolysis plant and spreading of biochar in agriculture.

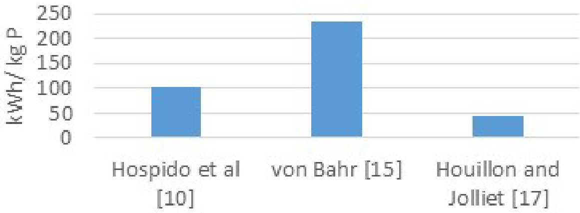

Fig. 3. Results for scenario 3 – use of biochar, produced from drying and pyrolysis of sludge, in agriculture.

Some LCA studies did not give the energy demand as a separate impact factor in their results, e.g. Hong et al. [21], who compared composting and agricultural reuse of sludge to incineration (without P reuse); unlike the most of the other studies they included production of equipment and the construction, transport and disposal of building materials in their system boundaries. They found that equipment production had a large overall environmental impact. Svanström et al. [22] compared (among other methods) agricultural use of sludge to incineration and extraction of P from ashes. They found incineration beneficial due to possible savings of oil and natural gas by production of district heat. Suh and Rousseaux [23] considered sludge treatment by composting, anaerobic digestion, lime stabilization or incineration, followed by landfill or agricultural use. They found that anaerobic digestion in combination with agricultural use was the option with least emissions and energy use.

Even though the results vary substantially between the studies, the comparison indicates that scenario 1 has potential to be the most energy efficient.

As shown in Table 1, different subsystems have been included in the energy demand calculations for the different studies in scenario 1. As previously mentioned the design of the different process steps, e.g. the sludge stabilization, also differs. Most LCA studies concerning sludge reuse/disposal do not consider the construction phase but only the operation of the concerned systems [5]. In those cases where construction was considered, the analysis might include only construction work associated with upgrades of an existing treatment plant [16]. The construction was though generally considered to have a minor impact on the overall environmental impact of the systems [16, 21, 22]. The environmental impact categories considered vary between different life cycle studies. Most consider energy and/or global warming potential. Additionally, many also include some other factor such as human toxicity, ecotoxicity, water use and/or air/water emissions [5].

Table 1. Subsystems included in the energy demand calculations in the different investigations considered in this study.

	Ref.									
Subsystem	[4]	[10]	[13]	[14]	[15]	[16]	[17]	[18]	[19]	[20]
Treatment of wastewater	x[1]			x						
Sludge treatment	x	x	x	x	x	x	x			x
Transport of sludge, chemicals	x		x	x	x	x	x	x	x	x
Spreading in agriculture		x	x		x	x	x	x	x	x
Credits for P and/or N			x[2]				x[3]	x[3]	x[3]	x[3]
Credits for replacement of electricity	x			x						
Credits for replacement of heat	x	x[1]		x						

[1] Not fully clear what parts are included

[2] Additional energy use for production of mineral fertilizers was considered for the composting case studied, since some fertilizers are lost during that process.

[3] The credits are not included in the numbers given in Fig. 1. In Linderholm et al. [18] only nitrogen fertilizer was credited.

According to Linderholm et al. [18] the energy use for production of mineral P, given in literature, varies from -4 kWh/kg P to 22 kWh/kg P, mainly due to different sources for sulphuric acid used in the production. The acid could be based either on waste from the oil and gas industry or on mined sulphur [18]. Whether the phosphate is mined as apatite rock or sedimentary phosphate rock, also influences the value [18]. According to von Bahr [15], the energy use for production of mineral P can vary from 1 to 10 kWh/kg P. Whether direct sludge use could be competitive with mineral fertilizers from an energy perspective thus seems to be dependent on the source and production of mineral P.

4. Conclusions

- Direct reuse of sludge in agriculture (3-71 kWh/kg P) seems to be preferable from an energy perspective compared to incineration and extraction of P (45-70 kWh/kg P, not including Lundin et al. [20] who got a deviating result) or pyrolysis (46-235 kWh/kg P).
- For scenario 1 the system boundary can be chosen in many different ways (e.g. including wastewater treatment process steps or not, including credits from avoided N fertilizer or not), which has a large impact on the result, and according to some calculations make direct sludge reuse more energy efficient than use of mineral P (-4-22 kWh/kg P).
- The energy demand for scenario 2 and 3 derives mainly from the additional energy input needed to dry sludge and/or fuel used during sludge incineration and the chemicals required to extract P in scenario 2.
- If direct sludge reuse is not possible, due to e.g. sludge quality or local regulation, one of the other options could be preferable. Especially if waste heat is available for drying.
- In the context of global warming it is also relevant to consider the type of energy used, as the energy mix varies across the globe. The replaced energy (by energy credits) is different in the different studies, e.g. Johansson et al. [19] used data based on the Swedish energy system while e.g. Amann et al. [4] used standard data from the database Ecoinvent.
- The results are relevant for existing, advanced municipal WWTPs and the studies included are made based on European case-studies, with exception of one study that was based on a Japanese case-study.
- Apart from the energy demand, other environmental impact factors, such as human toxicity and global warming potential, are important when choosing an appropriate option for P reuse.
- Energy aspects were in focus of this report. Other drivers and challenges for P-recycling from municipal wastewater are e.g. economic considerations, existing infrastructure, health restrictions/legal barriers, public opinions etc. These and other aspects are of interest in our further work.

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