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Potential of phosphorus recovery from sewage sludge and manure ash by thermochemical treatment

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ABSTRACT

All life forms require phosphorus (P), which has no substitute in food production. The risk of phosphorus loss from soil and limited P rock reserves has led to the development of recycling P from industrial residues. This study investigates the potential of phosphorus recovery from sewage sludge and manure ash by thermochemical treatment (ASH DEC) in Finland. An ASH DEC plant could receive 46–76 kt/a of sewage sludge ash to produce 51–85 kt/a of a P-rich product with a P_2O_5 content of 13–18%, while 320–750 kt/a of manure ash could be supplied to produce 350–830 kt/a of a P-rich product with a P content of 4–5%. The P_2O_5 potential in the total P-rich product from the ASH DEC process using sewage sludge and manure ash is estimated to be 25–47 kt/a, which is significantly more than the P fertilizer demand in Finland's agricultural industries. The energy efficiency of integrated incineration and the ASH DEC process is more dependent on the total solid content and the subsequent need for mechanical dewatering and thermal drying than on the energy required by the ASH DEC process. According to the results of this study, the treated sewage sludge and manure ash using the ASH DEC process represent significant potential phosphorus sources for P fertilizer production.

1. Introduction

Phosphorus (P) is an essential element for all living organisms and has no replacement in food production (Adam et al., 2012; Kahiluoto et al., 2014). Geological surveys currently estimate that 7 billion tons of phosphate rocks in the form of P_2O_5 could be economically mined in known reserves. Additionally, 80–90% of the phosphate produced is used for fertilizers (U.S. Geological Survey, 2010). Unfortunately, phosphate rock is a finite resource that takes approximately 10–15 million years to form and could be depleted within one century (Gilber, 2009). Therefore, recycling and conserving P from P-rich residues, such as sewage sludge and manure ash, are critical.

The potential and necessity for phosphate release and recovery from ash are being explored because phosphate rock prices have risen, and the direct application of incinerated ash in agriculture has been hindered due to high heavy metal contents (Anttila et al., 2008; Petzet and Cornel, 2013).

Agricultural land use in Finland covers only 8% of the total land area, but phosphorus losses from agricultural processes have reached approximately 60% (Vuorenmaa et al., 2002). Reducing the use of P and efficiently using P are essential for farmers competing in the agricultural market. Phosphorus recovery from residues has received little attention in Finland to date. Sewage sludge and manure ash could be used as fertilizers when heavy metal concentrations are reduced to acceptable limits (Anttila et al., 2008; Kuligowski et al., 2010).

The most popular utilization method for manure is spreading it on arable land (Pöyry Environment, 2007), but dry manures could also be incinerated (Lundgren and Pettersson, 2009; Tyni et al., 2010). The ash produced by incinerating manure could then be used as a fertilizer for maintaining P levels in soil (Kuligowski et al., 2010).

Sewage sludge is also rich in nutrients (i.e., nitrogen and phosphorus) but contaminated with heavy metals, poorly biodegradable trace organic compounds, and potentially pathogenic organisms. According to Svanström et al. (2004), treatment methods include land applications or spreading, landfilling, anaerobic digestion and incineration. In most European countries, landfilling of sludge has been banned in compliance with the EU Landfill Directive (99/31/EC); thus, incineration has become a common

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treatment method, leading to a potential sink for phosphorus. In Finland, nearly all sewage sludge is utilized in landscaping, and less than 3% is used as fertilizer in agriculture during 2005–2007. The aim of the national waste management plan is that 100% of sludge will be used either as a soil amendment or as an energy carrier by 2016 (Ministry of the Environment, 2012).

Phosphorus can be recovered from ash by leaching with acidic (Pettersson et al., 2008a, 2008b) or alkaline solutions or sequentially with acidic and alkaline solutions (Petzet et al., in press). Another phosphorus recovery method is to remove heavy metals from ashes using a thermochemical process to produce a P-fertilizer raw material or a finished fertilizer (Adam et al., 2007, 2009; Fraissler et al., 2009; Mattenberger et al., 2008; Vogel and Adam, 2011). Adam et al. (2009) showed that ash from the mono incineration of sewage sludge had a high phosphorus content (15–25% P_2O_5). In addition, Vogel et al. (2010) reported that thermochemically treated sewage sludge ash is a suitable raw material for the production of P fertilizers or multi-nutrient fertilizers, such as PK or NPK fertilizers. According to Adam et al. (2012), ash from the co-incineration of sewage sludge is mostly not suitable for phosphorus recovery, but manure ash could be used as a supplementary feedstock in ASH DEC plants (Havukainen et al., 2012).

Thermochemical treatment for removing heavy metals has been used in many studies. Vogel et al. (2010) used HCl to remove heavy metals from sewage sludge during thermochemical treatment. The bioavailability of P was increased by adding $MgCO_3$. Using a gaseous chlorine donor has the advantage of not needing to be mixed with ash before treatment. Fraissler et al. (2009) used $CaCl_2$ as a Cl donor and found that Cd and Pb were easily volatile, while Cu and Zn were semi-volatile and Cr and Ni were not very volatile. They also concluded that the material bed temperature of 900 °C might be too low and that using 1000 °C leads to better removal results. Mattenberger et al. (2008) used KCl and $MgCl_2$ as additives and found that the additive selection, the amount of additive and the treatment temperature were key factors in removing heavy metals. The result of Adam et al. (2009) showed that Hg can be removed by thermochemical treatment to meet the limits of fertilizer ordinances of European countries, but they concluded that in most cases, these limits were not met.

The ASH DEC process is a thermochemical treatment method that produces renewable phosphate, removes heavy metals and increases the bioavailability of nutrients contained in ash (ASH DEC, 2009). Similar technologies include the Leachphos and Mephrec processes. These three technologies were compared in the P-REX project funded by the European Commission (P-REX, 2009). ASH DEC utilizes thermal treatment in a rotary kiln, while Leachphos utilizes a sequential process including leaching and solid/liquid separation, and Mephrec includes briquetting followed by treatment in a Mephrec reactor. According to the P-REX project results, tMephrec and Leachphos consume electricity equal to 1.2 kW h/kg P recovered and 2.4 kW h/kg P recovered, respectively. The ASH DEC process consumes electricity equal to 1–1.2 kW h/kg P recovered and natural gas equal to 4.4–6.5 kW h/kg P recovered. The recovery rate of phosphorus was 98% for ASH DEC, which was higher than the 70% achieved using Leachphos; no data were available for the Mephrec process. The solubility of PNAC (P-solubility in neutral ammonium citrate) was higher for the Leachphos product (95%) compared to the ASH DEC product (81%).

Several studies of the thermochemical process have emphasized aspects of process engineering and heavy metal removal efficiency (Mattenberger et al., 2008; Vogel and Adam, 2011; Petzet and Cornel, 2013), but only a few have considered the regional and global potential of phosphorus recovery from ash. Thus, by combining data on P recovery efficiencies and recovery potential, P recovery from alternative sources can be wholly described. The objective of this study is to estimate the potential of phosphorus recovery from sewage sludge and manure ash by thermochemical treatment in Finland utilizing selected ASH DEC technology.

2. Materials and methods

2.1. Biomass potential and properties

The potential of sewage sludge and manure for incineration and ASH DEC treatment from all 16 central regions for economic development, transport and the environment (ELY) in Finland was investigated. The sources of sewage sludge investigated included municipal wastewater treatment plants that process domestic waste waters as well as industrial effluent. Data on the amounts of sewage sludge were taken from waste management center statistics and previous studies (Table 1).

Preliminary analysis showed a limited mass flow of sewage sludge; the volume was not sufficient for an ASH DEC treatment plant. Therefore, manure was included as an additional feedstock; first, dry manure was considered because it does not need any dewatering, followed by liquid manures. Sources of dry manure included cows, pigs, poultries, and others, which included 43% horse manure, 24% sheep and goat manures and 33% fur animal manure (e.g., female fur animals from regions with more than 5 fur farms) (Profur, 2012; MMM-RMO C4; Viljavuuspalvelu, 2010). Sources of liquid manure included cows and pigs.

The amounts of manure were calculated using information about the quantity of animals, manure type and grazing periods. Additional information was reported by Havukainen et al. (2012). Information about sewage sludge mass and the calculated manure masses are presented in Table 1.

Information about the biomass properties was collected primarily from the literature. The total solid (TS) content of the sewage sludge in a given ELY center region was collected from the same source as the mass information in Table 1. The TS content of the sewage sludge varied from 13% to 26% with an average of 20%. Other biomass properties were obtained from the literature, and when available, min and max values were used in the calculations to reflect the variation of biomass properties. The LHV on a dry basis and other used values are presented in Table 2. In the calculations, the moisture content was taken into account, and as-received LHV was used.

2.2. Dewatering, thermal drying, incineration and the ASH DEC process

This study was conducted to estimate the efficiency of phosphorus recovery from sewage sludge and manure ash using a thermochemical method. In addition, the product yields and energy balance were estimated. In this article, the ASH DEC process was selected as the thermochemical treatment method due to available technical data. Similar to biomass properties, calculations used min and max values. The ASH DEC process with the treatment steps for sewage sludge and manure including incineration is presented in Fig. 1.

A portion of the biomass was dewatered and thermally dried before incineration. The collected sewage sludge and dry manure were assumed to be thermally dried before incineration. The pig and cow liquid manures were assumed to be dewatered with decanting centrifugation (Møller et al., 2002) before thermal drying. The net heat consumptions of the thermal drying processes were 240 kW h/t_{H_2O} for the steam dryer (min value) and 669 kW h/t_{H_2O} for the disc dryer (max value). Technologies for sewage sludge or manure mono-incineration included multiple heart furnaces, fluidized bed incinerators (Anttila et al., 2008; Lapa et al., 2007), melting furnaces, rotary kilns and cyclone furnaces (Werther and Ogada, 1999). The sewage sludge and manure

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