Greenhouse gas emissions from different sewage sludge treatment methods in north

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Abstract

The most sustainable method for treating sewage sludge depends strongly on the situation and local circumstances. In sparsely populated northerly areas are demanding boundary conditions, e.g. cold and long winter, long transport distances and low amounts of generated sludge. In this study, commonly used calculators and emissions coefficients for calculating the greenhouse gas (GHG) emissions from sewage sludge treatment methods were assessed to create a calculator suitable for the Northern Finland context. The calculator was then used to determine which sewage sludge treatment method (composting, anaerobic digestion (AD), incineration (with and without thermal drying)) resulted in the lowest emissions of the GHG gases in different situations in Northern Finland. GHG gases included carbon dioxide (CO_2; including biobased), methane (CH_4) and nitrous oxide (N_2O), measured as carbon dioxide equivalents (CO_2eq). According to the calculator, AD generated the least CO_2eq emissions of all treatment methods studied. The second best option was incineration of sludge without thermal drying, while the third best was composting or incineration of sludge after thermal drying with e.g. fossil or other fuels. Most of the emissions were generated from the treatment process itself and the share of emissions generated during transport was minimal, despite the long transport distances when all CO_2 emissions (incl. biobased) were considered. The role of users of the end-products and the possibility to use the CO_2 generated were highly important when considering environmental perspective. These results can be utilized when selecting the locally most suitable method. In future, some of the treatment methods (i.e. AD, incineration) with CO_2 capture could be considered carbon sinks, as they also remove biobased CO_2 emissions.

Keywords: greenhouse gas emissions; carbon dioxide equivalent; sewage sludge treatment; north; calculator

1. Introduction

Currently, the main environmental threat from biodegradable waste (including sludge) is the generation of methane (EC, 2016). The European Union (EU) Landfill Directive (1999/31/EC) obliged member states to reduce the amount of biodegradable municipal waste that they landfill to 35% of the 1995 level by 2016 to reduce this problem. These waste targets aim to drive a transition from a linear to a circular economy where so-called waste can be turned into a resource (EC, 2014). Sewage sludge, like all biodegradable waste, should be seen as a resource for energy and material production (e.g. Thomsen et al., 2017), which would support the idea of a circular economy. However, there are challenges when considering sewage sludge as a product. It is demanding to define when sludge is waste and when product, and which environmental burdens to allocate to sludge in different cases (see review by Pradel et al., 2016). This is creating challenges when pondering how to treat sludge and how to utilise end-products (e.g. fertilizer, biogas) in future.

The amount of greenhouse gas (GHG) emissions should be one important evaluation aspect due to the climate change when selecting the best and most sustainable sewage sludge treatment technology (UN, 2000). Sewage sludge is treated different ways, e.g. by composting, anaerobic digestion (AD), incineration (mono- and co-incineration), hydrothermal processing or lime stabilisation (Suh and Rousseaux, 2002; Europa, 2017). In Europe, there are four main sewage sludge treatment systems; use as a fertiliser in agricultural land, composting, incineration and landfilling. The Finnish government regulation on landfills (331/2013) includes a ban on landfilling of biodegradable wastes since 2016 (Ministry of the Environment, 2016). For instance, in 2012, Portugal, Ireland, the United Kingdom, Luxembourg and Spain used more than 75% of the sludge generated as fertiliser for agricultural land, while 66-86% of sludge was composted in Lithuania, Finland and Estonia. The Netherlands, Belgium, Germany, Slovenia, Austria and Switzerland used incineration as their most important type of treatment in that year, while Malta, Romania, Italy and Bosnia-Herzegovina mainly landfilled their sludge (Europa, 2017).

It is estimated, that about one million tons of sludge (1 million m^3) is generated annually in Finland (Laitinen et al., 2014). The most commonly used method for treating sludge is currently composting (in Northern Finland windrow composting is particularly common), but the share of anaerobically digested sludge is increasing fast. Both composting and AD need pre and post treatment, possibly maturing in the windrow. Only a very small fraction of sludge is incinerated in co-incineration plants. Incineration plants with permission to incinerate sludge are located only in Central (Vapo Oy, 2013) or Southern Finland (Ekokem Oy Ab, 2010). All sludge treatment methods have advantages and disadvantages (Table 1). Selection of the most suitable method must be based on e.g. both environmental and economic considerations. The challenges in treating biodegradable waste are different in sparsely populated areas of Northern Finland than in densely populated areas in the south, as there are long transport distances (Lehtoranta et al., 2014), small amounts of generated waste, lack of proper recipient facilities (e.g. incineration or AD plants), high establishment costs of a new, well-functioning network and a severe climate, especially during winter (Piippo and Pongrácz, 2016). Decentralised sludge management systems face additional challenges, e.g. possible lack of reliable and continuous supply of feedstock (Righi et al., 2013).

Table 1. Advantages and disadvantages of the different sewage sludge treatment methods.

Treatment	Advantages	Disadvantages
Composting (Pöyry Environment Oy, 2007; Garrido-Baserba et al., 2015	Cheap Easy to establish and manage Short transport distances Production of compost, avoided use of mineral fertilisers Usually local solution providing jobs Usually no need for large-scale facilities	Odour Direct emissions, no possibilities to use the gases produced Possible harmful substances in compost Prone to freezing
Anaerobic digestion (Pöyry Environment Oy, 2007; Garrido-Baserba et al. 2015; Mannina et al., 2016; Piippo and Pongrácz, 2016, Thomsen et al. 2017)	Production of energy, avoided use of e.g. fossil fuels Production of digestate, avoided use of mineral fertilisers Less odours	Rather long transportation distances Possible harmful substances in digestate Very cold winter may cause challenges
Incineration (Pöyry Environment Oy, 2007; Garrido-Baserba et al. 2015; Thomsen et al., 2017)	Production of energy, avoided use of e.g. fossil fuels No odours	Not available in the far north No use of ash as fertiliser Long transport distances Emissions

In addition to the emissions from transport, uncontrolled anaerobic degradation of biodegradable material (e.g. sewage sludge) leads to considerable losses of carbon dioxide (CO_2) and methane (CH_4) (Salomoni et al., 2011). One option to reduce these GHG emissions to the atmosphere is carbon capture and storage (CCS), in which the aim is to capture CO_2 emissions e.g. from power generation and industry and store it permanently (Volkart et al., 2013). CCS has three steps: CO_2

capture (i.e. post-combustion, pre-combustion or oxy-fuel capture systems), CO_2 transportation and CO_2 storage (e.g. in deep reservoirs in geological structures) (Pires et al., 2011). In addition to CCS for the combustion process, controlled AD can be a way to transform biodegradable waste into biogas with almost complete CH_4 and CO_2 recovery and without losses to the atmosphere (Salomoni et al., 2011).

In a life cycle assessment (LCA) study of sludge treatment in France, Suh and Rousseaux (2002) found that a combination of AD and land application of the end-product caused the least emissions during operation. When considering only the economic point of view, a large-scale incineration plant (Piao et al., 2016) or AD plant (e.g. Garrido-Baserba et al., 2015) could be the most efficient way to treat sludge. However, when there are no such existing facilities nearby, costs and emissions from transport can be high (Righi et al., 2013). For instance, according to Pöyry Environment Oy (2007), the profitable transport distance for sludge from wastewater treatment plant (WWTP) to AD plant is about 150-250 km. In northernmost Finland, transport distances to some treatment facilities can easily be much longer.

Even though it is possible to find existing GHG calculators (e.g. Laitinen and Manninen, 2016) and life cycle assessment studies (e.g. Suh and Rousseaux 2002), some wastewater treatment plants and environmental authorities in the northern Finland considered that it is important to find or create new calculator which is as suitable as possible especially for northern conditions. That basic calculation tool should make it possible to compare GHG emissions from composting, AD and incineration since that kind of tool was missing. This information of emissions is needed e.g. to help environmental permit processes in future.

To gain needed information, the first aim of the study was to create a calculator suitable for determining the GHG emissions from different sewage sludge treatment methods under the conditions in Northern Finland. The second aim was to determine which sludge treatment methods (composting, anaerobic digestion, incineration with or without thermal drying) generated the lowest emissions of the GHG CO_2 (including biobased), CH_4 and nitrous oxide (N_2O), expressed as CO_2 equivalents (CO_2eq) in different conditions typical for Northern Finland. As a novel point of view, biobased CO_2 emissions (synonym biogenic; generated from the treatment of biomass) were included in the analysis to identify whether their contribution to total emissions is significant, e.g. for capture and utilisation purposes in future. Six existing wastewater treatment plants (WWTP) located in different areas of Northern Finland were used as the study objects. The distance from the

WWTP to the sludge treatment facility and the amounts of sludge generated varied greatly in the different cases. The starting hypothesis was that in addition to emissions from the main treatment processes, emissions from transport can be considerable due to the very long distances. The emissions were calculated using a developed calculation tool that took into account the high-latitude conditions as much as possible.

2. Material and methods

This study was supported as part of the project "Innovations for CO2 and bioeconomy - greenhouse gases from sludge treatments and novel C1 products". Funder and stakeholders (mentioned in acknowledgements) were willing to have these three treatment methods and six WWTPs to be part of the study.

2.1.Sludge treatment methods

The sludge treatment alternatives studied were: windrow composting; anaerobic digestion; thermal drying and incineration; and incineration without thermal drying. The evaluation did not consider the wastewater treatment itself or the drying of sludge inside the WWTP, but took into account the GHG emissions in the different phases of the sludge management chain (Figure 1). Separate emission coefficients with detailed data and needed values can be found in appendix (Excel sheet) as they are here presented in reference groups. These were: transportation from the WWTP to the sewage sludge treatment facility (LIPASTO, 2012a; Statistics Finland 2016a-c); the sludge treatment process itself (IPCC 2006a-b; Boldrin and Christensen 2010; RTI International, 2010; Manninen and Laitinen 2015; 2016; Manninen et al., 2016; Svenskt Vatten, 2016), including working machinery (LIPASTO, 2012b); transportation of the treated sludge to the utilisation site (LIPASTO, 2012a; Mannina et. al. 2016; Statistics Finland 2016a-c); and emissions from utilisation of the treated sludge (Johnke, 2002; Bruun et al., 2006; IPCC, 2006a-c; Boldrin et al., 2010; Karhu et al., 2012). End-products are e.g. compost or digestate to be used as soil or fertilizer. Also biogas is one of the end-products to be used as energy. The analysis also considered whether it was possible to replace some other material (e.g. mineral fertiliser or peat in landscaping) with the treated sludge end-product and thus reduce the amount of emissions from manufacturing of that material (so-called avoided emissions) (Bruun et al., 2006; Boldrin et al., 2010; Karhu et al., 2012; LIPASTO 2009; Manninen and Laitinen, 2015; Yoshida et al. 2015; Oulun Energia Oy, 2017a). Detailed list of used information and references is also in Postila et al. (2016).

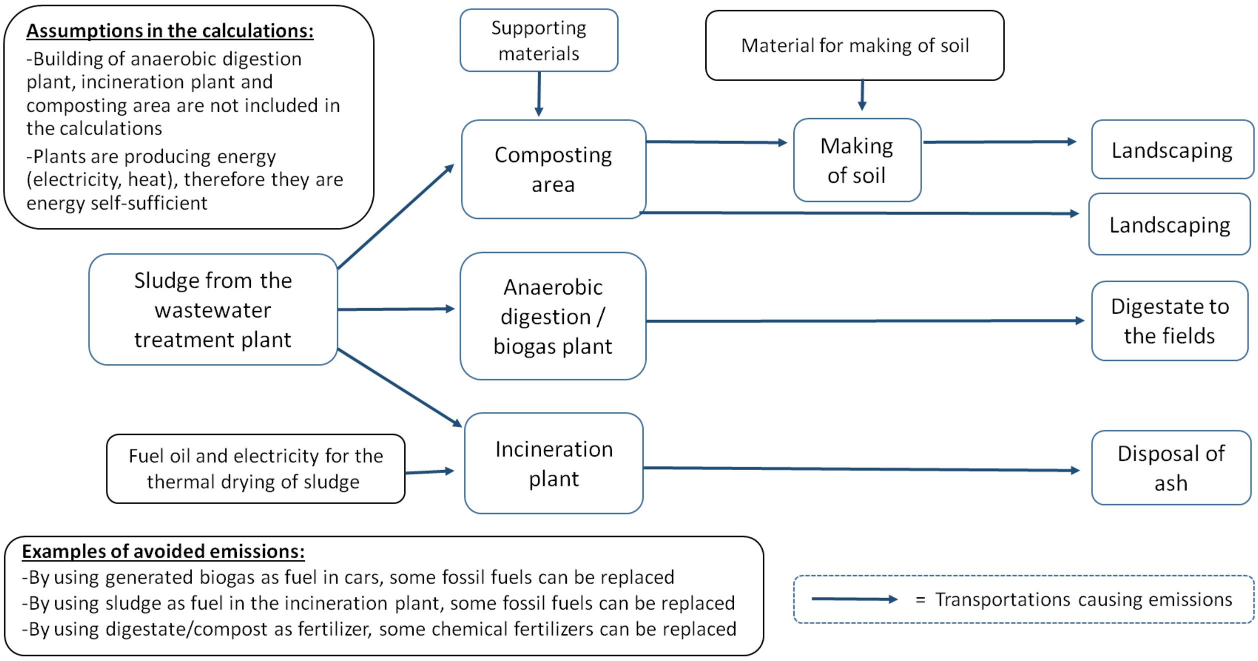

Figure 1. Focus areas and assumptions made in the study

2.2. Study location and sites

Finland is the most sparsely populated country in the EU, with less than 18 inhabitants per square km, while Northern Finland has less than 2 inhabitants per square km (This is Finland, 2014). The surface area of Lapland is over 25% of the total surface area of Finland (land area 338,424 km²), but it has only 3.4% of the population (ELY center for Lapland, 2011). Municipalities are small and far apart and the main road infrastructure may be scarce. There are also great contrasts in climate, since there are cold winters and fairly warm summers. In Northern Finland, the length of the thermal winter (average daily temperature <0°C) is 5-7 months (Finnish Meteorological Institute, 2016). Finnish circumstances are unique so they need to be taken into account when selecting the most suitable treatment method, especially in north. The calculations in this study were based on conditions at six WWTP of different sizes in Northern Finland: two in Northern Ostrobothnia, two in Kainuu and two in Lapland. These WWTP are in the municipalities of Kempele (Lakeuden Keskuspuhdistamo Oy), Oulu (Oulun Vesi, Taskila), Kajaani (Peuraniemi), Sotkamo (Mustola), Inari (Ivalo, Mellanaapa) and Kittilä (Levi) (Figure 2). Basic information gathered from the plants (Table 2) showed great variation, from the very small WWTP in rural Inari (population equivalent (PE) varying from 5,000 up to 15,000 and annual amount of sludge generated 568 t in 2015) to the city of Oulu (PE of 174,200 and annual amount of sludge 37,753 t in 2015). The prevalent or planned treatment methods also vary, from composting to AD, but none of the six plants is incinerating its sludge at the moment. The sludge composting area is usually located near the

WWTP, but the sludge needs to be transported for treatment in an AD plant. At the moment, sludge generated in Oulu is treated with Kemicond (wet-oxidative conditioning process which kills germs and disinfects sludge), but the treatment method is possibly going to change to something else in a few years.

Sludge treatment facilities used in the calculations were windrow composting areas in Oulu, Kempele, Kajaani, Inari and Kittilä; AD plants in Oulu (for WWTPs in Oulu, Kempele, Kajaani and Sotkamo) and Rovaniemi (for WWTPs in Inari and Kittilä); incinerator plants for mechanically dried sludge in Riihimäki and Oulu; and a thermal drying plant and incinerator plant for thermally dried sludge in Haapavesi. All the selected composting areas except that in Kajaani (which is now closed) are currently operating. The AD plant in Oulu is operating and treating sludge, but the AD plant in Rovaniemi is only in the planning phase. The incinerator plant in Oulu does not have permission to incinerate sludge at the moment. The other incineration plants (7 in fig. 2; (Ekokem Oy Ab, 2010) and 8 in fig. 2; (Vapo Oy, 2013)) have permission to incinerate sewage sludge but they are not allowed to incinerate large amounts of it (only about 2-10% of their input material). Plants that are currently not treating sewage sludge were selected for study due to their location and possible future treatment opportunities. In Oulu (capacity of 150,000 t; Oulun Energia Oy, 2017b) and Riihimäki (capacity of 120,000 t; Fortum, 2017), plants are purely waste incineration plants whereas in Haapavesi (capacity about 50,000 t; Vapo Oy, 2013) is co-incineration plant (major fuels peat and wood). More information about the plants can be found in the appendix.

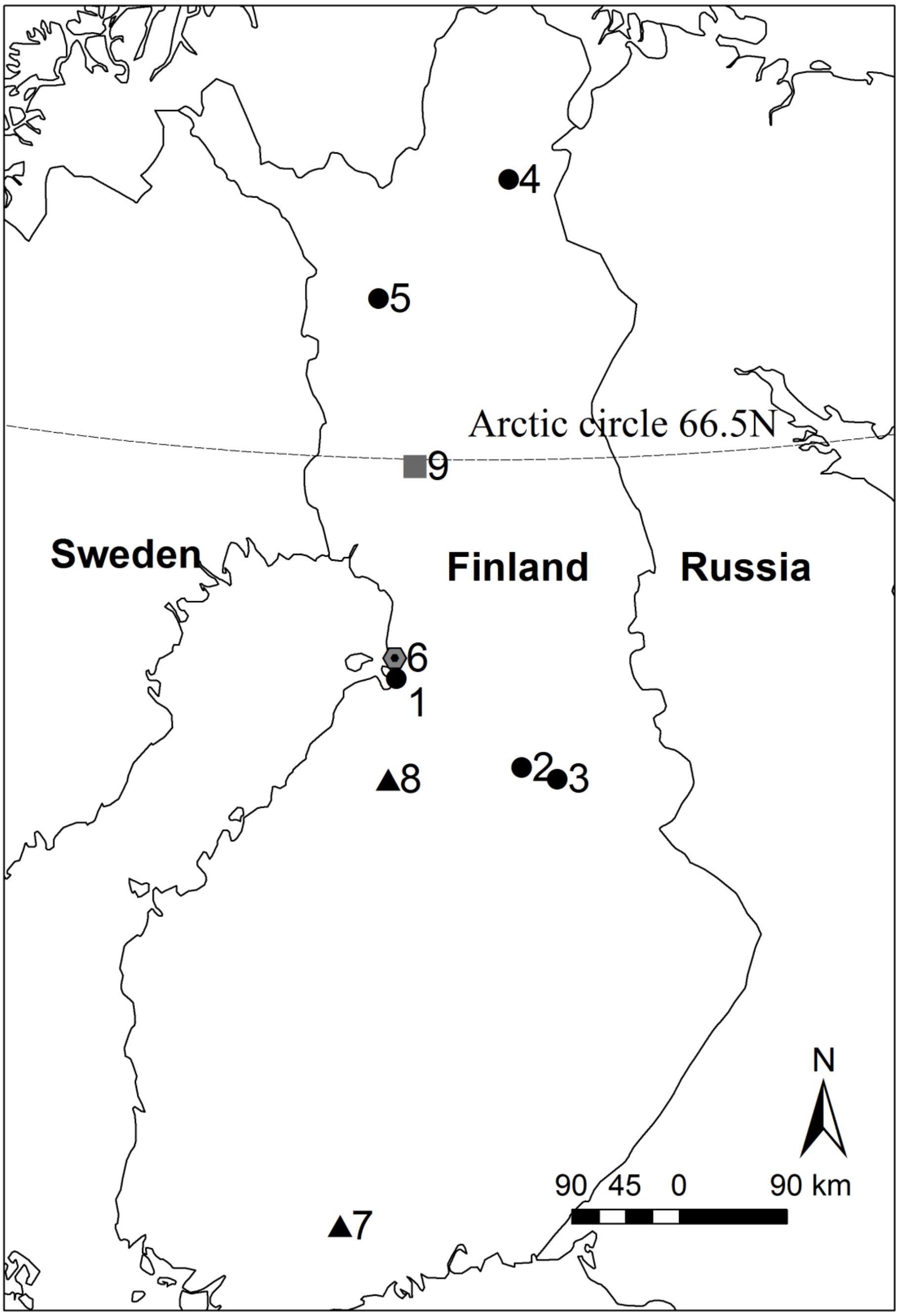

Figure 2. Map showing the location of the wastewater treatment plants studied: 1 = Kempele, 2 = Kajaani, 3 = Sotkamo, 4 = Inari, 5 = Kittilä and 6 = Oulu. One biogas plant and one incineration plant are located at point 6, but it is not allowed to incinerate sewage sludge at the moment. At points 7 (Riihimäki) and 8 (Haapavesi) there are other incineration plants with permission to incinerate part of the sludge. At point 9 (Rovaniemi) there is no existing biogas plant yet, but there are plans for biogas plant construction.

Table 2. Basic information on the six wastewater treatment plants (WWTP) and sewage sludge amounts, properties and transport distances.

WWTP[1]	PE[2]	Total amount of dewatered sludge (t/a)	TS[3] of dewatered sludge (%)[4]	Total amount of TS[3] (t)[4]	kg N/t sludge as TS[3,4]	kg P/t sludge as TS[3,4]	Transport distances from WWTP (km)		
							Composting area	AD plant	Incineration (to Haapavesi, Riihimäki or Oulu)
Oulu	174,200[5]	37,753	21.6	8,149	34.3	19.5	15	7	129 574 7
Kempele (without peat)	41,300[5]	6,000	22.1	1,327	45.4	26.9	1.4	22	114 559 17
Kajaani	28,900[5]	6,500	20.4	1,326	30.3	23.0	0.6 (finished)	178	129 510 187
Sotkamo (without peat)[6]	11,700[5]	1,729	18.8	325	34.0	19.0	-	198	165 542 194
Sotkamo[6]	11,700[5]	2,337	28.2	659	34.0	19.0	40 (finished)	-	-
Inari	15,000[5]/ 5,000[4,7]	568	30.0	170	13.8	14.6	Next to it	300	636 1,080 513
Kittilä	39,000[4,8]/ 21,300[5]	2,231	14.0	335	39.2	19.2	Next to it	180	515 959 392

[1]WWTP = Wastewater treatment plant
[2]PE = Population equivalent
[3]TS = Total solids
[4]Sewage information collected from site-specific information (e.g. from sludge laboratory analysis)
[5]Ministry of the Environment, 2013
[6]Sotkamo sewage sludge information without peat was used in anaerobic digestion (AD) and incineration calculations and the other information (with peat) in composting calculations.
[7]Outside of high season
[8]During high season (water from the tourist centre arriving at the WWTP)

2.3. Creation of the calculator

To identify the most sustainable treatment methods for sewage sludge in terms of GHG emissions, a calculator that is suitable for conditions in Northern Finland was created. First, information and equations from models (calculators), project reports, environmental impact assessment (EIA) reports, environmental permits, articles and other possible sources were collated. The existing calculators evaluated were Nordic, e.g. the Finnish prediction model Kasvener (Finnish Environment Institute and The Association of Finnish Local and Regional Authorities), the Finnish calculator created at Finnish Environment Institute (Manninen and Laitinen 2015; 2016) and the Swedish Klimatpåverkan – beräkningsverktyg: Tool for calculating the carbon footprint for wastewater treatment plants (Svenskt Vatten, 2016). All of these calculators provide valuable information about calculations, values and methods, but none is directly suitable and/or used as such for studies and calculations for Northern Finland. The most suitable emissions coefficients and calculation methods for this study were therefore evaluated by collecting the existing data and information on local conditions in the selected WWTP and GHG emissions from the different phases. If it was not possible to find unambiguous information, a careful estimate was made based on the literature and databanks by taking the most reliable values depending on the source of information (e.g. scientific articles, reports from IPCC and research institutes). The emissions coefficients were taken from reliable and commonly used databanks, e.g. IPCC (2006b-c). Using the global warming potential (GWP) values for methane (28) and nitrogen oxide (265), their emissions were converted into CO_2eq. The GWP of CO_2 is 1 (Greenhouse Gas Protocol, 2016). Only the most important greenhouse gases (CO_2, CH_4 and N_2O) were assessed. Biobased CO_2 emissions) were included in the analysis.

There was a need for some assumptions. As in many cases, there were no exact values relating e.g. to emissions from sludge treatment, so values from bio-waste treatment had to be used. Moreover, few studies (IPCC, 2006c; RTI International 2010) report emission coefficients for composting and the range is very wide, so the average had to be used. In addition, there have been few studies of sludge treatment in the far north and, as expected, no specific emission coefficients for the conditions in Northern Finland were found.

For the evaluation, information about the location of composting areas, AD and incineration plants in the study area (or as near as possible) was collected. Data from all the six WWTP concerning e.g. sludge amounts, composition, treatment and supporting material were obtained from contact individuals at the plants or from responses in questionnaire surveys, telephone interviews and joint meetings. The Microsoft-Excel-based calculator developed (Postila et al., 2016) can itself be modified freely, so whenever emission coefficients change the figures can be changed accordingly. By using the calculator, it was possible to calculate the emissions from composting, AD (where the generated biogas can be used as transport fuel or in a combined heat and power (CHP) plant) and incineration with and without thermal drying of sludge. These selection provides seven different treatment comparisons (composting; AD with two different utilization possibilities of biogas (CHP 100%; or CHP 50% and traffic fuel 50%) and incineration of sludge with thermal drying (two fuel sources: oil or steam with electricity; and incineration in Haapavesi) and with thermal drying (incineration in Oulu or Riihimäki). The results of the calculations were expressed as generated emissions, avoided emissions and net emissions. Generated emissions were also calculated in situations where CO_2 emissions from the composting, AD or incineration process were not taken into account, since they are biobased and their GHG potential is usually assumed to be zero in many calculators (Johnke, 2002; IPCC, 2006c; Manninen and Laitinen, 2015, but see Searchinger et al. 2009).

3. Results and discussion

3.1. Comparison of generated, avoided and net CO_2eq emissions from the six plants

The largest WWTP in Oulu, generated the largest amounts of CO_2eq emissions (Table 3 and 4). Table 3 shows the order of treatment methods measured as t CO2eq of generated emissions for the six plants. Examples of results for the WWTP in Kajaani are shown in Figure 3 and for all six WWTPs in Table 3. Table 4 has not all the seven treatment methods, but examples how the utilization of end-products affect on net emissions via avoided emission. However, as these avoided emissions are not realized at the moment, the generated emissions in Table 3 are representing the existing situation better. In addition to the size of the WWTP, other factors affected the net amount of emissions, e.g. distance from the plant to the treatment facilities, moisture content of the dewatered sludge and the share and content of supporting materials used.

Table 3. Order of treatment methods generated emissions as total t CO_2eq and t CO_2eq / t of sludge in the studied wastewater treatment plants. (1= the best with the least emissions, 7 = the worst with the largest emissions)

	Oulu	Kempele	Kajaani	Sotkamo	Inari	Kittilä
1	AD, use of biogas (50% as vehicle fuel, 50% electricity and heat)	AD, use of biogas (50% as vehicle fuel, 50% electricity and heat)	AD, use of biogas (50% as vehicle fuel, 50% electricity and heat)	AD, use of biogas (50% as vehicle fuel, 50% electricity and heat)	AD, use of biogas (50% as vehicle fuel, 50% electricity and heat)	AD, use of biogas (50% as vehicle fuel, 50% electricity and heat)

	t CO_2eq: 5,233 t CO_2eq/t sludge: 0.14	t CO_2eq: 878 t CO_2eq/t sludge: 0.15	t CO_2eq: 848 t CO_2eq/t sludge: 0.13	t CO_2eq: 220 t CO_2eq/t sludge: 0.13	t CO_2eq: 100 t CO_2eq/t sludge: 0.18	t CO_2eq: 270 t CO_2eq/t sludge: 0.12
2	AD, use of biogas in CHP (100 % heat and electricity) t CO_2eq: 5,765 t CO_2eq/t sludge: 0.15	AD, use of biogas in CHP (100 % heat and electricity) t CO_2eq: 969 t CO_2eq/t sludge: 0.16	AD, use of biogas in CHP (100 % heat and electricity) t CO_2eq: 920 t CO_2eq/t sludge: 0.14	AD, use of biogas in CHP (100 % heat and electricity) t CO_2eq: 238 t CO_2eq/t sludge: 0.14	AD, use of biogas in CHP (100 % heat and electricity) t CO_2eq: 110 t CO_2eq/t sludge: 0.19	AD, use of biogas in CHP (100 % heat and electricity) t CO_2eq: 291 t CO_2eq/t sludge: 0.13
3	Incineration with mechanical drying in Oulu t CO_2eq: 14,485 t CO_2eq/t sludge: 0.38	Incineration with mechanical drying in Oulu t CO_2eq: 2,307 t CO_2eq/t sludge: 0.38	Incineration with mechanical drying in Oulu t CO_2eq: 2,571 t CO_2eq/t sludge: 0.40	Incineration with thermal drying (using electricity and steam) (Haapavesi) t CO_2eq: 646 t CO_2eq/t sludge: 0.37	Incineration with mechanical drying in Oulu t CO_2eq: 237 t CO_2eq/t sludge: 0.42	Composting with soil manufacturing t CO_2eq: 627 t CO_2eq/t sludge: 0.28
4	Incineration with mechanical drying in Riihimäki t CO_2eq: 15,863 t CO_2eq/t sludge: 0.42	Incineration with mechanical drying in Riihimäki t CO_2eq: 2,552 t CO_2eq/t sludge: 0.43	Incineration with thermal drying (using electricity and steam) (Haapavesi) t CO_2eq: 2,615 t CO_2eq/t sludge: 0.40	Incineration with mechanical drying in Oulu t CO_2eq: 684 t CO_2eq/t sludge: 0.40	Incineration with mechanical drying in Riihimäki t CO_2eq: 260 t CO_2eq/t sludge: 0.46	Incineration with thermal drying (using electricity and steam) (Haapavesi) t CO_2eq: 677 t CO_2eq/t sludge: 0.30
5	Incineration with thermal drying (using electricity and steam) (Haapavesi) t CO_2eq: 16,037 t CO_2eq/t sludge: 0.43	Incineration with thermal drying (using electricity and steam) (Haapavesi) t CO_2eq: 2,607 t CO_2eq/t sludge: 0.43	Incineration with mechanical drying in Riihimäki t CO_2eq: 2,626 t CO_2eq/t sludge: 0.40	Incineration with mechanical drying in Riihimäki t CO_2eq: 735 t CO_2eq/t sludge: 0.43	Incineration with thermal drying (using electricity and steam) (Haapavesi) t CO_2eq: 353 t CO_2eq/t sludge: 0.62	Incineration with mechanical drying in Oulu t CO_2eq: 912 t CO_2eq/t sludge: 0.41
6	Composting with soil manufacturing t CO_2eq: 19,048 t CO_2eq/t sludge: 0.50	Composting with soil manufacturing t CO_2eq; 3,255 t CO_2eq/t sludge: 0.54	Composting with soil manufacturing t CO_2eq: 3,654 t CO_2eq/t sludge: 0.56	Incineration with thermal drying (using electricity and oil) (Haapavesi) t CO_2eq: 954 t CO_2eq/t sludge: 0.55	Incineration with thermal drying (using electricity and oil) (Haapavesi) t CO_2eq: 448 t CO_2eq/t sludge: 0.79	Incineration with mechanical drying in Riihimäki t CO_2eq: 993 t CO_2eq/t sludge: 0.45
7	Incineration with thermal drying	Incineration with thermal drying (using	Incineration with thermal drying (using	Composting with soil manufacturing	Composting with soil manufacturing	Incineration with thermal drying (using

	(using electricity and oil) (Haapavesi) t CO_2eq: 22,608 t CO_2eq/t sludge: 0.60	electricity and oil) (Haapavesi) t CO_2eq: 3,650 t CO_2eq/t sludge: 0.61	electricity and oil) (Haapavesi) t CO_2eq: 3,728 t CO_2eq/t sludge: 0.57	t CO_2eq: 1,465 t CO_2eq/t sludge: 0.63	t CO_2eq: 469 t CO_2eq/t sludge: 0.83	electricity and oil) (Haapavesi) t CO_2eq: 1,080 t CO_2eq/t sludge: 0.48

Table 4. Generated, avoided and net emissions as CO_2eq. Generated without CO_2 means that CO_2 emissions from the composting, anaerobic digestion or incineration process were not included because they are considered to be biobased, with no negative effects on the climate.

		Oulu	Kempele	Kajaani	Sotkamo	Inari	Kittilä
Composting	Generated with CO_2	19,048	3,255	3,654	1,465	469	627
	Generated without CO_2	11,438	1,910	2,140	840	255	412
	Avoided with CO_2	2,355	373	405	125	37	169
	Net with CO_2	16,693	2,882	3,249	1,340	432	458
Anaerobic digestion	Generated with CO_2	5,765	969	920	238	110	291
	Generated without CO_2	1,830	297	387	105	39	133
	Avoided with CO_2	4,613	787	627	157	84	187
	Net with CO_2	1,151	182	293	81	26	104
Incineration without thermal drying (Riihimäki)	Generated with CO_2	15,863	2,552	2,626	735	260	993
	Generated without CO_2	2,649	452	351	130	61	212
	Avoided with CO_2	7,686	1,222	1,323	352	116	454
	Net with CO_2	8,177	1,330	1,303	383	144	539
Incineration with thermal drying by using electricity and steam (Haapavesi)	Generated with CO_2	16,073	2,607	2,615	646	353	677
	Generated without CO_2	1,405	219	229	61	46	115
	Avoided with CO_2	8,538	1,388	1,388	340	178	327
	Net with CO_2	7,535	1,219	1,227	306	175	350

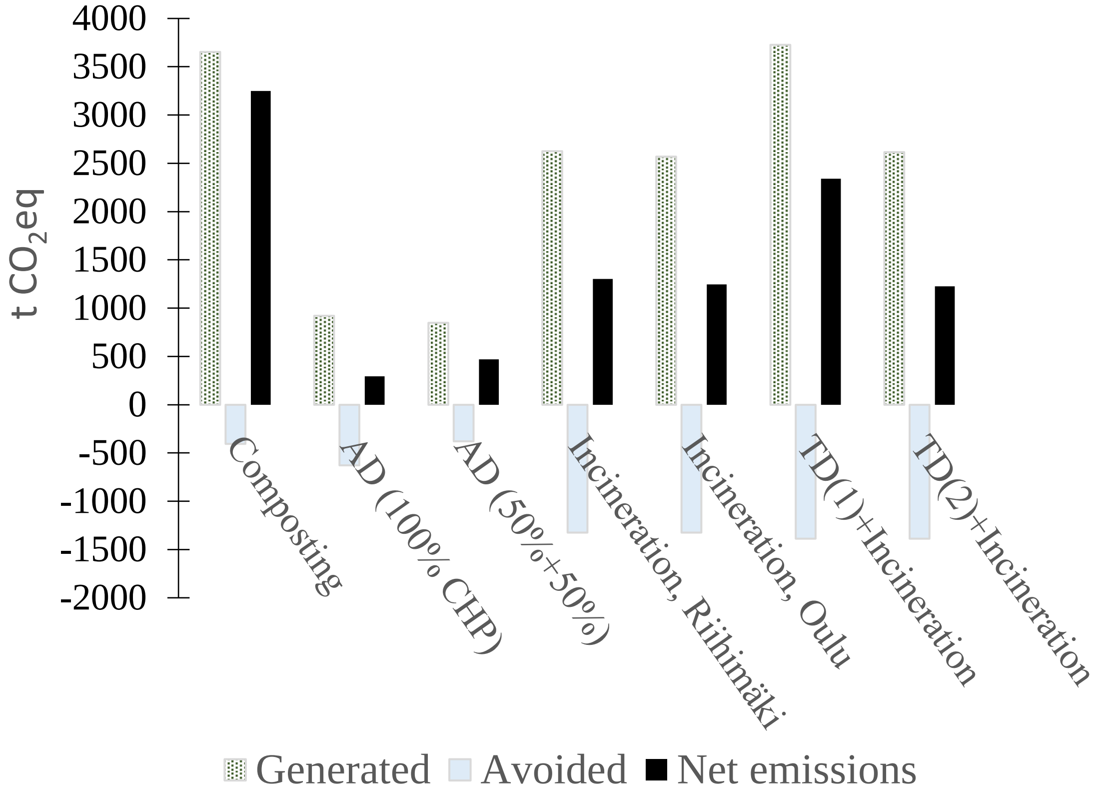

Figure 3. Generated, avoided and net greenhouse gas emissions (t CO_2eq) in different sewage sludge treatment alternatives in Kajaani. Composting includes soil manufacturing. Anaerobic digestion (AD) was divided into two alternatives, where all biogas was utilised in CHP production or where 50% was utilised in CHP production and 50% in transport fuel production. Emissions from incineration without thermal drying were calculated in the theoretical situations where the sludge could be incinerated in Riihimäki or Oulu. The next two incineration calculations included thermal drying (TD): (1) drying with electricity and oil, and (2) drying with electricity and steam.

When considering the different treatment methods, based on the calculations, the lowest generated emissions were obtained for AD of sludge, where the biogas generated was used both for processing traffic biogas and for CHP (Figure 3, Table 3) or for CHP purely. The second best option in terms of CO_2eq emissions was incineration without thermal drying or when dried with steam except in Kittilä, where composting was the second best option due to high sludge moisture content, long transport distances and lack of soil manufacturing from the composted material. The highest generated emissions were from thermal drying of sludge with electricity and light fuel oil and incineration of thermally dried sludge or from windrow composting of sludge, depending on the sewage treatment plant (Table 3). Greenhouse gases can be avoided if e.g. biogas replaces fossil fuel and soil or digestate replaces fertiliser. Avoided emissions were lower than generated emissions in every case. Manninen and Laitinen (2015) found that only AD could generate more avoided emissions than generated emissions, and not other methods (incineration and composting), but they studied emissions without biobased CO_2 emissions. Also Suh and Rousseaux (2002) found in their LCA study of sludge treatment in France that a combination of AD and land application of the end-product caused the lowest emissions during operation.

3.2. Comparison of CO_2eq emissions in different phases of the treatment chain

Based on the results of all six WWTP (Figures 4a, 5a, 6a, 7a), it was found that most of the emissions were generated from the treatment process itself, while the share of emissions generated during transport was minimal despite the long transport distances. This outcome was the same regardless of the treatment method (composting, AD, incineration), the amount of sludge or the transport distance. The avoided emissions in the AD and incineration processes consisted mainly of avoided energy production in the CHP plant using fossil fuels, by using other sources (Figure 8). In the composting process, the avoided emissions mainly came from the possibility to replace peat in landscaping.

3.3. Comparison of the results with and without biobased CO_2 emissions

Comparing the results with and without inclusion of biobased CO_2 emissions in the composting, AD or incineration process itself, it was found that the effect of biobased emissions was considerable (Figures 4-7 and Table 3). When biobased emissions were included in the calculations, total CO_2eq emissions were much higher, in some treatments several times higher, than when they were omitted. In composting total CO_2eq emissions were 469-19,048 tons with and 255-11,438 tons without biobased; in AD 110-5,765 tons with and 39-1,830 tons without biobased; in incineration without thermal drying 260-15,863 tons with and 61-2,649 tons without biobased; and in incineration after thermal drying 353-16,073 tons with and 46-1,405 tons without biobased emissions.

In situation where biobased emissions were omitted, avoided emissions were higher than generated emissions in every case except in composting. For the case without biobased emissions, the share (percentage) of emissions from e.g. transport was high compared with that when biobased emissions were included (e.g. ca. 39% versus 14% in AD in Inari, Figure 5; and ca. 64% versus ca. 11% in Kittilä in incineration after thermal drying, Figure 7). Also the share of emissions from the use of electricity is high in Figure 7. In studies of Lehtoranta et al. (2104) considering emissions from small, rural on-site WWTP in Finland, use of electricity and the transport of sludge to centralized treatment were found to be the major causes of carbon footprints. This is in line with our results without biobased emissions.

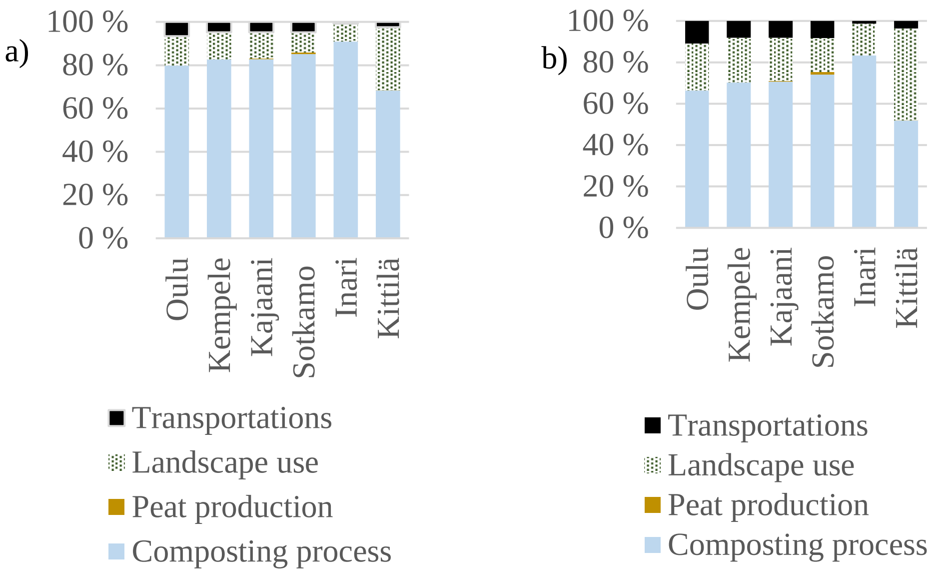

Figure 4. Percentages of generated emissions as CO_2eq in different phases of the sewage sludge composting process and utilisation of compost for landscaping purposes. 100% is the total amount of emissions generated. a) Generated emissions with CO_2 emissions from composting included, and b) generated emissions with CO_2 emissions from composting process excluded. Transport included working machines needed in the composting area.

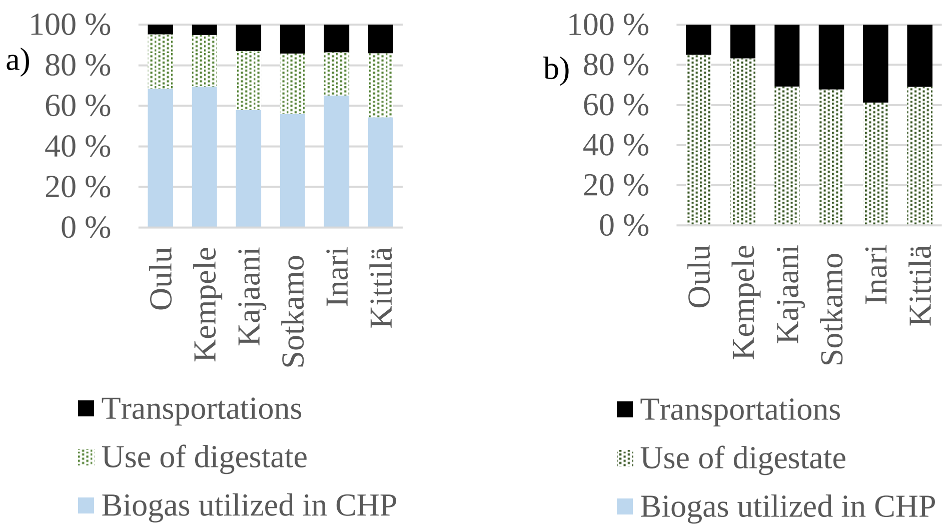

Figure 5. Percentages of generated emissions as CO_2eq in different phases of the sewage sludge anaerobic digestion (AD) process with biogas utilised in CHP production and digestate as fertiliser in agricultural fields. 100% is the total amount of emissions generated. The AD plant was assumed to be located in Rovaniemi (for Inari, Kittilä; plant in the planning phase) or in Oulu (for other WWTP). a) Generated emissions with CO_2 emissions from anaerobic digestion included, and b) generated emissions with CO_2 emissions from anaerobic digestion excluded.

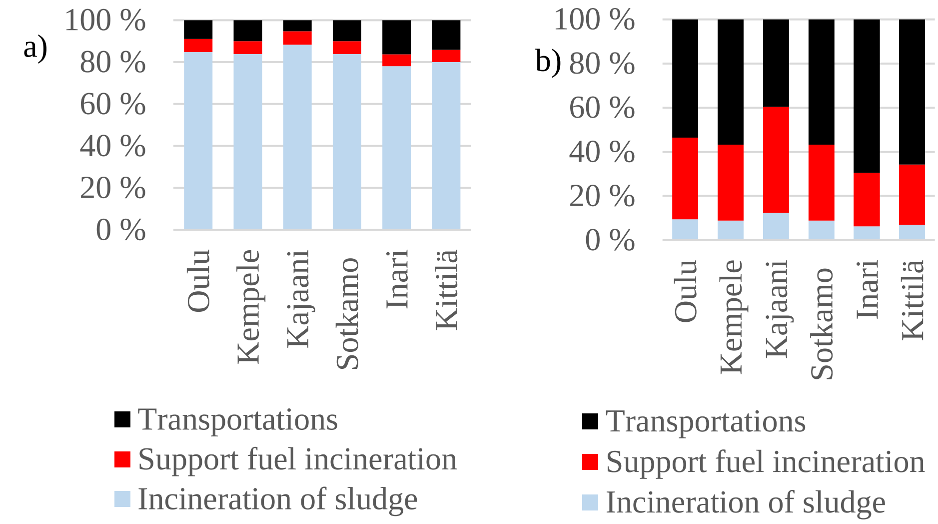

Figure 6. Percentages of generated emissions as CO_2eq in different phases of the sewage sludge incineration process for sludge incinerated in Riihimäki without thermal drying (theoretical option). 100% is the total amount of emissions generated. a) Generated emissions with CO_2 emissions from incineration included, and b) generated emissions with CO_2 emissions from incineration excluded.

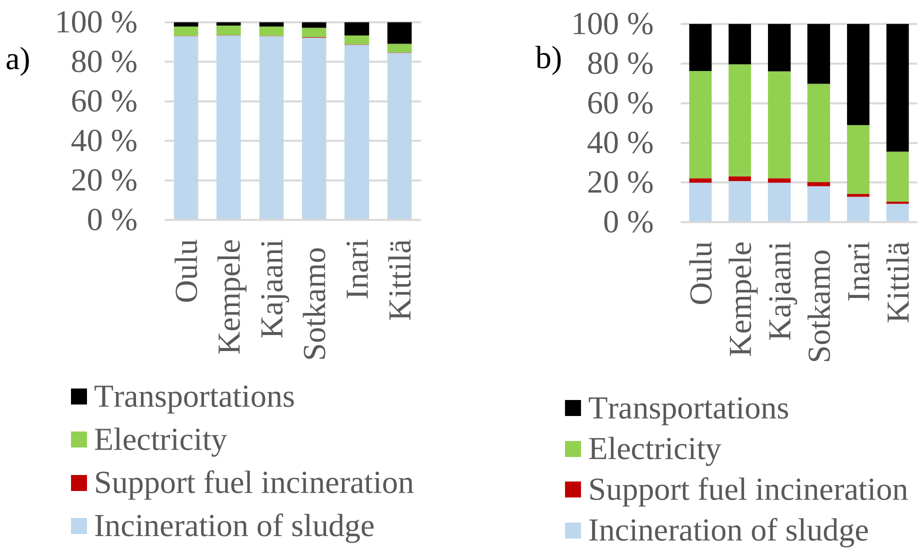

Figure 7. Percentages of generated emissions as CO_2eq in different phases of the sewage sludge incineration process with sludge incinerated in Haapavesi with thermal drying with electricity and steam (theoretical option). 100% is the total amount of emissions generated. For steam, CO_2eq emissions were expected to be zero. a) Generated emissions with CO_2 emissions from incineration included, and b) generated emissions with CO_2 emissions from incineration excluded.

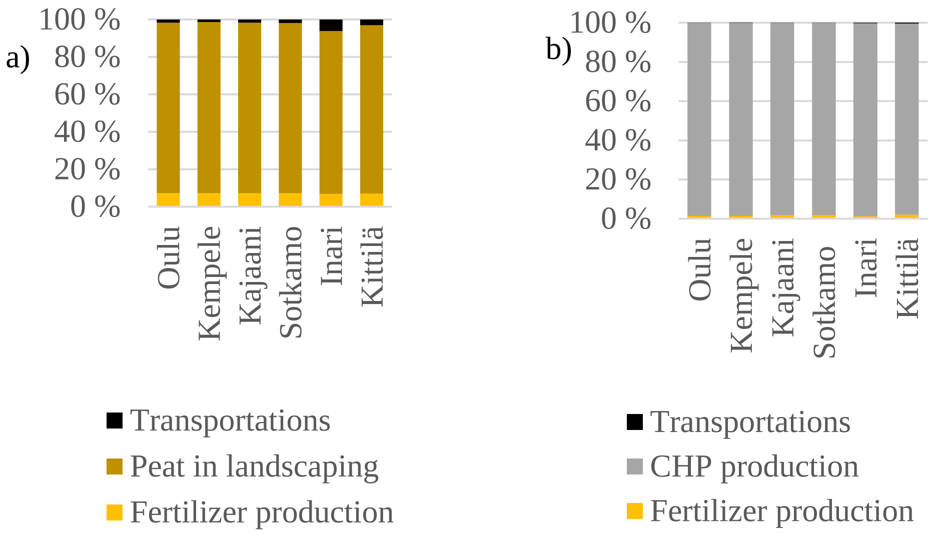

Figure 8. Percentages of avoided emissions as CO_2eq: a) from composting when using compost in landscaping to replace fertiliser and peat, b) from anaerobic digestation when using digestate as fertiliser on agricultural fields to replace fertiliser and when using biogas in a CHP plant to replace other energy sources (calculations assumed a combination of peat (52%), oil (4%), wood (28%) and waste (16%) as sources in Oulu energy CHP production in 2015 (Oulun Energia Oy 2017a)). 100% is the total amount of emissions generated. Some emissions are really low so they are not very visible in the figures.The energy from incineration was assumed to be utilised in a CHP plant, and the avoided emissions were 100% due to replacement of the other energy sources.

4. Discussion

In order to realise the avoided emissions, users of the end-products are needed, e.g. to utilise the generated biogas and compost or digestate. It was found that using sludge instead of fossil oil or other fuels to produce energy for the thermal heating of sludge reduced the emissions considerably. This was also true for the AD plant, as the generation of energy from biogas replaced the use of fossil-based fuels in vehicles and fossil and biobased fuels (wood, peat) in the CHP plant. When considering both the environmental perspectives and cost efficiency of the selected sludge treatment methods, the role of users of the end-products is highly important. In order to improve the possibilities to use the digestate or compost, it is necessary to know the exact chemical and physical composition of sludge so that the end-product can be used safely (Righi et al., 2013; Ahmad et al., 2016) To improve the generation and use of biogas, optimisation of biogas production (e.g. by increasing the biodegradation rate of volatile solids (VS)) is important when considering the environmental impacts (Gourdet et al., 2016). It is noteworthy that use of the end-product (e.g. digestate) not only fulfils the aim of a circular economy, but also has positive environmental impacts due to avoided emissions from manufacture, transport and use of mineral fertilisers and improved soil properties (Thomsen et al., 2017).

Our results also suggests that capturing and utilising the gases generated in sludge treatment systems can have a notable effect on the GHG emissions from the treatment chain, since it cannot be done in all treatment methods studied. This is especially important when considering biobased CO_2 emissions, which are usually not included in the calculations (Johnke, 2002; IPCC, 2006c; Manninen and Laitinen, 2015, but see Searchinger et al. 2009). If CO_2 could be captured from the emissions stream, for instance in the case of incineration or AD, this would have significant benefits for the GHG balance (Salomoni et al., 2011). Such treatment methods with CO_2 capture could even be considered carbon sinks, since they remove biobased CO_2 emissions.

5. Conclusions

This study examined commonly used sewage sludge treatment alternatives in terms of amounts of GHG emissions produced under the conditions in Northern Finland. There was need to find the most environmentally sustainable treatment method by creating the suitable calculator with possibility to include or exclude biobased CO_2 emissions. Anaerobic digestion of sludge was found to result in the lowest amount of emissions of the different treatment methods in all the six WWTP studied. The second best option was usually incineration of sludge without thermal drying. The third best was composting or incineration of sludge after thermal drying with e.g. fossil or other fuels. Although transport distances are long in Northern Finland, the share of emissions from transport was found to be rather low compared with the emissions from the treatment process itself when including biobased CO_2 emissions. However, when only non-biobased emissions were considered, the share of transportation was considerable. These results will help the decision makers to select the most suitable solution for the treatment methods. It is noteworthy, that as the number of plants and treatment methods in this study is limited, these results cannot be generalized

In addition to GHG emissions, the locally most suitable sludge treatment method depends on e.g. costs and existing infrastructure. Moreover, sludge should be viewed not as waste, but as a useful material that could be valuable for fuel and fertiliser production and also as a CO_2 resource for possible utilisation. As capturing and utilising the gases from sludge treatment processes has significant benefits for the GHG balance, some (AD, incineration) treatment methods with CO_2 capture can even be considered carbon sinks, since they also remove biobased CO_2 emissions. This novel finding (importance of local conditions and careful consideration of CCS possibilities) in our study needs more research in the future.

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References:

Ahmad, T., Ahmad, K., Alam, M., 2016. Sustainable management of water treatment sludge through 3'R' concept. J. Cleaner Production 124: 1-13.

Boldrin, A., Christensen, T. H., 2010. Seasonal generation and composition of garden waste in Aarhus (Denmark). Waste management, 30: 551-557.

Boldrin A., Hartling K. R., Laugen M., Christensen T. H., 2010. Environmental inventory modelling of the use of compost and peat in growth media preparation. Resources, Conservation and Recycling, 54: 1250–1260

Bruun S., Lund Hansen T., Christensen T. H., Magid J., Jensen L. S., 2006. Application of processed organic municipal solid waste on agricultural land Y a scenario analysis. Environmental Modeling and Assessment 11: 251-265.

EC, 2014. Environment: Higher recycling targets to drive transition to a Circular Economy with new jobs and sustainable growth. European Commission, press release. http://europa.eu/rapid/press-release_IP-14-763_en.htm (accessed 1.7.2017)

EC, 2016. Biodegradable Waste. European Commission web pages. http://ec.europa.eu/environment/waste/compost/index.htm (accessed 1.7.2017)

Ekokem Oy Ab, 2010. Application for the permit for the waste incineration plant of municipal, industrial and commercial waste of Ekokem Oy Ab (in Riihimäki) with pretreatment operations Decision Nro 56/2010/1, Dnro ESAVI/81/04.08/2010. (In Finnish).

ELY center for Lapland, 2011. Lapland's regional waste plan until 2020. (In Finnish).Centre for Economic development, Transport and the Environment for Lapland.

Europa, 2017. Water statistics. http://ec.europa.eu/eurostat/statistics-explained/index.php/Water_statistics (accessed 1.7.2017)

Finnish Meteorological Institute, 2016.Winter weather statistics. (In Finnish). http://ilmatieteenlaitos.fi/talvitilastot (accessed 1.7.2017)

Fortum, 2017. Annual report 2016 of air quality and state of the environment of Fortum Waste Solutions OY (previous Ekokem OYJ) (In Finnish)

Garrido-Baserba, M., Molinos-Senante, M., Abelleira-Pereira, J.M., Fdez-Güelfo, L.A., Poch, M., Hernández-Sancho, F., 2015. Selecting sewage sludge treatment alternatives in modern wastewater treatment plants using environmental decision support systems. J Cleaner Production. 107: 410-419.

Gourdet, C., Girault, R., Berthault, S., Richard, M., Tosoni, J., Pradel, M., 2017. In quest of environmental hotspots of sewage sludge treatment combining anaerobic digestion and mechanical dewatering: A life cycle assessment approach. J Cleaner Production. 143: 1123-1136.

Greenhouse Gas Protocol, 2016. Global Warming Potential Values. www.ghgprotocol.org/calculation-tools/all-tools (accessed 1.7.2017)

IPCC, 2006a. Guidelines for National Greenhouse Gas Inventories, Overview. www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/0_Overview/V0_1_Overview.pdf (accessed 1.7.2017)

IPCC, 2006b. Guidelines for National Greenhouse Gas Inventories, Volume 2, Chapter 2: Stationary combustion. www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf (accessed 1.7.2017)

IPCC, 2006c. Guidelines for National Greenhouse Gas Inventories, Volume 5, Chapter 4: Biological treatment of solid waste. www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_4_Ch4_Bio_Treat.pdf (accessed 1.7.2017)

Johnke, B., 2002. Emissions from waste incineration. p. 455-468. In IPCC, 2002. Good practice guidance and uncertainty management in national greenhouse gas inventories. www.ipcc-nggip.iges.or.jp/public/gp/bgp/5_3_Waste_Incineration.pdf (accessed 1.7.2017)

Karhu, K., Gärdenäs, A. I., Heikkinen, J., Vanhala, P., Tuomi, M., Liski, J., 2012. Impacts of organic amendments on carbon stocks of an agricultural soil — Comparison of model-simulations to measurements. Geoderma, 189–190: 606–616

Laitinen, J., Alhola, K., Manninen, K., Säylä, J., 2014. Treatment of the sewage sludge and bio-waste with nutrient recycling. Project report. (In Finnish). Finnish Environment Institute.

The Landfill Directive (1999/31/EC)

Lehtoranta, S., Vilpas, R., Mattila, T.J., 2014. Comparison of carbon footprints and eutrophication impacts of rural on-site wastewater treatment plants in Finland. J Cleaner Production 65: 439-446.

LIPASTO, 2009. LIPASTO. Traffic emissions, water traffic, emissions from ships. (In Finnish). http://lipasto.vtt.fi/yksikkopaastot/tavaraliikenne/vesiliikenne/tankkeri.htm (accessed 1.7.2017)

LIPASTO, 2012a. LIPASTO. Traffic emissions, road traffic, emissions from transortation. (In Finnish). http://lipasto.vtt.fi/yksikkopaastot/tavaraliikenne/tieliikenne/tavara_tie.htm (accessed 1.7.2017)

LIPASTO, 2012b. Average emissions of diesel vehicles (work machinery) in Finland in 2011. (In Finnish). http://lipasto.vtt.fi/yksikkopaastot/muut/tyokoneet/diesel_a_k.htm (accessed 1.7.2017)

Mannina, G., Ekama, G., Caniani, D., Cosenza, A., Esposito, G., Gori, R., Garrido-Baserba, M., Rosso, D., Olsson G., 2016. Greenhouse gases from wastewater treatment - A review of modelling tools. Science of the Total Environment 551–552: 254–270.

Manninen K., Laitinen J., 2015. Calculation methods for wastewater treatment. Finnish Environment Institute. (In Finnish).

Manninen K., Laitinen J., 2016. Calculation methods for wastewater treatment. Production of biogas, incineration, and composting of sludge. Excel based calculator. Finnish Environment Institute. (In Finnish).

Ministry of the Environment, 2013. Determining the presence of wastewater harmful substances to the aquatic environment by municipal wastewater treatment plants (In Finnish). Dnr YM9/401/2013.

Ministry of the Environment, 2016. Waste Act Reform. (In Finnish). www.ym.fi/en-US/Latest_news/Publications/Fact_sheets (accessed 1.7.2017)

Oulun Energia Oy, 2017a. Locally and regionally supplied energy. https://www.oulunenergia.fi/en/energy-and-environment/energy-production/locally-and-regionally-supplied-energy (accessed 1.7.2017)

Oulun Energia Oy, 2017b. Laanila Eco Power plant. https://www.oulunenergia.fi/energia-ja-ymparisto/energiantuotanto/voimalaitokset/laanilan-ekovoimalaitos (accessed 21.12.2017)

Piao, W., Kim, Y., Kim, H., Kim, M., Kim C., 2016. Life cycle assessment and economic efficiency analysis of integrated management of wastewater treatment plants. J Cleaner Production 113: 325-337.

Piippo, S., Pongrácz, E., 2016. Sustainable bio-waste management in Finland: One country, several strategies. Waste Management 47: I

Pires, J.C.M., Martins, F.G., Alvim-Ferraz, M.C.M., Simões, M., 2011. Recent developments on carbon capture and storage: An overview. Chemical Engineering Research and Design. 89: 1446-1460

Postila, H., Lauronen, M., Piippo, S., 2016. Sludge treatment GHG calculator. (In Finnish). www.vvy.fi/ajankohtaista/co2-bio_-hankkeessa_verrattiin_jatevesilietteen_eri_kasittelyvaihtoehtojen_kasvihuonekaasupaastoja_pohjoisissa_olosuhteissa.5845.news (accessed 1.7.2017)

Pradel, M., Aissani, L., Villot, J.., Baudez, J-C., Laforest, V., 2016. From waste to value added product: towards a paradigm shift in life cycle assessment applied to wastewater sludge – a review. J Cleaner Production. 131: 60-75

Pöyry Environment Oy, 2007. Present state of the sludge management and the competitivity of different methods in Finland. Report. (In Finnish). www.sitra.fi/julkaisut/lietteenkasittelyn-nykytila-suomessa-ja-kasittelymenetelmien-kilpailukyky-selvitys/ (accessed 1.7.2017)

Righi, S., Oliviero, L., Pedrini, M., Buscaroli, A., Della Casa, C., 2013. Life Cycle Assessment of management systems for sewage sludge and food waste: centralized and decentralized approaches. J Cleaner Production 44: 8-17.

RTI International, 2010. Greenhouse Gas Emissions Estimation Methodologies for Biogenic Emissions from Selected Source Categories: Solid Waste Disposal, Wastewater Treatment, Ethanol Fermentation, Draft. www3.epa.gov/ttnchie1/efpac/ghg/GHG_Biogenic_Report_draft_Dec1410.pdf (accessed 1.7.2017)

Salomoni, C., Caputo, A., Bonoli, M., Francioso, O., M.T. Rodriguez-Estrada, M.T., Palenzona, D., 2011. Enhanced methane production in a two-phase anaerobic digestion plant, after CO_2 capture and addition to organic wastes. Bioresource Technology 102: 6443-6448.

Searchinger, T.D., Hamburg, S.P., Melillo, J., Chameides, W., Havlik., P., Kammen, D.M., Likens, G.E., Lubowski, R.N., Obersteiner, M., Oppenheimer, M., Robertson, G.P., Schlesinger, W.H., Tilman, G.D., 2009.Fixing a Critical Climate Accounting Error. Science 326: 527-528.

Suh, Y.-J., Rousseaux, P., 2002. An LCA of alternative wastewater sludge treatment scenarios. Resources, Conservation and Recycling 35: 191-200.

Statistics Finland, 2016a. Classification of fuels. Definitions of the fuels and energy sources 2016. (In Finnish). www.stat.fi/static/media/uploads/tup/khkinv/polttoaineluokitus_maaritelmat_2016_fi.pdf (accessed 1.7.2017)

Statistics Finland, 2016b. Classification of fuels, excel file. (In Finnish). www.stat.fi/tup/khkinv/khkaasut_polttoaineluokitus.html (accessed 1.7.2017)

Statistics Finland, 2016c. Energy consumption of traffic calculator. Share of gasolin and diesel in energy consumption of the road traffic in 2016. (In Finnish).

http://pxnet2.stat.fi/PXWeb/pxweb/fi/StatFin/StatFin__ene__ehk/085_ehk_tau_121_fi.px (accessed 1.7.2017)

Statistics Finland, 2016d. Energy consumption of traffic calculator. Share of gasolin and diesel in energy consumption of the road traffic in 2016. (In Finnish). (In Finnish). http://pxnet2.stat.fi/PXWeb/pxweb/fi/StatFin/StatFin__ene__ehk/085_ehk_tau_121_fi.px/table/tableViewLayout1/?rxid=aae4bd2e-afcd-4869-9caf-50e6a5eeb07e (accessed 1.7.2017)

Svenskt Vatten, 2016. Kilmatpåverkan-beräkningsverktyg. (In Swedish). http://va-tekniksodra.se/klimatpaverkan-berakningsverktyg/ (accessed1.7.2017)

This is Finland, 2014. Finland in facts. http://finland.fi/Public/default.aspx?contentid=160032&nodeid=41803&culture=en-US (accessed 1.7.2017)

Thomsen, M., Seghetta, M., Mikkelsen, M.H., Gyldenkaerne, S., Becker, T., Caro, D. 2017. Comparative life cycle assessment of biowaste to resource management systems – A Danish case study. J Cleaner Production 142: 4050-4058.

UN, 2000. United Nations millennium development goals.

Vapo Oy, 2013. Revision of the regulations in environmental permit and the functional change of the operation of Haapavesi power plant, Haapavesi. Decision Nro 123/2013/1, Dnro PSAVI/362/04.08/2010. (In Finnish).

Volkart, K., Bauer, C., Boulet, C., 2013. Life cycle assessment of carbon capture and storage in power generation and industry in Europe. International Journal of Greenhouse Gas Control, 16: 91-106.

Yoshida H., Nielsen M. P., Scheutz C., Jensen L. S., Christensen T. H., Nielsen S., Bruun S., 2015. Effects of sewage sludge stabilization on fertilizer value and greenhouse gas emissions after soil application. Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, 65: 506–516.

Highlights

- Northern conditions need to be taken into account in the sludge management
- Calculator suitable for determining the greenhouse gas emissions was created
- Inclusion of biobased CO_2 emissions was novel feature of the study
- Anaerobic digestion generated the least CO2 equivalent emissions
- Capturing of CO_2 from the emission stream would benefit GHG balance