

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

Jouni Havukainen^{a,*}, Mai Thanh Nguyen^a, Ludwig Hermann^b, Mika Horttanainen^a, Mirja Mikkilä^a, Ivan Deviatkin^a, Lassi Linnanen^a

LUT Energy, Environmental Technology, Lappeenranta University of Technology, P.O. Box 20, FI-53851 Lappeenranta, Finland

^a Lappeenranta University of Technology, Laboratory of Environmental Engineering. P.O. Box 20, FI-53851, Lappeenranta, Finland

^b Outotec GmbH & Co. KG Ludwig-Erhard-Strasse 21, D-61440 Oberursel, Germany

*Corresponding author: Jouni Havukainen, Laboratory of Environmental Technology, Lappeenranta University of Technology, P.O. Box 20, 53851 Lappeenranta, Finland
Email: jouni.havukainen@lut.fi

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 to 76 kt/a of sewage sludge ash to produce 51 to 85 kt/a of a P-rich product with a P₂O₅ content of 13% to 18%, while 320 to 750 kt/a of manure ash could be supplied to produce 350 to 830 kt/a of a P-rich product with a P content of 4% to 5%. The P₂O₅ potential in the total P-rich product from the ASH DEC process using sewage sludge and manure ash is estimated at 25 to 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 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, treated sewage sludge and manure ash using the ASH DEC process represent significant potential phosphorus sources for P fertilizer production.

Keywords: thermochemical process, ASH DEC, incineration, phosphorus recovery, sewage sludge ash, manure ash

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.*, 2013). Geological surveys currently estimate that 7 billion tons of phosphate rock in the form of P_2O_5 in known reserves could be economically mined. Additionally, 80% to 90% of phosphate produced is used for fertilizers (U.S. Geological Survey, 2010). Unfortunately, phosphate rock is a finite resource that takes approximately 10 to 15 million years to form and could be depleted within one century (Gilber, 2009). Therefore, the recycling and conservation of P from P-rich residues, such as sewage sludge and manure ash, is critical.

The potential and necessity for phosphate release and recovery from ash is 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 the phosphorus losses from agricultural process have reached approximately 60% (Vuorenmaa *et al.*, 2002). Reducing the use of and efficiently using P is 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.*, 2008).

The most popular utilization method for manure is spreading 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 fertilizer to maintain 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 application 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 treatment method and potential sink for phosphorus. In Finland, nearly all sewage sludge is utilized in landscaping, and less than 3% was 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), alkaline or sequentially with acidic and alkaline solutions (Petzet *et al.*, 2012). Another phosphorus recovery method is to remove heavy metals from the ashes using a thermochemical process to produce a P-fertilizer raw material or a finished fertilizer (Adam *et al.*, 2007; Adam *et al.*, 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 (2012), the ash from the co-incineration of sewage sludge is primarily 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 in thermochemical treatment. Bioavailability of P was increased by adding $MgCO_3$. Using gaseous chlorine donor has the advance that there is no need to mix it with ash before treatment. Fraissler *et al.* (2009) used $CaCl_2$ as Cl donor and found that Cd, Pb are easily volatile, Cu and Zn semi-volatile and Cr and Ni low-volatile. They also concluded that material bed temperature of 900 °C might be too low and 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, treatment temperature key factors in removing heavy metals.

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 Leachphos and Mephrec processes. These three technologies were compared in P-REX project funded by European Commission (P-REX 2009). The ASH DEC utilizes thermal treatment in a rotary kiln, the Leachphos utilizes sequential process including leaching and solid/liquid separation and the Mephrec includes briquetting followed by treatment in Mephrec reactor. According to the P-REX project results, the Mephrec and Leachphos consume electricity equal to 1.2 kWh/kg P recovered and 2.4 kWh/kg P recovered, respectively. The ASH DEC process consumes electricity 1-1.2 kWh/kg P recovered and natural gas 4.4-6.5 kWh/kg P recovered. Recovery rate of phosphorus was 98% for ASH DEC which was higher than 70 % achieved using Leachphos, while there was no data available from Mephrec process. The solubility of PNAC (P-solubility in neutral ammonium citrate) was higher from Leachphos product (95%) compared to ASH DEC product (81%).

Several studies of thermochemical process have emphasized aspects of process engineering and heavy metal removal efficiency (Mattenberger *et al.*, 2008; Vogel and Adam, 2011; Petzet *et al.*, 2013), but only a few have considered the regional and global potential of phosphorus recovery from ash. Thus, combining data about P recovery efficiencies and recovery potential will holistically describe P recovery from alternative sources. 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 total 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 dry cow, pig, and poultry manures and other dry manures, which included 43% horse manure, 24% sheep and goat manures and 33% fur animal manure, which included manure from female fur animals from regions with more than 5 fur farms (Profur, 2012; MMM-RMO C4; Viljavuuspalvelu). Sources of liquid manure include liquid cow and pig manures.

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 mass are presented in Table 1.

Table 1. Obtained sewage sludge and calculated manure masses from ELY center regions in Finland.

Region	Sewage sludge (t/a)	Cow dry manure (t/a)	Cow liquid manure (t/a)	Pig dry manure (t/a)	Pig liquid manure (t/a)	Poultry manure (t/a)	Other dry manure (t/a)
Åland Islands	38 000 ¹	120 000	85 000	0	0	550	14 000
Southern Ostrobothnia	37 000 ³	470 000	310 000	130 000	310 000	77 000	75 000
Southern Savonia	16 000 ⁴	230 000	160 000	2 500	6 100	7 300	21 000
Häme	43 000 ³	290 000	210 000	45 000	110 000	5 300	30 000
South Karelia	43 000 ²	260 000	190 000	17 000	42 000	2 800	25 000
Kainuu	19 000 ⁵	190 000	140 000	0	0	460	5 500
Central Finland	34 000 ⁶	300 000	210 000	6 300	15 000	2 300	26 000
Lapland	73 000 ⁸	480 000	360 000	0	0	210	18 000
Pirkanmaa	69 000 ⁹	320 000	220 000	49 000	120 000	28 000	32 000
Ostrobothnia	33 000 ³	520 000	320 000	120 000	290 000	24 000	150 000
North Karelia	15 000 ¹⁰	500 000	360 000	2 800	6 800	1 400	16 000
Northern Ostrobothnia	73 000 ⁵	700 000	500 000	22 000	55 000	620	45 000
Northern Savonia	57 000 ¹⁰	780 000	570 000	15 000	37 000	950	24 000
Satakunta	64 000 ⁴	190 000	130 000	86 000	210 000	73 000	18 000
Uusimaa	120 000 ⁹	160 000	120 000	16 000	39 000	580	39 000
Finland Proper	68 000 ⁹	140 000	92 000	200 000	490 000	150 000	35 000
Total	800 000	5 600 000	4 000 000	710 000	1 700 000	370 000	580 000

1. Avfallsstatistik, 2010; 2. EKJH, 2010; 3. Rytönen, 2012; 4. Kahiluoto and Kuisma, 2010; 5. Turunen et al., 2008; 6. Yli-Kauppi et al., 2009; 7. Rasi et al. 2010 8. Lapin ELY, 2011; 9. Länsi-Suomen Ympäristökeskus, 2009; 10. Pohjois-Karjalan Ympäristökeskus, 2009.

Information about biomass properties was collected primarily from the literature. The sewage sludge total solid (TS) content in a given ELY center region was collected from the same sources

as the mass information in Table 1. The TS content of 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 calculations to reflect the variation of biomass properties. The LHV on dry basis and other used values are presented in Table 2. In the calculations the moisture content has been taken in to account and LHV on as received basis have been used.

Table 2. Material properties of studied feedstock.

	Min	Max	Reference
LHV _{dry} (MJ/kg)			
Sheep manure	14.9	14.9	Phyllis 2. 2012, Miller & Miller 2007
Cattle solid manure	10.5	16.9	Phyllis 2. 2012, Miller & Miller 2007, Choi et al. 2014
Cattle liquid manure	10.5	16.9	Phyllis 2. 2012, Sweeten et al. 2003
Poultry manure	12.1	13.9	Quiroga et al. 2010, Miller & Miller 2007, Zhu et al. 2005
Horse manure	18.4	19.1	Lundgren & Pettersson 2009, Edström et al. 2011
Pig solid manure	12.8	15.2	Thygesen & Johnsen 2012
Pig liquid manure	12.8	15.2	Phyllis 2. 2012, Prapasongsa et al. 2010, Choi et al. 2014
Fur animal	13.0	15.2	Assumed same as pig manure
Sewage sludge	15.3	20.7	Horttanainen et al. 2010, Anttila et al. 2008, Dogru et al. 2002, Murakami et al. 2009
TS (%)			
Sheep manure	18.0	34.9	Viljavuusalvelu 2010, Kumar & Bharti edit. 2012, Rasi et al. 2010, Luostarinen et al. 2011, Thygesen & Johnsen 2012
Cattle solid manure	19.0	25.0	
Cattle liquid manure	5.5	11.0	Viljavuusalvelu 2010
Poultry manure	38.0	50.1	Rasi et al. 2010, Viljavuusalvelu 2010, Zhu et al. 2005
Horse manure	32.0	32.9	Rasi et al. 2010, Viljavuusalvelu 2010
Pig solid manure	25.0	54.9	Viljavuusalvelu 2010, Thygesen & Johnsen 2012
Pig liquid manure	3.5	8.0	Prapasongsa et al. 2010, Viljavuusalvelu 2010
Fur animal	38.5	38.5	Viljavuusalvelu 2010
Sewage sludge	13.0	26.0	References in Table 1.
ASH content (% TS)			
Sheep manure	15.0	20.0	Kumar & Bharti edit. 2012, Miller & Miller 2007
Cattle solid manure	15.0	22.0	Kumar & Bharti edit. 2012, Rasi et al. 2010
Cattle liquid manure	15.0	32.0	Kumar & Bharti edit. 2012, Rasi et al. 2010, Thygesen & Johnsen 2012
Poultry manure	29.0	29.0	Rasi et al. 2010, Miller & Miller 2007, Zhu et al. 2005
Horse manure	40.0	40.0	Rasi et al. 2010
Pig solid manure	20.0	20.0	Rasi et al. 2010, Thygesen & Johnsen 2012
Pig liquid manure	15.0	27.0	Rasi et al. 2010, Prapasongsa et al. 2010

Fur animal	50.0	50.0	Wabio, Thygesen & Johnsen 2012
Sewage sludge	29.0	48.0	Ritari 2014, Lehtinen & Urho 2012
Phosphate content (kg/trs as P ₂ O ₅)			
Sheep manure	14.0	18.0	Viljavuusalvelu 2010
Cattle solid manure	14.0	18.0	Viljavuusalvelu 2010, Rasi et al. 2010
Cattle liquid manure	21.0	26.0	Ørtenblad 2004
Poultry manure	37.0	69.0	Viljavuusalvelu 2010
Horse manure	18.0	37.0	Viljavuusalvelu 2010
Pig solid manure	27.0	37.0	Viljavuusalvelu 2010
Pig liquid manure	35.0	52.0	Rasi et al. 2010
Fur animal	95.0	164.0	Viljavuusalvelu 2010
Sewage sludge	57.0	66.0	Rasi et al. 2010, Lehto 2005

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 ASH DEC process was selected as the thermochemical treatment methods due 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 Figure 1.

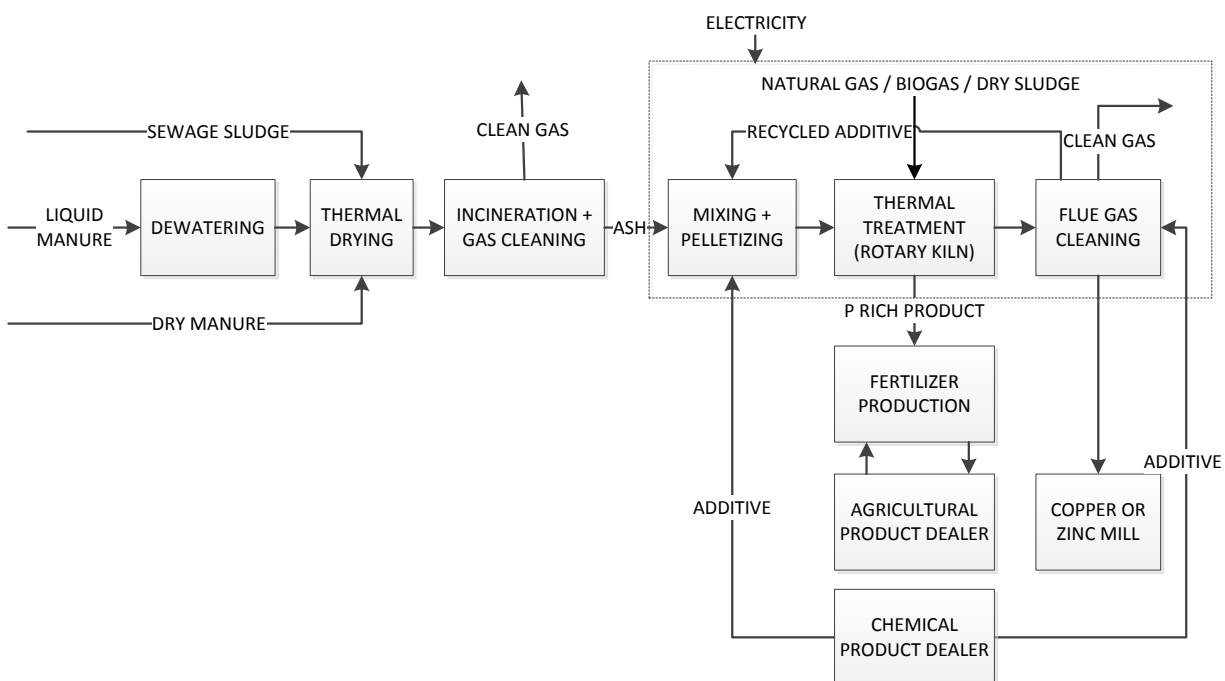


Figure 1. Biomass pretreatment, incineration and P recovery by ASH DEC process (ASH DEC, 2009).

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 manure was assumed to be dewatered with decanting centrifugation (Møller et al., 2002) before thermal drying. The net heat consumption of the thermal drying processes was 240 kWh/t_{H2O} for the steam dryer (min value) and 669 kWh/t_{H2O} 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 were assumed to be incinerated in a fluidized bed boiler with combined heat and electricity (CHP) production (Horttanainen et al., 2010). The used min and max values for dewatering, thermal drying, and incineration are presented in Table 3.

Table 3. Min and max values used for dewatering, drying, and incineration calculations (Horttanainen et al., 2010; Myllymaa et al., 2008; Møller et al., 2002).

	Min	Max	Unit
Dewatering			
TS separation efficiency to solid fraction	33	62	%
P separation efficiency to solid fraction	60	66	%
Electricity consumption	4.3	6.0	kWh/t
TS	18	28	%
Thermal drying			
Heat consumption	240	669	kWh/t _{H2O}
TS%	80	95	%
Incineration CHP efficiency			
Electricity	6	15	%
Heat	72	74	%

The remaining bottom and fly ash after incineration were assumed to be directed to the ASH DEC process. Information about the ASH DEC process was provided by Ludwig Hermann, who is one of the developers of the ASH DEC process. The ASH DEC process includes mixing of the ash and alkaline or chlorine donors and subsequent treatment in a rotary kiln for 20 minutes at 900-1050°C, during which heavy metals evaporate, and a P-rich product is obtained. The amount of P-rich product was 1.1 t/t ash. Toxic substances are retained in the air pollution control system

in the form of mixed metal oxides. The air pollution control system is largely the same as in sludge incineration. The system includes electrostatic filter precipitator and wet scrubber if integrated with sludge incineration or dry baghouse filter if ASH DEC system is a standalone plant. In a typical setup, the process requires 46 kg/t_{ash} NaCl, 39 kg/t_{ash} MgO and 49 kg/t_{ash} NaHCO₃ as additives. The ASH DEC process consumes 118 kWh/t_{ash} electricity and 520 kWh/t_{ash} fuel (i.e., natural gas or biomass). If the ASH DEC process is integrated with incineration, the fuel energy requirement reduces to 260 kWh/t ash. In Germany, industrial manufacturing plants using the ASH DEC process start with a treatment capacity of 16 kt/a of sewage sludge ash. The plant is located in South Germany near private sludge incineration and biogas plant. Additionally, this process has been tested at a pilot plant in Leoben, Austria; the plant treated up to 7 tons of ash per day (ASH DEC, 2009).

3. Results

3.1. Potential of sewage sludge for incineration and the ASH DEC process

In Finland, the annual amount of sewage sludge was approximately 800 kt/a (Table 1), which equals 160 kt TS/a. The total amount of sewage sludge ash produced by incineration was estimated to be 46-76 kt/a. The total potential of P-rich product from the ASH DEC process using sewage sludge ash was 51-85 kt/a (Table 4), and the total phosphorus (P₂O₅) mass potential was 9.1-11 kt/a or 13-18% P₂O₅ in the P-rich product. The results for the Uusimaa region show the highest P-rich product potential of 9.8-16 kt/a, while Finland Proper, Lapland, Pirkanmaa show moderate potentials (4.4-8.1 kt/a), and Kainuu, North Karelia and Southern Savonia show the lowest potentials (0.93-1.8 kt/a).

Table 4. Potential of P-rich products and P₂O₅ amounts using sewage sludge ash in the ASH DEC process

Region	Thermal drying Dry sludge (t/a)		Incineration ash (t/a)		ASH DEC P-rich product (t/a)		Phosphorus P ₂ O ₅ (t/a)	
	Low	High	Low	High	Low	High	Low	High
Åland Islands	7 200	8 500	2 000	3 300	2 200	3 600	390	450
Southern Ostrobothnia	7 000	8 300	1 900	3 200	2 200	3 600	380	440
Southern Savonia	3 600	4 300	990	1 600	1 100	1 800	190	230
Häme	9 900	12 000	2 700	4 500	3 000	5 000	540	630
South Karelia	8 700	10 000	2 400	3 900	2 700	4 400	470	550
Kainuu	3 000	3 600	840	1 400	930	1 500	170	190
Central Finland	7 100	8 400	1 900	3 200	2 200	3 600	380	450

Lapland	15 000	18 000	4 200	7 000	4 700	7 800	840	970
Pirkanmaa	16 000	19 000	4 400	7 200	4 900	8 100	870	1 000
Ostrobothnia	5 000	5 900	1 400	2 300	1 500	2 500	270	310
North Karelia	3 200	3 700	870	1 400	970	1 600	170	200
Northern Ostrobothnia	12 000	14 000	3 200	5 400	3 600	6 000	640	740
Northern Savonia	12 000	14 000	3 300	5 400	3 700	6 100	650	750
Satakunta	12 000	14 000	3 200	5 300	3 500	5 900	630	730
Uusimaa	32 000	38 000	8 800	15 000	9 800	16 000	1 700	2 000
Finland Proper	14 000	17 000	4 000	6 600	4 400	7 300	780	910
Total	170 000	200 000	46 000	76 000	51 000	85 000	9 100	11 000

3.2. Potential of manure for incineration and ASH DEC

The potential mass of manure was estimated to be 13 million tons per year, which contains 1800-2800 kt TS/a (Table 5). The total amount of manure ash was 320-750 kt/a, and the total potential of P-rich product from the ASH DEC process using manure ash was 350-830 kt/a. The phosphorus mass as P_2O_5 in the total P-rich product was estimated as 16-36 kt/a, which indicated P_2O_5 content of 4-5%. The highest P-rich product potentials from manure ash were in Ostrobothnia, Southern Ostrobothnia and Finland Proper (43-120 kt/a), while the Åland Islands showed the lowest amounts (5-11 kt/a).

Table 5. Potential of P-rich products and P_2O_5 amounts from utilizing manure ash in ASH DEC process.

Region	Manure kt/a	Manure TS kt/a		Incineration ash (kt/a)		ASH DEC P-rich product (kt/a)		Phosphorus (P_2O_5) t/a	
		low	high	low	high	low	high	low	high
Åland Islands	220	30	44	4	10	5	11	190	370
Southern Ostrobothnia	1 400	200	320	39	96	43	110	2 000	5 000
Southern Savonia	420	61	86	10	20	11	22	480	970
Häme	690	93	140	16	38	18	42	800	1 800
South Karelia	540	74	110	12	27	14	30	600	1 300
Kainuu	340	46	66	6	14	7	16	300	560
Central Finland	560	79	110	12	26	14	29	600	1 200
Lapland	860	120	170	16	36	17	40	720	1 400
Pirkanmaa	780	110	170	20	45	22	49	990	2 200
Ostrobothnia	1 400	200	340	39	110	43	120	1 900	5 400
North Karelia	890	120	170	17	38	19	42	800	1 500
Northern Ostrobothnia	1 300	180	270	27	63	30	70	1 300	2 700
Northern Savonia	1 400	190	280	28	63	31	70	1 300	2 600
Satakunta	710	100	170	22	51	25	56	1 100	2 800

Uusimaa	380	55	79	10	21	12	23	540	1 100
Finland Proper	1 100	160	280	39	93	43	100	2 000	5 300
Total	13 000	1 800	2 800	320	750	350	830	16 000	36 000

3.3. Potential of P-recovery from sewage sludge and manure ashes via thermochemical treatment

Total amount of ashes from incinerating 800 kt/a sewage sludge and 7300 kt/a manure was estimated to be 370-830 kt/a. Total P-rich product from the ASH DEC process using both sewage sludge and manure ash varied from 400 kt/a to 920 kt/a, from which 9-13% was sewage sludge. The total phosphorus mass potential as P_2O_5 was found to be 25-47 kt/a. The sewage sludge comprised only 10% of the total mass potential for incineration, but the share of P_2O_5 originating from the sewage sludge from the total P_2O_5 potential was 23-36% due to the higher ash and phosphorus content of sewage sludge compared to manure. The total P_2O_5 potentials from the regions in Finland are shown in Figure 2, where Finland Proper, Ostrobothnia and Southern Ostrobothnia show the highest potentials of 2.2-6.2 kt/a, while Kainuu shows the lowest (0.5-0.8 kt/a). Other regions show intermediate levels of P_2O_5 (0.6-3.6 kt/a).

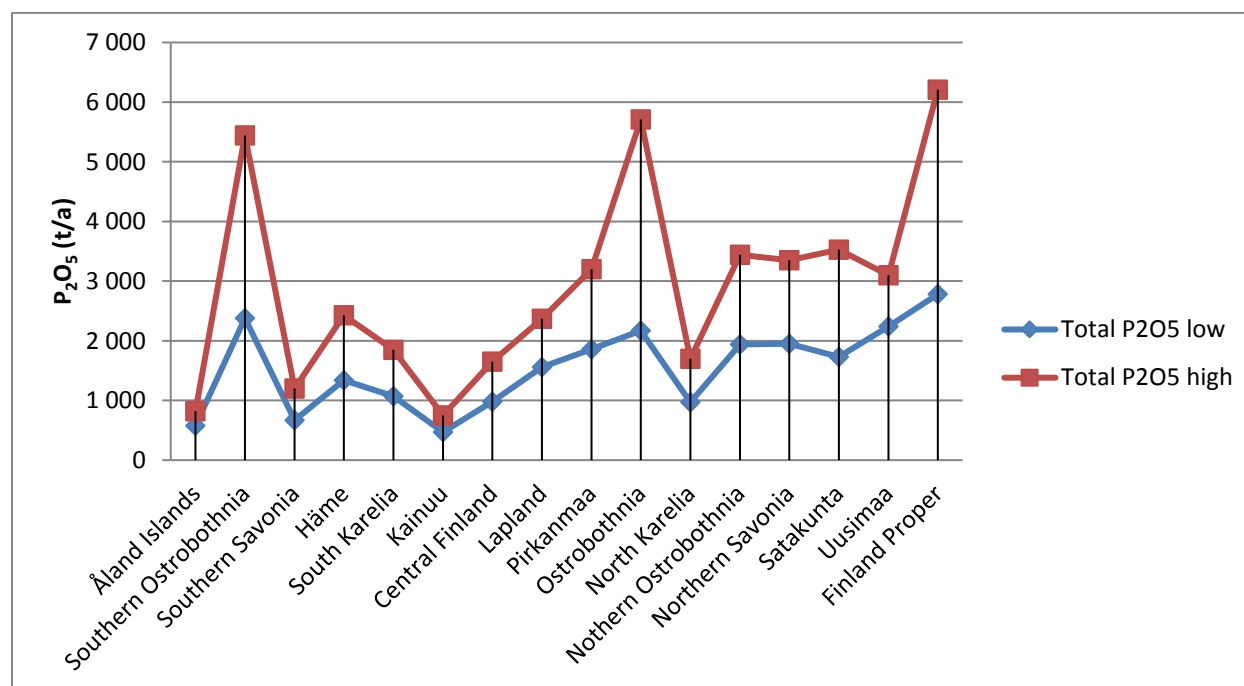


Figure 2. Amount of P_2O_5 that could be recovered from each region in Finland using the ASH DEC process.

3.4. Energy balance of P recovery process

Incineration could be used to treat waste to reduce its volume and hazardous characteristics by destroying potentially harmful substances. In addition, incineration is a suitable process for energy recovery from waste. Important aspects of incineration include the energy yield and energy consumption of the drying process. The total sewage sludge fuel energy from all regions was found to be 650-910 GWh/a (Table 6). The total net yields of electricity and heat from incineration after the heat requirement of thermal drying were 39-130 GWh/a and 250-320 GWh/a, respectively. To treat the ash, the ASH DEC process required 5.4-9 GWh/a of electricity and 12-40 GWh/a of fuel energy. The highest net electricity and heat potential was found in the Uusimaa region with 7.4-25 GWh/a of electricity and 70-72 GWh/a of heat.

Using part of the dried sludge as a fuel in the ASH DEC process would reduce the amount of fuel required by the process. This could be possible if the ASH DEC process was integrated into an incineration plant. Additionally, hot ash could possibly be directed into the ASH DEC process, which would reduce the fuel energy demand of the ASH DEC process by 50%. In this case, the fuel energy for incineration would be 640-890 GWh/a, and the net electricity and heat energies would be 33-120 GWh/a and 240-315 GWh/a, respectively, after subtracting the heat demand of thermal drying and the electricity demand of the ASH DEC process.

Table 6. Fuel energy to sewage sludge incineration, produced net heat and electricity after thermal drying and ASH DEC energy need.

Region	Incineration (including drying)						ASH DEC energy need			
	Fuel energy		Net heat		Net electricity		Electricity		Fuel energy	
	Low	High	Low	High	Low	High	Low	High	Low	High
	MWh/a	MWh/a	MWh/a	MWh/a	MWh/a	MWh/a	MWh/a	MWh/a	MWh/a	MWh/a
Åland Islands	28 000	39 000	7 900	13 000	1 700	5 600	230	390	1 000	1 700
Southern Ostrobothnia	27 000	38 000	8 100	13 000	1 600	5 500	230	380	1 000	1 700
Southern Savonia	14 000	19 000	6 100	7 200	830	2 800	120	190	510	850
Häme	39 000	54 000	18 000	20 000	2 300	7 800	320	540	1 400	2 400
South Karelia	34 000	47 000	12 000	16 000	2 000	6 800	280	470	1 200	2 100
Kainuu	12 000	17 000	1 700	4 900	710	2 400	99	160	440	720
Central Finland	27 000	38 000	10 000	14 000	1 600	5 600	230	380	1 000	1 700
Lapland	60 000	83 000	23 000	30 000	3 600	12 000	500	830	2 200	3 600
Pirkanmaa	62 000	86 000	28 000	32 000	3 700	13 000	520	860	2 300	3 800
Ostrobothnia	19 000	27 000	1 400	7 400	1 200	3 900	160	270	710	1 200

North Karelia	12 000	17 000	4 800	6 100	730	2 500	100	170	450	750
Northern Ostrobothnia	46 000	64 000	6 500	19 000	2 700	9 300	380	630	1 700	2 800
Northern Savonia	46 000	65 000	18 000	23 000	2 800	9 400	390	640	1 700	2 800
Satakunta	45 000	63 000	11 000	20 000	2 700	9 100	380	620	1 700	2 700
Uusimaa	120 000	170 000	70 000	72 000	7 400	25 000	1 000	1 700	4 600	7 600
Finland Proper	56 000	78 000	22 000	28 000	3 300	11 000	470	770	2 100	3 400
Total	650 000	910 000	250 000	320 000	39 000	130 000	5 400	9 000	24 000	40 000

Liquid manure was assumed to be incinerated after dewatering and thermal drying. Dry manure was assumed to be thermally dried before incineration. The electricity required for dewatering and the heat required for thermal drying of liquids were subtracted from the produced electricity and heat energy obtained from CHP. The total electricity required for dewatering liquid pig and cow manures was assumed to be 25-34 GWh/a, and the net heat need for thermal drying was assumed to be 1400-3900 GWh/a. A significant share of the produced heat from incinerating manure was found to be required for thermal drying (39-49%). The highest net heat potential from incineration was found in Southern Ostrobothnia and Ostrobothnia (260-500 GWh/a), while the highest net electricity potential was found in Ostrobothnia and Northern Savonia (26-140 GWh/a).

Table 7. Fuel energy for manure incineration, produced net heat and electricity after thermal drying and ASD DEC energy need.

Region	Incineration (including dewatering and drying)						ASH DEC energy need			
	Fuel energy		Net heat		Net electricity		Electricity		Fuel energy	
	Low GWh/a	High GWh/a	Low GWh/a	High GWh/a	Low GWh/a	High GWh/a	Low GWh/a	High GWh/a	Low GWh/a	High GWh/a
Åland Islands	78	190	30	63	4.3	24	0.50	1.1	2.2	5.0
Southern Ostrobothnia	550	1 200	260	480	30	130	4.6	11	20	50
Southern Savonia	160	360	69	120	9.2	45	1.2	2.4	5.1	10
Häme	250	550	110	200	14	62	1.9	4.5	8.4	20
South Karelia	200	440	85	150	11	52	1.4	3.2	6.3	14
Kainuu	110	280	44	91	6.3	35	0.75	1.7	3.3	7
Central Finland	210	470	87	160	12	58	1.5	3.1	6.4	14
Lapland	290	700	110	230	16	90	1.8	4.2	8.1	19
Pirkanmaa	300	650	140	240	17	75	2.3	5.3	10	23
Ostrobothnia	570	1 200	260	500	32	130	4.6	13	20	57
North Karelia	300	730	120	240	17	92	2.0	4.5	8.9	20
Northern Ostrobothnia	460	1 100	180	370	25	130	3.1	7.5	14	33
Northern Savonia	490	1 200	190	380	26	140	3.3	7.4	14	33
Satakunta	300	600	150	260	16	65	2.6	6	12	26
Uusimaa	160	320	75	110	9	36	1.2	2.5	5.4	11
Finland Proper	490	950	260	450	27	93	4.6	11	20	48
Total	4 900	11 000	2 200	4 100	270	1 300	37	88	170	390

4. Discussion

Because phosphorus sources are becoming scarce, the removal of phosphorus from ash is appealing. Sewage sludge and manure could be incinerated, and the resulting ash could then be used to recover P-rich products using the ASH DEC process. However, the mono-incineration of manure could be economically difficult to implement because the incineration of manure is considered to be waste incineration in Finland. Getting a permit for waste incineration is difficult, and small-scale waste incineration is expensive. Therefore, the co-incineration of sewage sludge and manure could result in increasing available feedstock within a given region and making incineration with the ASH DEC process a viable option. Havukainen et al. (2012) reported that manure could become an additional feedstock in regions with a high density of animal husbandry where the land area might not be sufficient for manure spreading.

The total ash potential from incinerating sewage sludge and manure was estimated to be 46-76 kt/a and 320-750 kt/a, respectively. P-rich products from manure ash typically have lower P_2O_5 contents (4-5%) compared to sewage sludge ash (13-18%) but have a larger potential of P-rich product (350-830 kt/a) compared to sewage sludge (51-85 kt/a). In Finland, Uusimaa has an ash potential of 9-15 kt/a, but other regions have only 0.9-7 kt/a. Thus, to obtain sufficient ash mass for an ASH DEC plant in Finland, sewage sludge ash would need to be transported from several regions to the ASH DEC plant or ash from manure incineration would need to be used with sewage sludge ash.

The P fertilizer potential from sewage sludge and manure ash was found to be substantial at the national level in Finland. P fertilizer demand in Finland was 26 kt in 2012 (Tike, 2013), and the potential of P_2O_5 in P-rich products was found to be 9-11 kt/a from sewage sludge alone and 25-47 kt/a from both sewage sludge and manure. The P_2O_5 content of P-rich products from sewage sludge ash was approximately 13-18%, which was comparable to conventional P fertilizers, such as single-superphosphate (SSP, 18% P_2O_5), and multi-nutrient fertilizers, such as PK and NPK fertilizers (9-12 % P_2O_5 , Adam et al., 2008). SSP sold by the Yara fertilizer company is currently called a “phosphorus nutrient” that contains 9% phosphorus and costs 580 €/t (Yara, 2012; Ylä-

Uotila, 2012). Additionally, recycled P-rich products have been marketed as a high quality PK 12-20 fertilizer with potassium and an NPK 20-8-8 fertilizer, both of which are fully licensed fertilizers since March 2006 in Austria and since 2008 in Germany; both products were sold at prices comparable to commercial fertilizers (ASH DEC, 2009). Hence, treated sewage sludge and manure ash show promising potentials as P-rich resources for fertilizer production. The heavy metal concentration in the ASH DEC product was examined in the P-REX project (P-REX 2015) and are mainly below the limits set for fertilizer products from sewage sludge in Finland (Ministry of Agriculture and Forestry 2001), Table 8. The limit of Cu and Zn are exceeded but exceptions may be made according to legislation if there is a lack of copper or zinc in soil. The composition of sewage sludge varies depending on source and therefore also concentrations of heavy metals which will affect the treatment and concentrations in product.

Table 8. Heavy metal concentration in ASH DEC product (P-REX 2015) and limits in Finland for heavy metals in fertilizer products (Ministry of Agriculture and Forestry 2001).

	ASH DEC product mg/kg	Limit mg/kg
As	3.6	25
Cd	0.3	1.5
Cr	127	300
Cu	601	600*
Hg	0.3	1
Ni	56.4	100
Pb	60.1	100
Zn	1710	1500*

* The limits of Cu and Zn can be exceeded if there is lack of Cu and Zn in the soil.

One of the primary consumers of energy during the P recovery process is the thermal drying of waste before incineration when utilizing wet feedstocks. Using efficient heat exchangers and drying processes, the net heat consumption of thermal drying can be reduced. The efficiency of incineration ($[\text{net heat} + \text{net electric}]/\text{fuel energy}$) of sewage sludge and manure is typically 78-85% without considering dewatering and drying energy use; when considering dewatering and drying, the efficiency drops to 44% when using max values in calculations and 56% when using min values in calculations. For manure, similar calculations result in efficiencies of 49% and

50%, respectively. Manure dewatering requires 3-8% of the produced electricity, and drying requires 39-49% of the produced heat from incineration. In the case of sewage sludge, drying requires 31-63% of the produced heat. The ASH DEC plant energy requirement is similar in both utilizing manure and sewage sludge with electricity demand of 14% in relation to the produced electricity when using min values and 7 % when using max values. The fuel demand of ASH DEC plant is approximately 4% in relation to the fuel energy of sewage sludge or manure directed to incineration. The fuel consumption of the ASH DEC plant itself can be reduced when it is integrated into the incineration plant because the hot ash requires less energy to be heated.

The logistic aspects are important in building a system of incineration and ash treatment by ASH DEC plant. The incineration of sewage sludge as well as manure require large enough mass for securing feasible operation. In Finland this could mean that transport of masses to the incineration plant would be needed. Therefore it might be feasible to add, in addition to dewatering, also thermal drying before transporting the masses. However, there are limits as to how long the transport distances can be and one critical factor affecting economically feasible transport distance is the end product prize. In case there is a possibility to build several incineration plants in a region, the ASH DEC plant could be located close to the largest incineration plant minimizing transportation of the ashes. Incorporation of the ASH DEC plant into the incineration plant reduces costs for peripheral and ancillary equipment because the same infrastructure can be used. The co-incineration of sewage sludge and manure could allow sufficient mass flow for economically viable facilities compared to the combustion of a single waste fraction.

The manure utilization in Finland means to date mainly spreading it to arable land and thereby benefiting from the nutrients included in manure. However, there is increasing demand for expanding energy production from manures by increasing the amount of biogas production. The digestate including the nutrients can then be directed to arable land. In places where the field application of digestate is not suitable, the digestate could be dewatered and dried by using heat coming from biogas plant. Also incineration of dry manures such as horse manure is facilitated in Finland in an attempt to increase the amount of energy production from manures.

The ASH DEC process and similar processes are more suitable for treating the sewage sludge ash since they might include heavy metals. These processes were in the first place developed to remove heavy metals from ashes and increase the usability of nutrients for plants. This study was made to investigate the needed material flows for system including incineration and phosphorus recovery from ashes. One problem with utilizing manure in this way is the low obtainable gate fee for incineration since the manure spreading on arable land is relatively cheap utilization method. The calculations on manure ash potential for ASH DEC plant can be seen as quite hypothetical. The ASH DEC and similar technologies are more clearly suitable for regions where the sewage sludge amounts are larger and where there is a clear risk of heavy metal contamination.

5. Conclusions

The risk of phosphorus loss from soil and limited phosphate rock reserves are the primary reasons for developing more efficient P recycling from sewage sludge and manure ash. The results of this study show that the treatment of sewage sludge and manure ash by thermochemical treatment represents a relevant phosphorus source that is a suitable secondary raw material for P fertilizer production. The potential of sewage sludge ash for an ASH DEC plant was found to be 46-76 kt/a in Finland, which could be used to produce 51-85 kt/a P-rich product with a P_2O_5 content of 13-18%. In addition, manure ash potential was found to be 320-750 kt/a, from which 350-830 kt/a of P-rich product with a P_2O_5 content of 4-5% could be produced. Phosphorus potential as P_2O_5 in the total P-rich product from ASD DEC process using sewage sludge and manure ash was estimated to be 25-47 kt/a, which, if produced, would surpass the demand for phosphorus in agriculture in Finland. In general, the co-incineration of both sewage sludge and manure could result in economically viable plants that produce the amount of ash required for an ASH DEC plant. The energy efficiency of the incineration and the ASH DEC process was found to be significantly more depending on TS content and thus mechanical dewatering and thermal drying than on the energy required by the ASH DEC process. Because the material can be considered to be relatively reliable, and the chosen calculation methodology has been shown to be valid, recovering phosphorus by the ASH DEC process could be an

effective way to recover phosphorus from incinerated ash. The technology can be seen more feasible in regions where the sewage sludge amounts are larger than in Finland and where there is a risk for heavy metal contamination. It should be borne in mind that ASH DEC is just one example of thermochemical treatment process which can be used to increase phosphorous recovery from ashes. It is clear, that the phosphorus recovery is important topic in Europe which is heavily dependent on phosphorus import and has a lack of control over phosphorus emissions from diffuse sources and therefore aspects are considered both in Roadmap for Resource Efficiency in Europe and European Commission communication on sustainable phosphorous use.

Acknowledgements

The research was carried out within Transition Towards Sustainable Nutrient Economy project funded by Tekes Green Growth program.

Rereferences

- 99/31/EC. Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste.
- Adam, C., Kley, G., Simon, F.G., 2007. Thermal treatment of municipal sewage sludge aiming at marketable P-fertilisers. *Materials Trans.* 12, 3056-061.
- Adam, C., Peplinski, B., Michaelis, M., Kley, G., Simon, F.G., 2009. Thermochemical treatment of sewage sludge ashes for phosphorus recovery. *Waste Manag.* 29, 1122-1128.
- Adam, C., Suhendra, Vogel, C., Krueger, O., Tetzlaff, K., 2012. Production of marketable multi-nutrient fertilizers from different biomass ashes and industrial by-products. ASH 2012, Stockholm, Sweden Janury 25-27, 2012. Available from: http://www.varme-forsk.se/files/program/askor/Adam_et_al_final.pdf.
- Alakangas, E., 2000. Suomessa käytettävien polttoaineiden ominaisuuksia. Available from: <http://www.vtt.fi/inf/pdf/tiedotteet/2000/T2045.pdf>.
- Anttila, J., Bergman, R., Horttanainen M., Kaikko, J., Kakko, K., Lana, A., Lindh, T., Luoranen, M., Malinen, J., Manninen, H.M., Marttila, E., Nerg, J., Pasila-Lehtinen, M., Pyrhönen, J., 2008. Hajautetun energiantuotannon modulaarinen yhdyskunnan sivuainevirtoja hyödyntävä CHP-laitos. Available from: <http://www.doria.fi/bit-stream/handle/10024/43043/isbn9789522146953.pdf?sequence=1>.
- ASH DEC., 2009. Short Description ASH DEC PhosKraft® Fertiliser Process & Manufacturing Plants.

- Avfallsstatistik, 2010. Available from http://www.stat.fi/til/jate/2010/jate_2010_2012-05-16_sv.pdf.
- Choi, H.L., Sudiarto, S.I. a, Renggaman, A., 2014. Prediction of livestock manure and mixture higher heating value based on fundamental analysis. *Fuel* 116, 772–780.
- Dogru, M., Midilli, A., Howarth, C.R., 2002. Gasification of sewage sludge using a throated downdraft gasifier and uncertainty analysis. *Fuel Process. Technol.* 75, 55–82.
- Edström, M., Schüßler, I., Luostarinen, S., 2011. Combustion of manure, manure as fuel in a heating plant. Available from: http://balticmanure.odeum.com/download/Reports/baltic_manure_combustion_final_2_2011_total.pdf.
- EKJH. Vuosikertomus 2010. Available from: <http://www.ekjh.fi/Dokumentit/Vuosikertomukset/Vuosikertomus2010.pdf>.
- Fraissler, G., Jöller, M., Mattenberger, H., Brunner, T., Obernberger, I., 2009. Thermodynamic equilibrium calculations concerning the removal of heavy metals from sewage sludge ash by chlorination. *Chemical Engineering and Processing: Process Intensification* 48, 152–164.
- Gilber, N., 2009. The disappearing nutrient. *Nature* 461, 716–718.
- Havukainen, J., Horttanainen, M., Linnanen, L., 2012. Feasibility of ASH DEC process in treating sewage sludge and manure ash in Finland. Research Report 26. Lappeenranta University of Technology. ISSN 1798-132. Available from: <http://www.doria.fi/bitstream/handle/10024/90919/isbn9789252653307.pdf?sequence=2>.
- Herman, L., 2009. P-recovery from sewage sludge ashes by thermachemical treatment. Presentation in BALTIC 21- Phosphorus recycling and good agricultural management practice, September 28-30, 2009.
- Horttanainen, M., Kaikko, J., Bergman, R., Pasila-Lehtinen, M., Nerg, J., 2010. Performance analysis of power generating sludge combustion plant and comparison against other sludge treatment technologies. *App. Thermal. Engin.* 30, 110–118.
- Kahiluoto, H., Kuisma, M., 2010. Elintarvikeketjun jätteet ja sivuvirrat energiaksi ja lannoitteiksi. Available from: www.mtt.fi/mttkasvu/pdf/mttkasvu12b.pdf.
- Kahiluoto, H., Kuisma, M., Koukkanen, A., Mikkilä, M., Linnanen L., 2014. Taking planetary nutrient boundaries seriously: Can we feed the people? *Global Food Secur.* 3, 16–21.
- Kuligowski, K., Poulsen, T.G., Rubæk, G.H., Sørensen, P., 2010. Plant-availability to barley of phosphorus in ash from thermally treated animal manure in comparison to other manure based materials and commercial fertilizer. *Eur. J. Agro.* 33, 293–303.
- Kumar, S., Bharti, A. edit. 2012. Management of organic waste. InTech. ISBN 978-953-307-925-7. 198 pages.
- Länsi-Suomen Ympäristökeskus 2009. Etelä- ja Länsi-Suomen jätesuunnittelu Taustaraaportti Yhdyskunta- ja haja-asutuslietteet. Available from: <http://www.ymparisto.fi/download.asp?contentid=108297&lan=fi>.
- Lapa, N., Barbosa, R., Lopes, M.H., Mendes, B., Abelha, P., Gulyurtlu, I., Oliveira, J.S., 2007. Chemical and ecotoxicological characterization of ashes obtained from sewage sludge combustion in a fluidised-bed reactor. *J. Hazard. Mater.* 147, 175–183.
- Lapin ELY-keskus, 2011. Lapin alueellinen jätesuunnitelma vuoteen 2020. Available from: http://www.elykeskus.fi/fi/ELYkeskukset/LapinELY/Ymparistonsuojelu/Documents/Lapin_jatesuunnitelma_2011_12_19.pdf.
- Lehtinen, E., Urho, A. 2014. Jätevedenpuhdistus pääkaupunkiseudulla 2013 - Viikinmäen ja Suomenojan puhdistamot. Helsinki: Helsinki Region Environmental Services Authority.

- http://www.hsy.fi/tietoahsy/Documents/Julkaisut/2_2014_Jatevedenpuhdistus_paakaupunkiseudulla2013.pdf
- Lehto, T. 2005. Biojätteiden kierrätys ja ravinteiden virrat paikallisessa ruokajärjestelmässä. Etelä-Savon ympäristökeskuksen moniste. 64
- Lohiniva, E., Mäkinen, T., Sipilä, K., 2001. Lietteiden käsittely. Uudet ja käytössä olevat tekniikat. Valtion teknillinen tutkimuskeskus. VTT Tiedote 2081. Espoo: Valtion teknillinen tutkimuskeskus. Read 7.9.2012. Available from: <http://www.vtt.fi/inf/pdf/tiedotteet/2001/T2081.pdf>.
- Lundgren, J., Pettersson, E., 2009. Combustion of horse manure for heat production. *Biores. Tech.* 100, 3121-3126.
- Mattenberger, H., Fraissler, G., Brunner, T., Herk, P., Hermann, L., Obernberger, I., 2008. Sewage sludge ash to phosphorus fertiliser: Variables influencing heavy metal removal during thermochemical treatment. *Waste Manag.* 28, 2709-2722.
- Ministry of Agriculture and Forestry. 2011. Decree 24/11 (Record No. 1784/14/2011) on fertilizer products [in Finnish].
- Ministry of the Environment. 2012. Follow up of the national waste plan 1.st interim report. (Valtakunnallisen jätesuunnitelman seuranta 1. Väliraportti). <http://www.ymparisto.fi/download.asp?contentid=135152&lan=fi>
- Miller, S.F., Miller, B.G., 2007. The occurrence of inorganic elements in various biofuels and its effect on ash chemistry and behavior and use in combustion products. *Fuel Process. Technol.* 88, 1155–1164.
- MMM-RMO C4. Liite 12 MMM:n asetukseen tuettavaa rakentamista koskevista rakentamismääräyksistä ja suosituksista (100/01). Available from: <http://www.finlex.fi/pdf/normit/8673-01100fil12.pdf>.
- Murakami, T., Suzuki, Y., Nagasawa, H., Yamamoto, T., Koseki, T., Hirose, H., Okamoto, S., 2009. Combustion characteristics of sewage sludge in an incineration plant for energy recovery. *Fuel Process. Technol.* 90, 778–783. doi:10.1016/j.fuproc.2009.03.003
- Møller, H.B., Sommer, S.G., Ahring, B.K., 2002. Separation efficiency and particle size distribution in relation to manure type and storage conditions. *Biores. Tech.* 85, 189-196.
- Myllymaa, T., Moliis, K., Tohka, A., Rantanen, P., Ollikainen, M., Dahlbo, H., 2008. Jätteiden kierrätyksen ja polton käsittelyketjujen ympäristö-kuormitus ja kustannukset. Available from: https://helda.helsinki.fi/bitstream/handle/10138/39792/SYKEra_28_2008.pdf?sequence=1.
- Outotec. 2015. ASH DEC. Available at: <http://www.outotec.com/en/About-us/Acquisitions/ASH-DEC/>
- Pettersson, A., Åmand, L.E., Steenari, B.M., 2008a. Leaching of ashes from co-combustion of sewage sludge and wood—Part I: Recovery of phosphorus. *Biomass & Bioenergy* 32, 224-235.
- Pettersson, A., Åmand, L.-E., Steenari, B.M., 2008b. Leaching of ashes from co-combustion of sewage sludge and wood—Part II: The mobility of metals during phosphorus extraction. *Biomass & Bioenergy* 32, 244-236.
- Petzet, S., Cornel, P., 2013. Phosphorus Recovery from Wastewater, in: Hester, R.E., Harrison, R.M. (Eds.), *Waste as a Resource*. Royal Society of Chemistry.
- Petzet, S., Peplinski, B., Cornel, P., 2012. On wet chemical phosphorus recovery from sewage sludge ash by acidic or alkaline leaching and an optimized combination of both. *Water Research*. Article in Press.

- Phyllis 2. 2012. Database for biomass and waste. Available from: <https://www.ecn.nl/phyllis2/> viewed 1.12.2014
- Pohjois-Karjalan Ympäristökeskus, 2009. Itä-Suomen jätesuunnitelma vuoteen 2016. Available from: https://helda.helsinki.fi/bitstream/handle/10138/38027/SY47_2009.pdf.
- Prapasongsa, T., Christensen, P., Schmidt, J.H., Thrane, M., 2010. LCA of comprehensive pig manure management incorporating integrated technology systems. *J. Clean Prod.* 18, 1413-22.
- P-REX. 2015. Sustainable sewage sludge management fostering phosphorus recovery and energy efficiency. [Accessed 3.6.2015]. Available from: http://p-rex.eu/uploads/media/P-REX_D4_1_Comparative_review_of_ash_processes.pdf
- Profur. Statistics 2012 (in Finnish). Available from: <http://profur.fi/modules/system/stdreq.aspx?P=64&VID=default&SID=769136329418648&S=0&C=21373>.
- Pöyry Environment Oy, 2007. Lietteenkäsittelyn nykytila Suomessa ja käsittelymenetelmien kilpailukyky. Suomen itsenäisyyden juhlarahasto (Sitra). Read 12.9.2012. Available from: <http://www.sitra.fi/julkaisu/2011/lietteenkasittelyn-nykytila-suomessa-ja-kasittelymenetelmien-ilpailukyky-selvitys>
- Quiroga, G., Castrillón, L., Fernández-Nava, Y., Marañón, E., 2010. Physico-chemical analysis and calorific values of poultry manure. *Waste Manag.*, 880-884.
- Rasi, S., Lehtonen, E., Aro-Heinilä, E., Höhn, J., Ojanen, H., Havukainen, J., Uusitalo, V., Manninen, K., Heino, E., Teerioja, N., Anderson, R., Pyykkönen, V., Ahonen, S., Marttinen, S., Pitkänen, S., Hellstedt, M., Rintala, J. From waste to traffic fuel. Available from: <http://www.wfuel.info/ajan-kohtaista.php?id=110>.
- Ritari, J. 2014. Joutsenon Oravaharjun jätevedenpuhdistamon velvoitetarkkailujen neljännesvuosiyhteenveto loka-joulukuu 2013 ja vuosiyhteenveto 2013 <http://www.lappeenrannanenergia.fi/palvelut/LRE%20tiedostot/JOUTPMO%202013.pdf>
- Rytönen, T., 2012. Puhdistamoliete, lähtevä jätevirta vuosi 2010, Vahti 26.3.2012.
- Svanström, M., Fröling, M., Modell, M., William, A.P., Jefferson, T., 2004. Environmental assessment of supercritical water oxidation of sewage sludge. *J. Resour. Conserv. Recycl.* 41(4), 3231-3238.
- Sweeten, J.M., Annamalai, K., Thien, B., McDonald, L.A., 2003. Co-firing of coal and cattle feedlot biomass (FB) fuels. Part I. Feedlot biomass (cattle manure) fuel quality and characteristics☆. *Fuel* 82, 1167 - 1182.
- Tike. 2013. Yearbook of Farm Statistics 2013. Helsinki: Information Centre of the Ministry of Agriculture and Forestry. http://www.maataloustilastot.fi/sites/default/files/vuosikirja_2013_etukannella.pdf
- Thygesen, O., Johnsen, T., 2012. Manure-based energy generation and fertiliser production: Determination of calorific value and ash characteristics. *Biosyst. Eng.* 113, 166-172.
- Turunen, T., Sallmén, M., Meski, S., Ritvanen, U., Partanen, E., 2008. Oulun läänin alueellinen jätesuunnitelma. Available from: <http://www.ymparisto.fi/default.asp?contentid=276908-&lan=fi&clan=fi>.
- Tyni, S.K., Tiainen, M.S., Laitinen, R.S., 2010. The suitability of the fuel mixture of horse manure bedding materials for combustion. *Proceeding of the 20th international conference on fluidized bed combustion* 8, 1130-1135.
- U.S. Geological Survey, 2010. Mineral commodity summaries 2010, Phosphorus. United States Government Printing Office. Available from: http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/.

- Viljavuuspalvelu. 2010. Lantatilasto vuosilta 2006-2009. <http://viljavuuspalvelu.fi/fi/tilastot> (Ladattu 31.10.2014)
- Vogel, C., Adam, C., 2011. Heavy metal removal from sewage sludge ash by thermochemical treatment with gaseous hydrochloric acid. *Environ. Sci. Tech.* 45, 7445-7450.
- Volgel, C., Adam, C., Peplinski, B., Wellendorf, S., 2010. Chemical reactions during the preparation of P and NPK fertilizers from thermochemically treated sewage sludge ashes. *Soil Sci. Plant Nutri.* 56(4), 627-635.
- Vuorenmaa, J., Rekolainen, S., Lepistö, A., Kenttämies, K., Kauppila, P., 2002. Losses of nitrogen and phosphorus from agricultural and forest areas in Finland during the 1980s and 1990s. *Environ. Monit. Assess.* 76, 213-48.
- Werther, J., Ogada, T., 1999. Sewage sludge combustion, *Progress in Energy and Combustion Science* 25, 55-116.
- Yara, 2012. Täydennyslannoitteet. Available from: http://www.yara.fi/fertilizer/products/supplement_fert/fosforiravinne.aspx.
- Ylä-Uotila, 2012. Regional sales manager, Yara. E-mail. 28.5.2012.
- Yli-Kauppila, H., Helolahti, A., Koivisto, K., Koivula, N., 2009. Keski-Suomen alueellinen jätesuunnitelma vuoteen 2016. Available from: https://helda.helsinki.fi/bitstream/handle/10138/.../KSUra_2_2009.pdf
- Zhu, S., Lee, S.W., 2005. Co-combustion performance of poultry wastes and natural gas in the advanced Swirling Fluidized Bed Combustor (SFBC). *Waste Manag.* 25, 511-8. doi:10.1016/j.wasman.2004.09.003
- Ørtenblad, H. 2004. The use of digested slurry within agriculture. Herning Municipal Utilities, Denmark. Available from: http://www.adnett.org/dl_fertiliser.pdf