Liquid fertilizer products from anaerobic digestion of food waste: mass, nutrient and energy balance of four digestate liquid treatment systems

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Abstract

This study compared four different digestate liquid treatment systems of a theoretical anaerobic digestion plant in order to facilitate the utilization of municipal food waste nutrients in agriculture. The mass, nutrient and energy balances of a theoretical plant digesting 60 kt/y of food waste were used to evaluate the feasibility of the treatments to concentrate nutrients into liquid fertilizer products. The studied technologies for digestate liquid treatment were ammonia stripping, ammonia stripping combined with reverse osmosis (RO), evaporation combined with RO, and stripping combined with both evaporation and RO. As a result, processing of digestate into concentrated fertilizer products consumed less than 10% of the produced energy from food wastes and was also sufficient for the heat-demanding digestate liquid treatments, evaporation and stripping. The digestate liquid treatment systems were considered as nitrogen and potassium concentration methods which were able to concentrate up to

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67% of the feedstock nitrogen into transportable fertilizer products with low mass. Of the studied digestate systems evaporation combined with RO was evaluated as the most efficient nutrient recovery technology for the production of transportable fertilizer products due to the high concentration of nutrients and nutrient availability as well as low product mass and energy consumption. Overall, the selection of the treatment technology is dependent on the location of the anaerobic digestion plant relative to the agricultural land and the type of fertilizer products needed.

Keywords

Anaerobic digestion, food waste, digestate liquid treatment, stripping, evaporation, reverse osmosis

1. Introduction

Anaerobic digestion (AD) of food waste (FW) is increasingly used to produce renewable energy, in the form of heat and power or vehicle fuel, and nutrient-rich digestate for agriculture, to decrease the use of energy intensive mineral fertilizers (Laureni et al., 2013). However, the digestate has usually unbalanced nutrient ratios for plant growth (Camilleri-Rumbau et al., 2014). Large mass due to high water content increases the transportation need of the digestate, as the AD plants treating municipal FW are usually located far from agricultural lands (Babson et al., 2013). Digestate treatment by solid-liquid separation is an increasingly used treatment for the production of phosphorus containing solid digestate and liquid digestate containing water-soluble nitrogen and potassium. The solid-liquid separation of the digestate divides most of the mass into the liquid fraction decreasing its nutrient concentrations (Hjorth et al., 2010). Low nutrient concentrations and large mass complicate the use of the liquid digestate in agriculture and increase the transportation need (Chiumenti et al., 2013). To efficiently utilize the FW nutrients, the treatment of liquid digestate is needed to decrease its mass and increase nutrient concentrations.

The digestate liquid can be treated to remove water and simultaneously concentrate nutrients. This lowers the environmental impact (i.e. global warming potential and acidification) and reduces transportation costs to areas with nutrient deficits compared with digestate use as such (Rehl and Müller, 2011). In addition to the decreased transportation costs, the additional economic benefits of the digestate liquid treatment are related to the profit gained from the selling of the fertilizers (Fuchs and Drosg, 2013, Rehl and Müller, 2011). With the combination of solid-liquid separation and digestate liquid treatment, fertilizer products with optimal composition can be produced (Hjorth et al., 2010). Produced fertilizers can be designed to match the crop nutrient requirements and to achieve better control of the nutrient contents of the applied fertilizer to reduce the nutrient run-off and leaching. These products could be also used to supplement the raw digestate fertilization by replacing mineral fertilizers.

Technologies for digestate liquid treatment such as ammonia stripping, evaporation, struvite precipitation, membrane separation, as well as various combinations of these, have been previously studied considering nutrient recovery and production of nutrient-rich products with, e.g., digestate liquids, manure and urine (Antonini et al., 2011, Bonmatí et al., 2003, Bonmatí and Flotats, 2003a, b, Chiumenti et al., 2013, Ek et al., 2006, Ledda et al., 2013). However, to ensure the usability and sustainability of different digestate liquid treatment techniques and to facilitate the agricultural utilization of the nutrients over longer transportation distances, the total digestate treatment chain and all produced mass flows should be taken into consideration as well as all the process inputs, e.g., chemicals and energy (Mehta et al., 2015). As life cycle assessment and energy efficiency studies have mainly concentrated on the use of raw digestate or separated solid digestate (e.g. Bacenetti et al., 2013, Berglund and Börjesson, 2006, Evangelisti et al., 2014, Pöschl et al., 2010, Smyth et al., 2009) only a few studies exist where the digestate liquid and its treatment has been taken into consideration (Rehl and Müller, 2011). In addition, these life cycle studies focus solely on environmental and ecological effects and do not evaluate the fertilizer products from the viewpoint of biogas plant efficiency or agriculture and plant nutrition. From these perspectives information about the mass, nutrient and energy balances of an AD plant with digestate liquid treatment is important, in addition to environmental aspects.

The aim of this study was to compare the potential of four digestate liquid treatment systems of a theoretical AD plant digesting municipal FW to produce fertilizer products with low water and concentrated nutrient contents. The studied treatment systems were different combinations of ammonia stripping, evaporation and membrane filtration, which have been applied in the full scale treatment of digestate or manure based liquids (see e.g. Boehler et al., 2015, Flotats et al., 2011, Fuchs and Drosg, 2013). For all four systems the mass, nutrient and energy balances were calculated and the nutrient recovery, mass reduction and energy efficiencies were compared based on typical literature values from laboratory, pilot and full scale studies. The performance of the treatment systems was also assessed in relation to the energy consumption of fertilizer product transportation to see the effect of digestate liquid treatment on the transportability of the products.

2. Materials and methods

2.1. Overview of the theoretical AD plant

This study investigated a theoretical mesophilic AD plant which was assumed to digest source-segregated municipal FW (60 kt/y, kilotonnes per year). Figure 1 presents the applied AD plant system boundaries which include pretreatment, a digester, digestate treatment and biogas upgrading. The FW was pretreated and hygienized (1 h at 70 °C) and subsequently diluted to a total solids (TS) content of 15% with processed water or water from the local water supply. The digestate treatment was assumed to include the separation of the digestate into liquid and solid digestates using a centrifuge. The liquid digestate was assumed to be treated with one of the four digestate liquid treatment systems consisting of ammonia stripping, evaporation and membrane (reverse osmosis, RO) technologies (Figure 2). The formed biogas was assumed to be upgraded in a combined heat and power unit (CHP) into heat and electricity to be used in the AD plant and the excess electricity was to be fed to the power grid.

2.2. Pretreatment, hygienization, AD and gas upgrading

2.2.1 Mass and nutrient balances

The feed for AD was based on the characteristics of source-segregated FW: TS 25%, volatile solids (VS) 23%, Ntot 7.5 kg/tFM (fresh matter), NH_4-N 0.4 kg/tFM, Ptot 0.9 kg/tFM, Ktot 2.8 kg/tFM (Tampio et al., 2014, 2015). The FW (60 kt/y) was assumed to be pretreated as in Banks et al., (2011) by shredding/maceration and then hygienized (1 h at 70 °C according to European Council, 2011, European Parliament and the Council, 2009). Pretreatment and hygienization were not considered to affect the FW mass and nutrient content as material was not removed during the pretreatment step. The dilution water was assumed to be added to the FW during the maceration step (40 kt/y water to achieve TS of 15%, mixture referred to as feedstock). The mass of the produced digestate was calculated by subtracting the mass of the biogas from the feedstock (60 kt of FW + 40 kt of dilution water). The calculation of the biogas mass was based on biogas composition (60% CH_4, 40% CO_2) and component densities (CH_4 0.72 kg/m^3, CO_2 1.96 kg/m^3, see Supplementary material for calculations). In the digestate, the total nutrient concentrations (Ntot, Ptot, Ktot, kg/tFM) were assumed to be the same as in the feedstock, while the ammonium nitrogen in FW was assumed to increase from 0.4 kg/tFM to 4 kg/tFM after digestion (Tampio et al., 2014, 2015).

2.2.2 Energy balance

The energy balance included both heat and electricity consumption and production in the AD plant. The amount of thermal energy (th) needed for heating the

FW (60 kt) to 75 °C to maintain the required temperature during hygienization was calculated assuming the specific heat capacity of the feedstock to be the same as that of water (4.18 kJ/kg°C, see Supplementary material for calculations). The heat energy from the hygienization was assumed to be sufficient for the mesophilic (40 °C) digester (Berglund and Börjesson, 2006, Prapaspongsa et al., 2010) and thus, no additional heating was allocated for the heating of FW prior to the digester. However, the heating of the dilution water (40 kt/y) was calculated with the specific heat capacity of water using temperature difference from 15 to 40 °C. Heat losses from the hygienization and digester units were assumed to be in total 15% of the heat demand (digester heat loss 15% in Smyth et al., 2009, 20% in Rapport et al., 2011) being dependent on the reactor design as well as the difference between the reactor and outdoor temperature. The electricity (el) consumption of 37.5 kWh/tFM feedstock for the hygienization and pretreatment unit (reviewed in Pöschl et al. 2010, see Supplementary material), and 18 kWh/tFM for the digester was used (reviewed in Berglund and Börjesson, 2006, reviewed in Pöschl et al., 2010, see Supplementary material).

The energy content (MWh/y) of the produced biogas was calculated by multiplying the biochemical methane potential of the FW (BMP, 450 m^3CH_4/tVS, Tampio et al. 2014) with the amount of feedstock VS fed to the reactor. The conversion factor of 1 $m^3(CH_4)$=10 kWh was used. For the conversion of the biogas into heat and electricity in the CHP unit, the energy conversion efficiencies of 38% for electricity and 48% for heat were used (Bacenetti et al., 2013, Poeschl et al., 2012). Additionally, for the CHP-unit electricity the consumption of 5% of the energy produced in CHP was applied (Banks et al., 2011, Havukainen et al., 2014, Naegele et al., 2012, Pöschl et al., 2010, see Supplementary material). However, the use of different desulfurization methods for the biogas prior to CHP can increase the energy consumption, which was not taken into consideration in this study. E.g. in Karellas et al. (2010) the combined desulfurization with a spray scrubber and CHP was reported consuming 15% of the electricity produced in CHP in an AD plant treating pig manure, wheat straw and glycerol (45 kt/y).

2.3 Digestate treatment

The digestate was assumed to be separated with a decanter centrifuge producing liquid and solid fractions of which the liquid fraction was further treated to produce fertilizer products. The solid digestate was assumed to be used as such in agriculture, as it is the practice e.g. in the UK, Scandinavia and Switzerland, where the legislation does not require further treatment with e.g. composting (Saveyn and Eder 2014). Centrifuge separation efficiencies for mass, TS, VS and nutrients (Ntot, NH_4-N, Ptot, Ktot) were adopted from the literature and the electricity consumption was assumed to be 3.5 kWh/tFM digestate (Flotats et al., 2011, reviewed in Hjorth et al., 2010, Ledda et al., 2013, Møller et al., 2000, 2002, Table 1, see Supplementary material). Polymer/flocculent additions used in separation were not included in the mass balance as the annual total amount of additions was considered negligible (for example 1.625 $g/gTS_{digestate}$ of both polymer and mineral conditioner, Alvarenga et al., 2015).

It was assumed that all outputs from the different digestate liquid treatment systems were suitable for agricultural use and/or processed water suitable for discharging (Figure 2). Processed water was used as dilution water before the digester and the surplus water was assumed to be discharged. Additional treatments of processed water with, e.g., active carbon filters (Zarebska et al., 2015) were not taken into consideration. With each treatment system, the consumption of chemicals (NaOH, H_2SO_4, m^3/y) was included in the calculation of the output mass and characteristics.

2.3.1. Reference system, S0

In the reference system (referred as S0), the digestate liquid did not undergo any treatment after digestate separation (Figure 2). Thus, due to the lack of liquid treatment, the water for feedstock dilution came from the local water supply, i.e., outside the system boundaries. The digestate liquid was not used for dilution due to the high nitrogen content which could accumulate during digestion and inhibit the process.

2.3.2 Stripping, S1

Ammonia stripping combined with H_2SO_4 scrubbing (system referred to as S1) was studied to produce ammonium sulfate and stripping residue (Figure 2). During stripping, NH_4-N is transformed to NH_3 along with the temperature and a pH increase and further recovered with H_2SO_4 in the form of ammonium sulfate ($(NH_4)_2SO_4$) during scrubbing. In the mass and nutrient balance calculations the nitrogen (NH_4-N) recovery efficiency was assumed to be 95% based on laboratory, pilot and full scale studies (Basakcilardan-Kabakci et al., 2007, Bonmatí and Flotats, 2003a, Flotats et al., 2011, Guštin and Marinšek-Logar, 2011, Laureni et al., 2013, Liu et al., 2015, Table 1, see also Supplementary material). $(NH_4)_2SO_4$ was assumed to be a chemically pure product with no TS, VS, Ptot or Ktot, while the Ntot was assumed to consist solely of the NH_4-N. The NH_4-N mass balance was based on the assumption that the NH_4-N concentration in the produced ammonium sulfate was 40 kg/tFM (Laureni et al., 2013). The energy consumption during stripping consisted of the heat energy for the temperature increase from the digester to the stripper (from 40 to 80 °C) which was calculated using the specific heat capacity of water. Electricity consumption for stripping of 2 kWh/kgN recovered was used (reviewed in van Eekert et al., 2012, Table 1, see Supplementary material). The stripping was assumed to be executed in atmospheric pressure and thus, no energy consumption for the production of vacuum was allocated. NaOH (50%) consumption for the pH increase before stripping was assumed to be the same as the pH increase of urine (pH from 9 to 10, 20 L/m^3, Antonini et al., 2011). NaOH consumption could be reduced with CO_2 stripping before ammonia stripping (Boehler et al., 2015), which was, however, not taken into consideration in this study. The H_2SO_4 (93%) consumption during ammonia stripping was calculated using the molar ratios of H_2SO_4 and $(NH_4)_2SO_4$ and the nitrogen concentration of 40 kg/tFM in the ammonium sulfate, from which the consumption of 0.08 m^3/t liquid digestate was used.

2.3.3. Stripping and reverse osmosis, S2

Ammonia stripping was combined with reverse osmosis treatment (system referred as S2) to produce ammonium sulfate, retentate and processed water (Figure 2). After stripping, the stripping residue was directed to the RO treatment producing processed water flow for discharge. For stripping treatment, the mass and nutrient separation/recovery efficiencies, chemical and energy consumptions calculations were based on the same values as in system S1 (Table 1). The mass and nutrient balances for the RO treatment were calculated based on the typical values from the literature (Table 1) and the electricity use of 2.5 kWh/t stripping residue was applied (Carretier et al., 2015, Chiumenti et al., 2010, Ek et al., 2006, Flotats et al., 2011, Ledda et al., 2013, Mondor et al., 2008, see Supplementary material). The regeneration and/or change of RO membranes were not taken into consideration.

2.3.4. Evaporation and reverse osmosis, S3

Evaporation combined with RO (referred as S3) was studied to concentrate nutrients in the liquid digestate and a major part of the liquid into condensate which was further treated with RO to produce retentate. The retentate was in turn recycled back to separation, and processed water was directed to discharge (Figure 2). The pH of the digestate liquid was controlled with H_2SO_4 to prevent the volatilization of NH_4^+ during evaporation where the liquid was heated to 80 °C. The mass and nutrient balance calculations for the evaporation were based on typical literature values from laboratory, pilot and full scale studies (Bonmatí and Flotats, 2003b, Chiumenti et al., 2013, Ek et al., 2006, Flotats et al., 2011, Mauer et al., 2003, Table 1, see also Supplementary material). The TS and VS separation efficiencies in the concentrate were assumed to be 100% and the NH_4-N recovery rate the same as in Ntot (80%). The H_2SO_4 (93%) consumption of 0.005 m^3/t digestate liquid for the pH decrease during evaporation was based on the pH decrease of urine and manure with strong H_2SO_4 (pH from 9 to 6 in Ek et al., 2006, pH from 7.2 to 5.5 in Sørensen and Eriksen, 2009). The consumption of other chemicals such as antifoaming additives was not included. The energy consumption of evaporation consisted of the heat energy needed to increase the digestate liquid temperature from 40 to 80 °C plus the electricity consumption of 5 kWh/t liquid digestate based on typical literature values (Bonmatí and Flotats, 2003b, Chiumenti et al., 2013, Ek et al., 2006, Flotats et al., 2011, Mauer et al., 2003, Table 1, see also Supplementary material). No vacuum conditions for the evaporation were applied as the process temperature was high (80 °C). Mass and nutrient separation/recovery efficiencies, chemical and energy consumptions considering RO were the same as in S2.

2.3.5. Stripping, evaporation and RO, S4

Combined stripping, evaporation and RO (S4) were studied to produce both ammonium sulfate and concentrate. After stripping, the stripping residue was evaporated to produce concentrate and condensate. The condensate was treated in RO after which the retentate was further recycled back to digestate separation and the processed water was discharged (Figure 2). The same mass and nutrient separation/recovery efficiencies, chemical and energy consumptions for stripping were used as in system S1, for evaporation as in system S3 and for RO as in system S2 (Table 1). However, it was assumed that heat from the stripping (80 °C) was sufficient for the evaporation and thus, no heat energy was allocated for evaporation (Ervasti et al., 2011).

In systems S1-S4, no heat losses were calculated for stripping and evaporation, nor the energy consumption of the membrane changes for RO, due to the lack of reference data in the literature. As the operational temperatures were the same in stripping and evaporation (80 °C), the effect of heat losses in the total energy balances between systems S1-S3 was assumed to be relatively small. In the full scale stripping and evaporation plants the heat losses due to the convection and radiation through treatment apparatus, and through the evaporation of material, are reduced with the insulation and use of heat exchangers.

2.4 Transportation

The energy consumption during the transportation of the fertilizer products from the digestate liquid treatments was calculated using the energy consumption of a semitrailer truck in Finland, 0.17 kWh/t-km (full 25t load, EURO 5 truck type, VTT, 2012). The transportation of liquid products from each digestate liquid treatment systems was studied from 0 to 250 km.

3. Results

3.1 Mass and nutrient balance of AD and digestate treatment

The mass and nutrient flows of digestate and digestate liquid treatments formed the mass and nutrient balance of the systems showing the concentration of nutrients into fertilizer products. The calculations were based on the mass flow of the feedstock (FW + diluting water) and added chemicals as well as the characteristics of the digestate. The mass of the digestate accounted for 87% of the initial feedstock fed to the AD plant (60 kt of FW + 40 kt of dilution water), while 13% of the feedstock was transformed into biogas during AD. The digestate separation produced liquid (79 kt/y) more than eight times the amount of solid digestate (9 kt/y) (Table 2, Table 3).

The treatment of the digestate liquid with stripping (S1) concentrated 45% of the initial feedstock nitrogen into ammonium sulfate (40 kg/tFM) with the mass of 11 kt/y (Table 2, Table 3). The mass of the ammonium sulfate accounted for only 5% of the feedstock mass flow when the chemical additions were not considered (Table 3). The remaining stripping residue flow was 85 kt/y with low nitrogen concentration (1.5 kgN/tFM) compared with the untreated digestate liquid (4.0 kgN/kgFM) but with comparable in the concentrations of both phosphorus (0.1 kgP/tFM in the stripping residue and digestate liquid) and potassium (1.9 kgK/tFM in the stripping residue, 1.8 kgK/tFM in the digestate liquid). In total, the amount of outputs from the stripping system was 85 kt/y (ammonium sulfate + stripping residue, Table 2) which was 70% of the feedstock nitrogen, 10% of phosphorus, 85% of potassium and 79% the feedstock mass without chemical additions (Table 3).

In combined stripping + RO treatment (S2), stripping produced the same amount of ammonium sulfate as in a system with stripping only (S1, 11 kt/y), while the RO treatment of stripping residue produced retentate and processed water flows of 21 kt/y and 53 kt/y, respectively (Table 2). The retentate still contained nutrients (5.4 kgN/tFM, 0.2 kgP/tFM, 6.9 kgK/tFM), and was assumed to be used as fertilizer in agriculture (as in Ledda et al., 2013), and not recycled within the digestate liquid treatment as in systems S3 and S4. Thus, in this system the mass of the fertilizer products (ammonium sulfate, retentate) was 32 kt/y (Table 2), and concentrated 70% of the feedstock nitrogen, 10% of phosphorus and 84% of potassium into 26% of the feedstock mass without chemical additions (Table 3).

Evaporation treatment combined with RO (S3) produced only 16 kt/y of nutrient-rich concentrate (17.9 kgN/tFM, 0.3 kgP/tFM, 9.0 kgK/tFM). Subsequently, RO treatment produced 18 kt/y of retentate and 45 kt/y of processed water from the condensate (Table 2). Without chemical additions the fertilizer product from system S3 (concentrate) accounted for 63% of the feedstock nitrogen, 10% of phosphorus, 85% of potassium and 16% of the feedstock mass (Table 3).

When stripping and evaporation were combined with RO (S4) two fertilizer product flows, ammonium sulfate and concentrate, were produced as well as retentate and processed water (11 kt/y, 15 kt/y, 16 kt/y, 42 kt/y, respectively, Table 2). In total, with fertilizer products, ammonium sulfate and concentrate, 67% of the nitrogen, 10% of phosphorus and 85% of potassium from the feedstock was recovered and concentrated into 20% of the mass flow of the feedstock, when the chemical additions were not considered (Table 3). The nitrogen recovery of 67% in S4 was 3% lower compared with system S1 with stripping, which was due to the produced retentate and processed water flows in S4, which contained traces nitrogen but were not considered as fertilizer products. The nutrient concentrations in the concentrate from S4 were similar to the concentrate from S3 (0.3–0.4 kgP/tFM, 9–9.6 kgK/tFM), except for the nitrogen content, which was for the most part recovered with stripping (6.8 kgN/tFM in S4, 17.9 kgN/tFM in S3, Table 2).

The efficiency of the four liquid digestate treatment systems in concentrating nitrogen from the feedstock into fertilizer products was assessed with the ratio between the recovered nitrogen (% of the feedstock) and the recovered mass (% of the feedstock, from Table 3). The resulting efficiencies were 0.9 for systems S0 and S1 and 2.7, 4.0 and 3.4 for systems S2, S3 and S4, respectively, where the increasing ratio demonstrates increasing the concentration of nitrogen into products with low mass. The most efficient system for the digestate liquid treatment was S3, combining both evaporation and RO to produce a fertilizer product with low mass and high nitrogen concentration.

3.2 Energy balance

The energy production in AD was based on the methane production of the FW, around 62 GWh per year, which was utilized in CHP for the production of electricity (24 GWh_{el}/y), and heat (29 GWh_{th}/y, Table 4). In total, AD consumed 9% of the produced total energy as electricity for pretreatment and hygienization of the feedstock (2250 MWh_{el}/y), gas conversion in CHP (1180 MWh_{el}/y) and digestion (1860 MWh_{el}/y). The heat consumption of the AD in total was 10% of the produced total energy including hygienization (4200 MWh_{th}/y), digester (1200 MWh_{th}/y) and heat losses (800 MWh_{th}/y) (Table 4).

All the four studied digestate treatment systems (S1-S4) and the reference system (S0) included solid-liquid separation with a centrifuge, which used 300 MWh of electricity per year (0.5% of the produced energy, Table 4) as the material electricity consumption was calculated per produced digestate. The digestate stripping (S1, S2) had an electricity demand of 400 MWh_{el}/y, while the addition of the RO treatment (S2) increased the electricity demand by 190 MWh_{el}/y (total 590 MWh_{el}/y in S2). Evaporation (S3) consumed a similar amount as stripping and the electricity consumption of RO was 160 MWh_{el}/y (total 550 MWh_{el}/y in S3). In the system combining stripping + evaporation + RO (S4), the electricity consumption in total was 920 MWh_{el}/y, which accounted 1.5% of the energy produced in AD. The heat demand in all four studied treatment systems (S1-S4) was similar, around 3700 MWh/y (6% of the produced energy in AD), as the heat consumption for both stripping and evaporation was similar, RO did not use any heat, and in the system combining stripping + evaporation + RO (S4) the heat demand was allocated only for stripping (Table 4).

The total energy consumption of the digestate liquid treatment systems increased from systems S1 to S4 as the units in the treatment of digestate liquid increased being 4100, 4300, 4200 and 4600 MWh/y in systems S1, S2, S3 and S4, respectively (Table 4). The combined energy consumption of the digestate treatment systems and AD was 15.9–16.4 GWh, which accounted for 26% of the total energy produced.

The energy consumption of the digestate liquid treatment per recovered nitrogen in the concentrated fertilizer products (ammonium sulfate, concentrate) were the lowest (150 kWh/kgN) with the following systems: evaporation + RO (S3); stripping + evaporation + RO (S4) (Table 4). In systems with stripping (S1 and S2) the energy consumption was higher (200–210 kWh/kgN) due to the lower amount of nitrogen in the produced ammonium sulfate compared with the products from systems S3 and S4. However, when only electricity consumption was taken into consideration, the evaporation + RO (S3) and stripping (S1) had lower electricity consumptions per recovered nitrogen (19–20 kWh_{el}/kgN in S1 and S3, around 30 kWh_{el}/kgN in S2 and S4, Table 4) as the electricity demand per year was low and nitrogen recovery efficiency higher compared with the systems stripping + RO (S2) and stripping + evaporation + RO (S4).

3.3 Transportation of fertilizer products

The energy consumption associated with the transportation of the fertilizer products in the digestate liquid treatment systems (S0-S4) was evaluated in relation to the increasing transportation distance (from 10 to 250 km, Figure 3). Of the studied products, the concentrate from the evaporation treatment (S3) used less than 700 MWh/y during 250 km transportation, and was considered as the most energy efficient to transport longer distances. In contrast, the transportation the digestate liquid as such (S0) and stripping residue from S1 consumed the largest amount of energy (around 700 MWh/y transportation distance 50 km, 3300–3600 MWh/y distance 250 km) (Figure 3, Table 2).

4. Discussion

4.1 Energy consumption of AD, digestate liquid treatment and transportation

The present results, based on typical literature values from laboratory, pilot and full scale studies, show that the processing of digestate through solid-liquid separation and digestate liquid treatments into concentrated fertilizer products consumed less than 10% of the produced energy in an AD plant treating 60 kt/y of FW. In total AD, solid-liquid separation and digestate liquid treatment accounted for 26% of the produced energy, of which around 19% was used in the AD and separation of the digestate into solid and liquid fractions. The lower energy consumption of only 8–17% of the total energy produced was previously reported for a theoretical AD plant treating FW (90 kt/y) combined with ammonia stripping and hydrogen recovery, where the additional energy input from the assumed produced hydrogen most likely lowered the ratio between energy input and output (Babson et al., 2013). Compared with the present study, similar energy demand, 17% and 20% of the total energy production, was previously assumed in life cycle assessment studies for ADs combined with digestate solid-liquid separation treating 20–60 kt/y of an organic fraction of municipal solid waste and a mixture of municipal and agricultural substrates (Berglund and Börjesson, 2006, Pöschl et al., 2010, respectively). In the present study the differences in the total energy produced in AD and the lower ratio between energy demand and total energy production compared with a study by Berglund and Börjesson (2006) were due to the high energy content of the FW feedstock in the present study (450 m^3CH_4/tVS compared to around 300 m^3CH_4/tVS in Berglund and Börjesson, 2006). If similar digestate liquid treatment systems as those studied in this paper would be applied to an AD plant treating solely, e.g., manure, which produces less methane and has lower VS content (cow manure 148 m^3CH_4/tVS, VS 11%, Møller et al., 2004), the total energy production of the plant would be lower (9800 MWh/y) and digestate treatment (solids separation and liquid treatment) would require all of the feedstock's energy and the energy balance would be negative (900 MWh/y needed in addition to the AD plant's energy production). In this sense, the digestate liquid treatment systems are more rational options when feedstock has a high methane potential and initial organic matter and nutrient concentrations, such as FW.

Heat consumption of all the studied digestate liquid treatments accounted for 80–90% of the total energy demand, because with both stripping and evaporation increased process temperature (80 °C applied in this study) is needed to achieve efficient nutrient recovery (Mehta et al., 2015). As the electricity consumption between stripping and evaporation was similar (390–400 MWh/y), the total energy consumption was 4100 kWh/y with both stripping and evaporation, while the RO treatment consumed only electricity (150–180 MWh/y) as no heat was required. Similarly, evaporation treatment was reported to consume over 50% more energy compared with the treatment with combined microfiltration, reverse osmosis and ion exchange when digestate originated from a mixture of manure and plant materials (AD with the electric power of 186 kW_{el}, Rehl and Müller, 2011). Accordingly, due to the large heat demand of digestate liquid treatments with stripping and evaporation, the use of these treatments is rationalized by integration with AD, which enables the recovery of the plant's excess heat (Bonmatí et al., 2003, Fuchs and Drosg, 2013, Hjorth et al., 2010, Mehta et al., 2015), especially in situations where the AD plant's heat energy is not utilized in, e.g., district heating systems.

The results showed that the nitrogen recovery from the digestate liquid treatments consumed 150–210 kWh/kgN, as the consumption was allocated to the recovered nitrogen in the concentrated fertilizer products. This is over 15 times more than the energy consumption of mineral nitrogen fertilizer production in Europe (35.2 GJ/tNH_3 ~ 9.8 $kWh/kgNH_3$, Yara, 2015a). However, despite the higher energy consumption of the treatment of digestate liquids, the advantage with the use of liquid fertilizers from waste materials is the promotion of nutrient recycling and mitigation of greenhouse gas emissions through anaerobic digestion compared to the manufacturing of mineral fertilizers (Evangelisti et al., 2014). The energy demand in all four digestate liquid treatments combining two to three treatment technologies was also higher compared to a pilot-scale stripping treatment with urine (18.8–28.2 kWh/kgN recovered, Antonini et al., 2011), where the lower treatment temperature (40 °C vs. 80 °C in the present study) decreased energy consumption. Lower energy consumption was also reviewed with ion exchange, membrane distillation and chemical precipitation technologies (0.04–0.63 kWh/kgNH_3, Zarebska et al., 2015), where the treatments did not require heat energy for nutrient recovery. The energy consumption of the studied digestate liquid treatment technologies could be, however, reduced by using lower process temperatures. For example successful ammonia stripping (N recovery >80%) has also been reported at temperatures from 35 to 50 °C (Antonini et al., 2011, Laureni et al., 2013, Liu et al., 2015), while the use of lower temperatures (35–40 °C) with evaporation is possible with the increase of vacuum (pressure 5–7 bars, Bonmatí and Flotats, 2003b, Chiumenti et al., 2013). Additionally, the heat consumption of the treatment processes could be reduced by using heat exchangers to recycle the process heat, which was not taken into consideration in this study.

As the energy consumption during transportation was affected by the mass of fertilizer products (from 16 to 87 kt/y), up to an 80% decrease in the energy consumption during transportation of the fertilizer products was possible using the studied digestate liquid treatment systems when compared to the transportation of the untreated digestate liquid. Energy savings of 80%, 67% and 59% during transportation were possible with the following treatment systems, respectively: evaporation combined with RO (S3); combined stripping, evaporation and RO (S4); stripping combined with RO (S2). This was due to the lower transportable mass compared with the untreated digestate liquid in the reference system (S0). Decreased energy consumption of transportation supports the use of these digestate liquid treatments in AD plants treating FW, which are usually located far from agricultural lands (Babson et al., 2013) and where the reuse of the FW nutrients is challenging due to long transportation distances. Similar energy savings from transportation of municipal waste-based digestate have been reported after solid-liquid separation, where the energy consumption of transportation of solid digestate after separation decreased 50% (distance 5 km, Pöschl et al., 2010), thus the transportation of the liquid digestate was not discussed. The advantage with the digestate liquid treatment systems applying RO treatment is the reduction of the total mass of the transportable products compared with the untreated digestate liquid, as some mass exits the system as treated water and retentate. With stripping only (S1), where no RO was included in treatment of digestate liquid, the mass of ammonia sulfate was low, but with the stripping residue also aimed for use in agriculture, the total mass of products was high (87 kt/y), which is feasible to transport only by minimizing the distance between the AD plant and the fields to be fertilized. A high total mass of 87 kt/y with stripping (S1) was due to the addition of chemicals during stripping which also led to 10% higher energy consumption during transportation compared to the reference system (S0).

4.2 Characteristics of fertilizer products

The results, based on typical literature values, showed that liquid digestate treatment with evaporation, combined with RO (S3), produced the most concentrated nutrient product by concentrating the original FW mass of 60 kt/y into 16 kt/y. The high nitrogen and potassium and low phosphorus concentrations within the concentrate (18 kgN/tFM, 12 kgNH_4-N/tFM, 0.3 kgP/tFM, 9 kgK/tFM) compared with the untreated digestate liquid (4 kgN/tFM, 2.7 kgNH_4-N/tFM, 0.1 kgP/tFM, 1.8 kgK/tFM), were dependent on the mass and nutrient recovery and characteristics of the feedstock. Previously similar (18.7 kgN/tFM) and slightly higher (>20 kgN/tFM) nitrogen concentrations have been reported after acid evaporation with pig slurry digestate (Chiumenti et al., 2013, Bonmatí and Flotats, 2003b, respectively). Compared with the concentrate from evaporation, commercial mineral fertilizers in solid form have remarkably higher nutrient concentrations (e.g. 303 kgN/tFM, 114 kgP/tFM, 245 kgK/tFM, Abubaker et al., 2012, 266 kgN/tFM, 13 kgP/tFM, 43 kgK/tFM, Yara, 2015b), thus, the characteristics of N and K were in line with commercial liquid fertilizers intended for, e.g., vegetables fertilization (24 kgN/tFM, 55 kgP/tFM, 40 kgK/tFM, Yara, 2015c). Hence, the concentrate from evaporation could potentially replace liquid mineral fertilizers, especially in cases where phosphorus fertilization is not needed.

All four studied digestate liquid treatment systems produced fertilizer products containing either N (ammonium sulfate) or N, P and K (concentrate, retentate, stripping residue) in different proportions, which affect their use as fertilizers in agriculture and also affect the amount of fertilizers spread on agricultural lands. The proportion of mineral nitrogen in total N (NH_4-N/Ntot) was 100% in the ammonium sulfate from stripping (S1, S2, S4) and 68% in the concentrate from evaporation (S3), indicating the high availability of N to plants and fast growth response after fertilization (Abubaker et al., 2012). In concentrate from combined stripping, evaporation and RO (S4), retentate from stripping and RO (S2) and stripping residue from stripping alone (S1) the NH_4-

N/Ntot was 10%, 9% and 7%, respectively, indicating slower N release in soils. When considering the NPK ratios, potassium was the dominant nutrient in all fertilizer products (except ammonium sulfate), as the NPK ratios (per FM) were around 100:5:130 in the stripping residue from stripping (S1), the retentate from stripping combined with RO (S2) and the concentrate from combined stripping, evaporation and RO (S4). The concentrate from the system combining evaporation and RO (S3) showed the most balanced NPK ratio of 100:2:50, which was also somewhat similar to the NPK need of herbaceous plants, 100:14:68 (Knecht and Göransson, 2004), thus with remarkably lower P content. The low share of phosphorus was due to the digestate solid-liquid separation, which distributed only 10% of the P in FW into the liquid digestate, while the water-soluble N and K were the predominant nutrients. As follows, all the studied fertilizer products can be used in agriculture supplementing especially N or N and K fertilization in situations where the soil P content is already high.

The low nutrient concentration within especially stripping residue (from stripping, S1, 1.5 kgN/tFM, 0.1 kgNH_4-N/tFM, 0.1 kgP/tFM, 1.9 kgK/tFM) increases the fertilizer application amounts per hectare and discourages the use of the residue in agriculture. The amount of the stripping residue to be spread during fertilization (assumed N fertilization rate 170kgN/ha) was high, over 100 t/ha, due to the low nutrient concentrations, which could affect the soil properties due to soil wetting/water logging (Rigby and Smith, 2011). More practical volumes were achieved with fertilizer products from other treatment systems, as the amount of mass applied to soils was 4 t/ha for ammonium sulfate from stripping (S1, S2, S4), 9 t/ha for concentrate from evaporation and RO (S3) and around 25–30 t/ha for concentrate from stripping, evaporation and RO (S4) and retentate from stripping and RO (S2).

All in all, the most suitable digestate liquid treatment system for concentrated fertilizer products considering nutrients, energy and transportability was the concentrate from the system with evaporation and RO (S3), thus, the production of a different fertilizer product (e.g. ammonium sulfate) is possible with slightly larger energy input with a system combining stripping, evaporation and RO (S4) or stripping and RO (S2). However, along with the recovery of useful nutrients the evaporation and also RO treatment are able to concentrate some undesired components, such as heavy metals, into the concentrate, which could affect the fertilizer use of the products (Mehta et al., 2015). Furthermore, the addition of chemicals to the digestate liquid during the treatment, and their effects on soil after fertilization, should be noticed. E.g. sulfuric acid additions during/after stripping (S1, S2, S4) and before evaporation (S3, S4), both lower the pH value and increase the salinity, which are likely to cause corrosion (Vaneeckhaute et al., 2013b). Like sulfur, also sodium acts as micronutrient in plant nutrition. However, in large doses sodium increases the soil salinity and affects the soil structure (reviewed in Kronzucker et al., 2013, Veneeckhaute et al., 2013a). The Na concentration in the stripping residue from system S1 was calculated to be around 6 g/kgFM which is about double the amount of Na in manure and manure based digestate (Vaneeckhaute et al., 2013a,b). It is thus important to measure the pH and salinity of the produced liquid fertilizer products and monitor the effect of these products in soils after fertilization.

5. Conclusions

This theoretical study showed the feasibility of FW nutrient recovery through AD and digestate liquid treatment and the production of transportable fertilizer products with the energy produced in AD. Despite the use of heat-demanding treatments, such as evaporation and stripping, the energy produced in AD was sufficient for digestate liquid treatment consuming fewer than 10% of the total energy produced in AD. The studied digestate liquid treatment systems were mostly considered as nitrogen concentration methods which are able to concentrate up to 67% of feedstock nitrogen into liquid fertilizer products with low mass. Of the studied digestate systems evaporation combined with RO was evaluated as the most efficient nutrient recovery technology for the production of transportable fertilizer products for agricultural application due to the highest concentration of nutrients, nutrient availability, the low mass of the product and low energy consumption of the treatment. Stripping was an efficient technology for the recovery of nitrogen, however, the high mass of the residue containing the remaining K and P should be further managed sustainably. Overall, the selection of the treatment technology is dependent on the location of the AD plant relative to agricultural lands and the type of fertilizer products needed (N fertilizer, NPK fertilizer).

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Table 1. The separation efficiency of decanter centrifuge, nutrient recovery efficiencies of digestate liquid treatment technologies and energy consumption of each treatment. Values chosen based on literature (see also Supplementary material).

Material	Separation/recovery efficiency, %							Energy consumption,
	Mass	TS	VS	Ntot	NH_4-N	Ptot	Ktot	kWh/t to be treated
Solid-liquid separation of digestate								
Liquid digestate	90[a]	20[a]	20[b]	70[a]	81[a]	10[a]	85[a]	3.5[a]
Digestate liquid treatment								
Stripping								
Ammonium sulfate	-	-	-	-	95[c]	-	-	2[d] + heat[e]
Evaporation								
Concentrate	20[f]	-	-	90[f]	-	100[f]	100[f]	5[f] + heat[e]
Reverse osmosis								
Rententate	28[g]	100[g]	100[g]	-	95[g]	95[g]	99[g]	2.5[g]

[a] Flotats et al., 2011, reviewed in Hjorth et al., 2010, Ledda et al., 2013, Møller et al., 2000, 2002

[b] Separation efficiency for VS was assumed to be same as for TS

[c] Basakcilardan-Kabakci et al., 2007, Bonmatí and Flotats, 2003a, Flotats et al., 2011, Guštin and Marinšek-Logar, 2011, Laureni et al., 2013, Liu et al., 2015

[d] kWh/kgN recovered in ammonium sulfate, reviewed in van Eekert et al., 2012

[e] Calculated with the specific heat capacity of water

[f] Bonmatí and Flotats, 2003b, Chiumenti et al., 2013, Ek et al., 2006, Flotats et al., 2011, Mauer et al., 2003

[g] Carretier et al., 2015, Chiumenti et al., 2010, Ek et al., 2006, Flotats et al., 2011, Ledda et al., 2013, Mondor et al., 2008

-, not applicable

Table 2. Mass and nutrient flows presented as tonnes per year (t/y), and concentrations (kg/tFM, in parentheses) in feedstock, digestate, separated solid and liquid digestate fractions and outputs of the digestate liquid treatment systems (S0-S4). Fresh matter (FM), reverse osmosis (RO).

Material	Mass	TS	VS	Ntot	NH_4-N	Ptot	Ktot
Reactor feedstock							
Food waste	60000	15000 (250.0)	13800 (230.0)	450 (7.5)	24 (0.4)	54 (0.9)	168 (2.8)
Dilution water (recycled water in S3-S4)	40000	-	-	-	-	-	-
Biogas, digestate and solid-liquid separation							
Biogas	12586	12586	12586	-	-	-	-
Digestate	87414	2414	1214	450	264	54	168
Liquid digestate, S0 no treatment	78673	483 (6.1)	243 (3.1)	315 (4.0)	214 (2.7)	5 (0.1)	143 (1.8)
Solid digestate, S0-S4	8741	1932 (221.0)	972 (111.1)	135 (15.4)	50 (5.7)	49 (5.6)	25 (2.9)
Digestate liquid treatment							
Stripping, S1							
Ammonium sulfate	11373[a]	0 (0)	0 (0)	203 (40)	203 (40)	0 (0)	0 (0)
Stripping residue	73594[b]	483 (6.4)	243 (3.2)	112 (1.5)	11 (0.1)	5 (0.1)	143 (1.9)
Stripping + RO, S2							
Ammonium sulfate	11373[a]	0 (0)	0 (0)	203 (40)	203 (40)	0 (0)	0 (0)
Stripping residue (to RO)	75168[b]	483 (6.4)	243 (3.2)	112 (1.5)	11 (0.1)	5 (0.1)	143 (1.9)
Retentate	20606	483 (23.4)	243 (11.8)	111 (5.4)	10 (0.5)	5 (0.2)	141 (6.9)
Processed water (recycled)	52988	0 (0)	0 (0)	1 (0.01)	1 (0.01)	0 (0.01)	1 (0.03)
Evaporation + RO, S3							
Concentrate	15820[c]	483 (30.5)	243 (15.4)	284 (17.9)	192 (12.2)	5 (0.3)	143 (9.0)
Condensate (to RO)	62938	0 (0)	0 (0)	32 (0.5)	21 (0.3)	0 (0)	0 (0)
Retentate (recycled)	17623	0 (0)	0 (0)	30 (1.7)	20 (1.2)	0 (0)	0 (0)
Processed water (recycled)	45316	0 (0)	0 (0)	1 (0.02)	1 (0.02)	0 (0)	0 (0)
Stripping + evaporation + RO, S4							
Ammonium sulfate	11373[a]	0 (0)	0 (0)	203 (40)	203 (40)	0 (0)	0 (0)
Stripping residue (to evaporation)	73594[b]	483 (6.4)	243 (3.2)	112 (1.5)	11 (0.1)	5 (0.1)	143 (1.9)
Concentrate	14798[d]	483 (32.6)	243 (16.4)	101 (6.8)	10 (0.7)	5 (0.4)	143 (9.6)
Condensate (to RO)	58875	0 (0)	0 (0)	11 (0.2)	1 (0.02)	0 (0)	0 (0)
Retentate (recycled)	16485	0 (0)	0 (0)	11 (0.7)	1 (0.1)	0 (0)	0 (0)
Processed water (recycled)	42390	0 (0)	0 (0)	0 (0.001)	0 (0.001)	0 (0)	0 (0)

[a]H_2SO_4 addition of 6293 m^3/y, [b]NaOH addition of 1573 m^3/y, [c]H_2SO_4 addition of 85 m^3/y, [d]$H_2SO_4$80 m^3/y
-, not applicable

Table 3. The partition of feedstock mass and nutrients in the digestate, separated solid and liquid digestates and fertilizer products from the digestate liquid treatment systems (S0-S4). The partition is presented as % of the feedstock. The mass is calculated from the feedstock fed to the digester (60 kt food waste + 40 kt dilution water). The addition of chemicals is not taken into consideration in the mass partition. Reverse osmosis (RO).

% of feedstock	Mass	Ntot	NH_4-N	Ptot	Ktot
Digestate and solid-liquid separation					
Digestate	87	100	1100	100	100
Liquid digestate, S0	79	70	891	10	85
Solid digestate, S0-S4	9	30	209	90	15
Stripping, S1					
Ammonium sulfate	5	45	846	0	0
Stripping residue	74	25	45	10	85
Fertilizer products in total	79	70	891	10	85
Stripping + RO, S2					
Ammonium sulfate	5	45	846	0	0
Retentate	21	25	42	10	84
Fertilizer products in total	26	70	888	10	84
Evaporation + RO, S3					
Concentrate	16	63	802	10	85
Stripping + evaporation + RO, S4					
Ammonium sulfate	5	45	846	0	0
Concentrate	15	22	40	10	85
Fertilizer products in total	20	67	886	10	85

Table 4. Energy production of the studied anaerobic digestion (AD) plant and the energy consumption during AD (including pretreatment and hygienization, biogas upgrading and digester), digestate separation and digestate liquid treatment. Energy consumption of the digestate liquid treatment is calculated towards the recovered concentrated fertilizer fractions (ammonium sulfate, concentrate), where stripping residue from S1 and retentate from S2 were not included. Reverse osmosis (RO), combined heat and power (CHP), electricity (el), thermal (th).

Process	Electricity (MWh_{el}/y)	Heat (MWh_{th}/y)	Total (MWh/y)	Total (kWh/kgN)	Electricity (kWh_{el}/kgN)
Energy production					
Primary energy production in AD	-	-	62100	-	-
Energy in CHP	23598	29187	52785	-	-
Energy consumption					
AD	5293	6142	11435	-	-
Solid-liquid separation	306	-	306	-	-
Energy consumption in digestate liquid treatment					
No treatment, S0	0	0	0	0	0
Stripping, S1	406	3727	4133	203	20
Stripping + RO, S2	590	3727	4317	213	29
Evaporation + RO, S3	551	3658	4209	148	19
Stripping + evaporation + RO, S4	922	3727	4649	153	30

-, not applicable

Figure Captions

Figure 1. System boundaries of the studied anaerobic digestion plant and digestate liquid treatment with material and energy flows. Grey boxes represent feedstock/product and white boxes represent studied unit operations.

Figure 2. Digestate liquid treatment systems (S0-S4) and products evaluated in this study. White boxes represent treatments and grey boxed represent treatment inputs and outputs.

Figure 3. Energy consumption of transportation (megawatt hours per year, MWh/y) of fertilizer products produced in each digestate liquid treatment system in relation to the transportation distance.

Fig. 1.

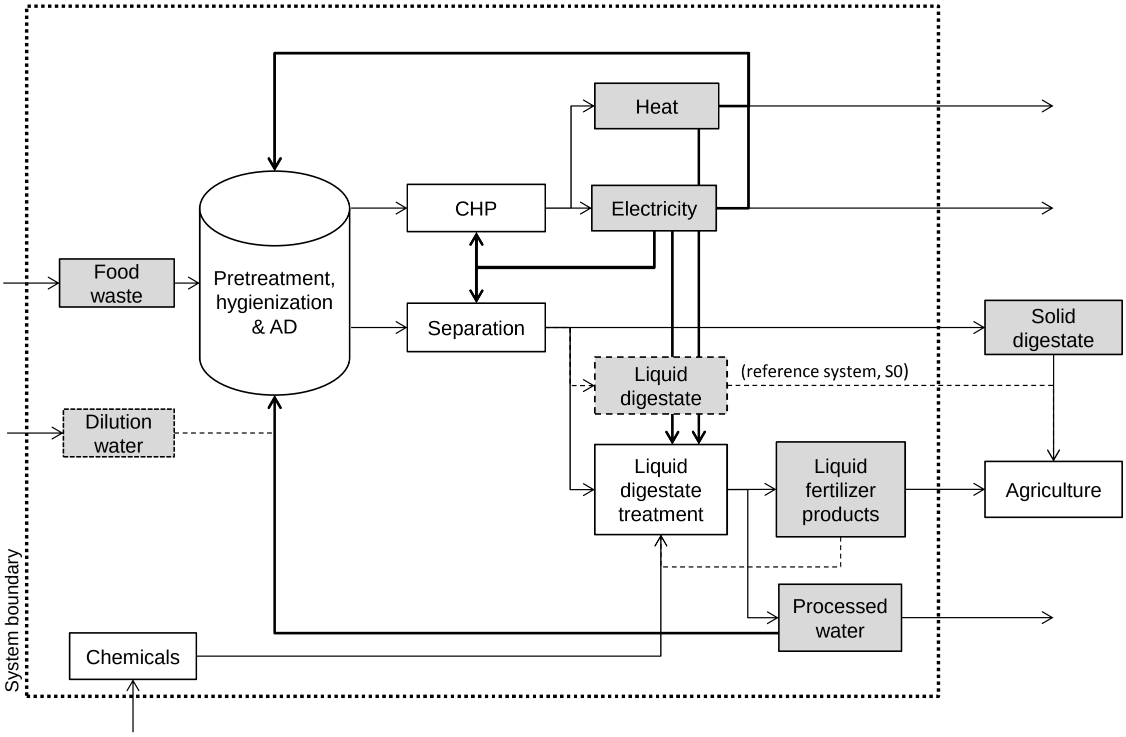

Heat
CHP
Electricity
Food waste
Pretreatment, hygienization & AD
Separation
Solid digestate
Liquid digestate
(reference system, S0)
Dilution water
Liquid digestate treatment
Liquid fertilizer products
Agriculture
Processed water
Chemicals
System boundary

Fig. 2.

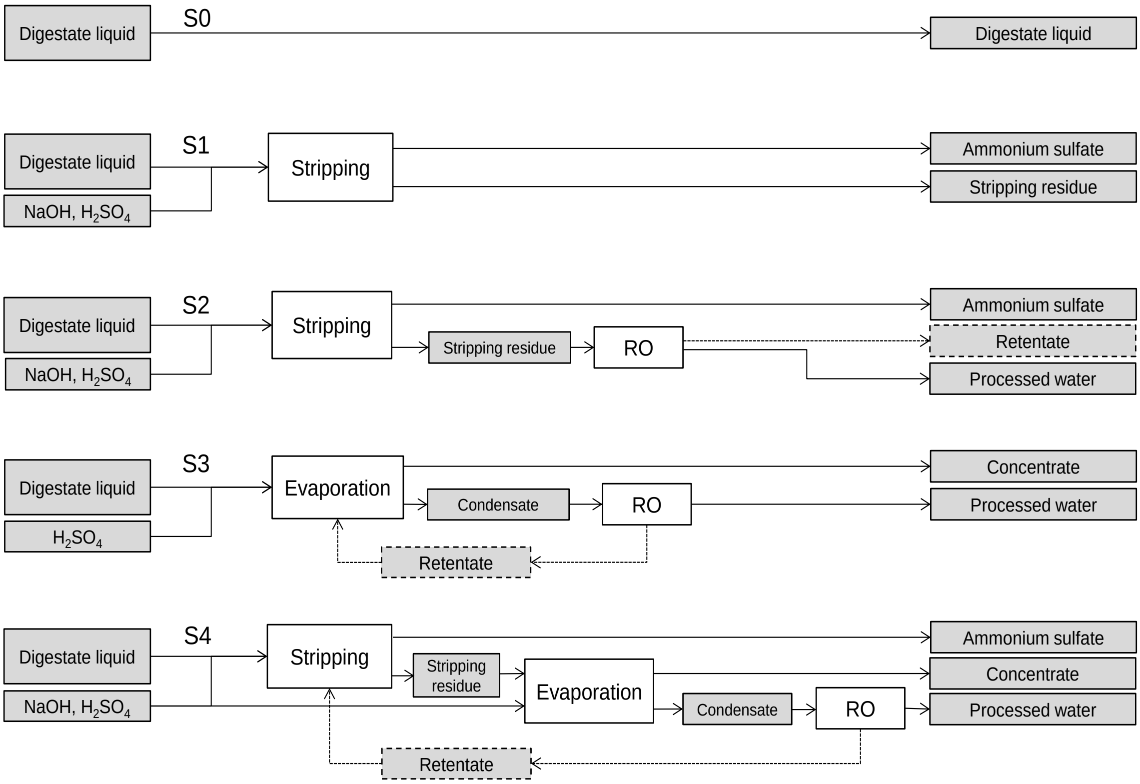
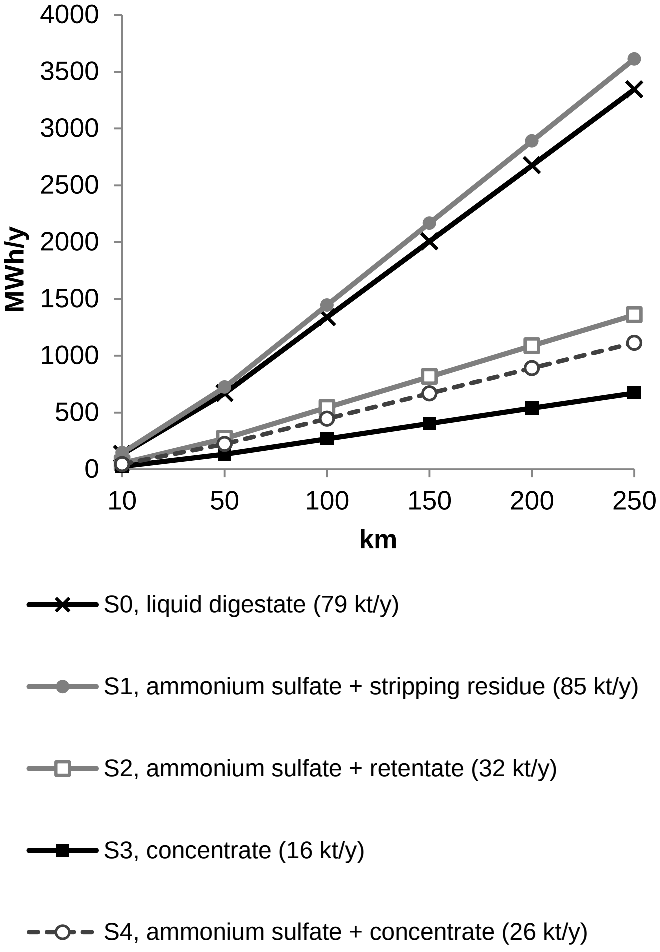

S0
Digestate liquid
Digestate liquid
S1
Digestate liquid
NaOH, H2SO4
Stripping
Ammonium sulfate
Stripping residue
S2
Digestate liquid
NaOH, H2SO4
Stripping
Stripping residue
RO
Ammonium sulfate
Retentate
Processed water
S3
Digestate liquid
H2SO4
Evaporation
Condensate
RO
Retentate
Concentrate
Processed water
S4
Digestate liquid
NaOH, H2SO4
Stripping
Stripping residue
Evaporation
Condensate
RO
Retentate
Ammonium sulfate
Concentrate
Processed water

Fig. 3.


4000
3500
3000
2500
2000
1500
1000
500
0
MWh/y
10
50
100
150
200
250
km
S0, liquid digestate (79 kt/y)
S1, ammonium sulfate + stripping residue (85 kt/y)
S2, ammonium sulfate + retentate (32 kt/y)
S3, concentrate (16 kt/y)
S4, ammonium sulfate + concentrate (26 kt/y)

Supplementary Material for

Liquid fertilizer products from anaerobic digestion of food waste: mass, nutrient and energy balance of four digestate liquid treatment systems

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1. Hygienization and digester

1.1 Mass balances

The volume of methane produced during anaerobic digestion per year (AD, m^3/y) was calculated by multiplying the amount of volatile solids (VS) fed to the reactor (t/y) with the methane potential of the feedstock (m^3/tVS). The mass of methane was calculated according to equation:

$$m = V \times \rho / 1000$$

where the m is the mass of CH_4 (tFM/y), V is the volume of CH_4 (6.21 Mm^3/y) and ρ is the density of CH_4 (0.72 kg/m^3).

The volume of CO_2 annually produced in the AD was calculated using the carbon dioxide content (40%), the assumed methane content (60%) and the volume of methane (6.21 Mm^3/y). The mass of CO_2 was calculated the same way as the mass of CH_4 using the CO_2 density of 1.96 kg/m^3. Subsequently, the digestate mass was calculated by subtracting the biogas mass (CH_4 + CO_2, 12 586 t/y) from the feedstock mass.

For the calculation of the mass balances of total solids (TS) and VS, it was assumed that the produced biogas was produced from TS and VS. Subsequently, the TS and VS contents of the produced digestate were calculated as the difference between feedstock TS or VS (t/y) and biogas mass (t/y). The nutrient content in digestate was assumed to be the same as in the feedstock except in the case of NH_4-N, which concentration was assumed to increase from 0.4 g/kg fresh matter (FM) (feedstock) to 4 g/kgFM (digestate) according to Tampio et al. (2014, 2015).

1.2 Energy balances

In the hygienization unit the feedstock (60 kt of food waste) was heated to 75 °C. The amount of energy needed for feedstock mixture heating was calculated with the specific heat capacity of water according to the equation:

$$\Delta E = c \times m \times \Delta t$$

where ΔE is the energy needed for heating the feedstock mixture, c is the specific heat capacity of water ($c_{water} = 4.18$ kJ/kg°C), m is the mass of the mixture (kg) and Δt is the change of the temperature (from 15 to 75 °C). For the digester, the amount of energy needed was allocated only for the dilution water (40 kt/y). This is because the heat from the hygienization unit was assumed to be sufficient for the heating of the FW feedstock (60 kt/y) (Berglund and Börjesson 2006, Prapaspongsa et al. 2010). The heating of water from 15 to 40 °C was calculated with the specific heat capacity of water as above. A similar method, based on the heat capacity of water for the calculation of the heat demand, was also used e.g. by Bacenetti et al. (2013), Rapport et al. (2011) and Smyth et al. (2009).

For the biogas production the conversion factor 1 $m^3(CH_4)$ = 10 kWh was used for the calculation of the energy content of the produced biogas.

Heat loss from the hygienization and digester was assumed to be 15% of the heat demand according to Smyth et al. (2009). Also higher values for digester heat loss have been reported, e.g., 20% of the heat demand in Rapport et al. (2011).

The electricity and heat consumption during feed pretreatment and hygienization as well as during digestion and gas upgrading in CHP-unit (combined heat and power) were calculated according to the literature values (Table S1). The CHP efficiency was also chosen according to the literature information (Table S1).

Table S1. Energy consumption of hygienization and pretreatment, anaerobic digestion and gas upgrading in CHP obtained from the literature and values chosen for the calculations.

Energy consumption	Electricity	Heat	Reference
Pretreatment + hygienization			
	150 kWh/tTS	10% of heat in CHP	reviewed in Pöschl et al. 2010
	37.5 kWh/t	Calculated value	Present study
Digester			
	3% biogas (18.6 kWh/t[a])	9.6% biogas (55.8 kWh/t)[a]	reviewed in Pöschl et al. 2010
	7.5% of electricity in CHP (17.7 kWh/t)[a]	20% of heat in CHP (47.2 kWh/t)[a]	reviewed in Pöschl et al. 2010
	18 (15-22) kWh/t	31 (19-50) kWh/t	reviewed in Berglund and Börjesson 2006
	5 kWh/t biomass	34 kWh/m^3 raw material	DEA 2005
	18 kWh/t	Calculated value	Present study
CHP-unit			
	4.5 % of electricity in CHP	-	Pöschl et al. 2010
	6.3% of electricity in CHP	-	Havukainen et al. 2014
	8.5-8.7% of electricity in CHP	-	Naegele et al. 2012
	4.2% of electricity in CHP	-	Banks et al. 2011
	5 % of electricity in CHP	-	Present study
CHP efficiency			
	40.9 %	44 %	Bacenetti et al. 2013
	37 %	47.1 %	Bacenetti et al. 2013
	35.7 %	51 %	Bacenetti et al. 2013
	40 %	48 %	Poeschl et al. 2012
	38 %	47 %	Present study

[a] Calculated with the results from the present study

-, not available

2. Digestate separation

The digestate solid-liquid separation efficiency and energy consumption of a decanter centrifuge were based on the literature values (Table S2).

Table S2. Centrifuge separation efficiencies and energy consumption obtained from the literature and values chosen for the calculations. Separation efficiency presented as the percentage in the liquid fraction. Digestate (D), digestate liquid (DL), manure (M).

Separation efficiency, %							Energy	Material	Reference
Mass	TS	VS	N	NH_4-N	P	K	Electricity (kWh/m^3 digestate)		
-	31-46	-	69-76	-	9-48	-	3.1-5.6	D	Møller et al. 2002
91	36	-	72	89	10	99	-	DL_{pig}	Ledda et al. 2013
76	17	-	48	81	4	77	-	DL_{cow}	Ledda et al. 2013
22.5	-	-	87	-	19	33.5	1.8-2.2	M_{pig}	Melse and Verdoes 2005
-	38-67	-	71-87	-	34-40	-	4.3-6.3	M_{pig}	Møller et al. 2002
-	35-45	-	51-73	-	18-22	-	4.3-7.3	M_{cow}	Møller et al. 2002
75-95	5-66	-	46-99	72-92	9-52	-	-	$M_{pig, cow}$	reviewed in Hjorth et al. 2010
-	-	-	-	-	-	-	2-4	-	Flotats et al. 2011
-	-	-	-	-	-	-	3	-	Møller et al. 2000
90	20	20	70	81	10	85	3.5	-	Present study

-, not available

3. Stripping of digestate liquid

The digestate liquid stripping efficiency and energy consumption were based on the literature values (Table S3). The heat demand of the stripping was calculated with the temperature change between digester (40 °C) and stripper (80 °C) using the heating capacity of water as in Chapter 1.2 of the Supplementary material.

Table S3. Recovery efficiency, process parameters and energy consumption of stripping obtained from the literature and values chosen for the calculations. Recovery efficiency presented as percentage in ammonium sulfate. Digestate (D), manure (M), digestate liquid (DL), urine (U).

Recovery efficiency (%)		Process parameters		Consumption	Scale	Material	Reference
N	NH_4-N	pH	Temperature (°C)	Energy (kWh/kgN recovered)			
-	97	-	35	-	lab	D	Liu et al. 2015
-	>96	8.5-11.5	80	-	lab	D	Bonmatí and Flotats 2003a
-	>80	9.5	40-50	-	lab	D, M_{pig}	Laureni et al. 2013
65-80	80-92.2	8.5-11	30-70	-	pilot	DL	Guštin and Marinšek-Logar 2011
65-76	-	9-9.5	60	-	full	DL	Morales et al. 2013
94	-	10	40	18.8-28.2[a]	pilot	U	Antonini et al. 2011
-	92	12	16	-	lab	U	Basakcilardan-Kabakci et al. 2007
-	65-98.8	7.7-11.5	80	-	lab	M_{pig}	Bonmatí and Flotats 2003a
90	-	9.3	60	11-14	full	-	reviewed in Morales et al. 2013
-	-	-	-	7.3 (aeration)	-	-	reviewed in Mauer et al. 2003
-	-	-	-	0.8-23 (electricity)	-	-	reviewed in van Eekert et al. 2012
-	95	9-10	<100	-	-	-	Flotats et al. 2011
-	95	-	80	2 + heat[b]	-	-	Present study

[a] kWh/kg NH_4-N

[b] Calculated with the specific heat capacity of water

-, not available

4. Reverse osmosis treatment for stripping residue and condensate

The recovery efficiency and energy consumption of the reverse osmosis (RO) treatment were based on the literature values (Table S4).

Table S4. Recovery efficiency, process parameters and energy consumption of reverse osmosis obtained from the literature and values chosen for the calculations. Recovery efficiency presented as percentage in retentate. Digestate (D), digestate liquid (DL), urine (U), sewage reject water (S), manure (M).

Separation/recovery efficiency, %							Process parameters			Consumption	Scale	Material	Reference
Mass	TS	VS	N	NH_4-N	P	K	pH	Tempera-ture (°C)	Pres-sure (bar)	Energy (kWh/m^3 stripping residue/condensate)			
-	-	-	-	-	-	-	-	-	10-30	2.5-10	lab	D	Carretier et al. 2015
28	86-100	-	99.7	99.6	72	99.5	-	-	-	-	full	DL	Ledda et al. 2013
29	97-100	-	97	97	100	99	-	-	-	-	full	DL	Ledda et al. 2013
28	-	-	-	-	-	-	-	-	-	-	full	DL	Chiumenti et al. 2010
-	-	-	95	-	90	99	6-9.2	10-45	-	8 (electricity) 4 (heat)	lab	U	Ek et al. 2006
-	-	-	90	-	92	97	6-9.2	10-45	-	5 (electricity) 0 (heat)	lab	S	Ek et al. 2006
-	92.3	98-100	-	66	-	-	8.8	22.5	55		lab	M_{pig}[a]	Mondor et al. 2008
-	-	99	-	99.5	-	-	-	-	10-100	1.5-10	-	-	Flotats et al. 2011
28	100	100	-	95	95	99	-	-	-	2.5	-	-	Present study

[a] After electrodialysis treatment

-, not available

5. Evaporation treatment for digestate liquid and stripping residue

The digestate liquid evaporation efficiency and energy consumption were based on the literature values (Table S5). The heat demand of evaporation was calculated as the temperature change between the digester (40 °C) and evaporator (80 °C) using the heating capacity of water as in Chapter 1.2 of the Supplementary material. In system stripping + evaporation + RO (S4) no heat was allocated for evaporation, thus it was assumed that heat from the stripping (80 °C) was sufficient for the evaporation as was presented in Ervasti et al. (2011).

Table S5. Recovery efficiency, process parameters and energy consumption of evaporation obtained from the literature and values chosen for the calculations. Recovery efficiency presented as percentage in concentrate. Digestate (D), digestate urine (U), sewage reject water (S).

Recovery efficiency, %				Process parameters			Consumption	Scale	Material	Reference
Mass	N	P	K	pH	Temper-ature (°C)	Pres-sure (bar)	Energy (kWh/m^3 digestate liquid or stripping residue)			
-	80-84	84-96	90-99	5.9-6.5	40	6.7	-	lab	D	Bonmatí and Flotats 2003b
20.2	99.2	-	-	3.5-5	35	5.3	-	-	D	Chiumenti et al. 2013
10	-	-	-	-	78	0.2	1.9^{a} (electricity) 3^{a} (fuel)	-	U	Mauer et al. 2003
-	95	100	99	4.5-5.5	>30	-	30 (electricity) 0 (heat)	lab	U	Ek et al. 2006
-	95	100	100	4.5-5.5	>30	-	30 (electricity) 0 (heat)	lab	S	Ek et al. 2006
15-20	98	-	-	<5.5	-	-	21 (electricity) 107-353 (heat)	-	-	Flotats et al. 2011
20	90	100	100	-	80	-	30 + heat^{b}	-	-	Present study

[a] kWh/kgN

[b] Calculated with the specific heat capacity of water

-, not available

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