Risk assessment of nutrient discharges from biogas production: Finland

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1 Introduction and objectives

Biogas has been part of the Finnish energy infrastructure for several decades. During the 30’s and the 40’s biogas was already fuelling vehicles derived of imported petroleum products. The use of biogas declined after the Second World War, but gained new interest after the oil crisis in the 70’s [1]. The biogas renaissance in Finland started as a part of municipal and industrial wastewater treatment processes’ development in the 80’s,but has established a significant role in municipal waste management and agriculture during the last four decades [2].

The trend from the 80’s up to present day has been on centralised infrastructure and large processing unit size. Biogas plants treating sewage sludge and mixed feestocks such as biowaste have been built, typically at municipal level or adjacent to large industrial plants and facilities. Biogas production in agricultural scale is fairly limited both in number and output of the biogas plants. Most of these plants are run by universities, institutes and publicly and privately funded research farms [1] Agricultural products and side streams are, however, processed also in centralized co-digestion plants.

Various feedstocks are treated in biogas plants, the most important feedstocks being sewage sludge and separately collected biowaste. In addition to biogas, the biogas plants produce significant amounts of organic side product, digestate. If the digestate is mechanically dewatered, also nutrient-rich reject water is produced. The properties of digestate and reject and their utilization depend on the feedstock to biogas plant, the biogas process and the digestate treatment process. Most of the digestate is processed into fertilizer products and used as fertilizer in agriculture or filling material in landscaping. Reject water is either discharged into sewer network in treated or untreated form or used as a fertilizer.

Municipal installations typically use biogas for combined heat and power (CHP) with plants being connected to the district heating system. Other uses for biogas include refining to methane fuels and injection to natural gas distribution networks, especially in the Greater Helsinki region [2][3].

The role of biogas production is estimated to significantly increase in the near future. According to moderate estimates at least 25% of all bioenergy needs could be covered by biogas [22]. Today, there are more than 6000 agricultural biogas plants operating in the Baltic Sea area, most of them in Germany. In Finland, the sum of heat and power production from biogas was 0.5% in 2012, while the available potential is estimated to be 7-20 % of renewable energy (in 2015) per year [23]. If this happens, it means that the possible risks and effects of biogas production will be multiplied.

The objective of this report is to give a review the status and extent of the biogas production in Finland, and to estimate the environmental risks from production of biogas especially in terms of nutrient leakages to waters. The aim is also to discuss the legal regulations and restrictions, as well as present several case examples to give a more detailed picture of status quo of biogas production and related nutrient flows.

2 Overview

2.1 Feedstocks

A variety of feedstocks are treated in biogas plants in Finland. The most important feedstocks are sewage sludge, separately collected biowaste from individuals and retail sector, organic waste streams of industry and agricultural feedstocks including animal manure, agricultural residues and energy crops [34]. Biogas can also be produced by anaerobic treatment of wastewater, even though this technology is not widely applied in Finland [39]. In this report, anaerobic treatment of wastewater is regarded as wastewater treatment rather than biogas production and is therefore excluded from the scope of this report.

By treatment capacity, sewage sludge is the most important feedstock, while biowaste, industrial side streams and agricultural residues have a smaller, yet significant role as biogas plant feedstocks (Table 3).

Total amount of manure produced in Finland was about 17 million tons in 2014. According to Luke [10], only about 1.1%, or 190 000 t/a of manure was treated by AD. In 2016 73 % of sewage sludge was treated anaerobically, corresponding to approximately 117 000 t TS/a (t TS/a = tons of dry solids per year) [30] Based on biogas production, as shown in Table 3, only 34 % of all biogas is produced from solely sewage sludge. The estimated amounts of biomass production and their use in AD are shown in Table 1.

Table 1. Biomasses produced and their use in anaerobic digestion, data from 2013 - 2017 [10]

Biomass	**Total amount (t/a)**	**Proportion treated in AD**
Manure	17 300 000	1.1 %
Hay & Grass	1 510 000	0 %
Residential & Industrial sewage sludge [30]	832 200	73 %
Biowaste (separately collected)	809 000	19 %
Waste streams from food industry	259 000	4 %
Sludges from forest industry	578 000	0 %
Total	21 288 200	

Agricultural residues and energy crops are used as AD feedstock in Finland only in quite small scale, mainly by the biogas plants located at farms. Gasum, which is the biggest biogas producer in Finland, does not use agricultural residues or energy crops at any plants. [38] These feedstocks, however, have the greatest potential for biogas production [39]

Various feedstocks can be mixed and treated in AD process together; this method is called co-digestion. Co-digestion may be preferred to optimise the conditions in AD process or to control the quality of produced digestate. Use of certain feedstocks involves the requirement for certain treatment or limit the use of digestate, which may also affect the applicability of co-digestion. In past years, the trend in Finland has been towards separate digestion of sewage sludge and biowaste due to constraints in sewage sludge digestate use.

Typical feedstock properties, including total and organic (volatile) solids content, along with nutrient content of different feedstocks are shown in Table 2.

Table 2. Typical solids and nutrient content in different biogas feedstocks in Finland [39]

Feedstock	**Total Solids (TS) (%)**	**Volatile fraction of solids (VS/TS) (%)**	**Total phosphorus (g/kg TS)**	**Total Nitrogen (g/kg TS)**	
Sewage sludge					
Dewatered	20 - 30%	64 - 75 %	20 - 30	35 - 60	
Non-dewatered	1 - 4 %	64 - 75 %	20 - 30	35 - 60	
Biowaste	20 - 35 %	70 - 90 %	2 - 10	15 - 100	
			Total phosphorus (kg/m3)	**Total Nitrogen (kg/m3)**	**Soluble Nitrogen (kg/m3)**
Manure	15 - 70%	85 %			
Cattle			1	4	1.1
Pig			2.8	4.6	1.2
Poultry			3.6 - 5.6	8.0 - 9.4	2.7 - 4.2
Horse			0.5	2.6	0.4
Manure slurry	< 12 %				
Cattle			0.5	2.9	1.7
Pig			0.8	3.4	2.2
Agricultural residues and crops	22 - 92 %				
Straw	86 - 90 %	92 %			

2.2 Biogas process

In the biogas process, also referred to as anaerobic digestion (AD), organic matter is biologically degraded under anaerobic conditions. This produces biogas, a mixture of gases consisting mainly of methane (CH_4) and carbon dioxide (CO_2), which can be utilized as a fuel in various applications. The process stabilizes treated organic material and decreases its mass. The AD process may be characterised according to process temperature (meso-/termophilic), moisture content (wet/dry process) and feeding method (continuous /batch).

Mesophilic AD processes have temperature within 35 – 43 °C, while thermophilic processes operate at temperatures of 50 – 55 °C. Retention time in AD is typically 20 – 30 days. The feedstock in wet process has a TS content of less than 15 %, whereas in dry process TS% of feedstock is about 20 – 40 %. Most wet processes are continuously fed, whereas dry processes can be designed either as batch or continuously fed process. Continuously fed dry process is typically designed as plug flow process. [39]

Certain amount of organic matter is turned into biogas, typically corresponding to approximately 2 – 10 % of feedstock solids mass in wet process and 12 – 30 % in dry process. The amounts of nutrients (N, P, K) are practically unchanged in AD process, and therefore the nutrients in the feedstock will be found in similar amounts in the digestate [39]. Organically bound nutrients, however, are partially turned into soluble form. Most notably, the amount of ammonium nitrogen increases significantly in the process. The effect on phosphorus depends on the form of phosphorus in feestock. If phosphorus is precipitated with metal salt, as is the case for most of sewage sludge, only a minor fraction is solubilized.

Mandated by Side product law (EY 1069/2009), facilities treating animal-based waste products (regardless of the product) need to implement thermal hygienisation pre- or post-treatment at 70 °C for minimum of one hour. Municipal biowaste is regarded to include animal-based ingredients and therefore hygienization is required [39]. Thermophilic AD process is, in this case, considered sufficient for hygienisation. Fertilizer product law (539/2006) and Evira Fertilizer type name list [37] require similar or equivalent validated hygienisation step for facilities that produce fertilizer products from sewage sludge. Prior to AD process, the feedstock may need pre-treatment, such as shredding, sieving of mixing with other material. For instance, the hygienization requirements pose certain limits for the material grain size.

2.3 Treatment of digestate and end products

Digestate from AD process can be used to produce different types of fertilizer and soil additive products. All commercially sold products have to be classified according to the national type name list for Fertilizer type name list [37] by Evira. The regulative framework regarding fertilizer products is discussed in detail in Chapter 5 The most important treatment methods and end uses are illustrated in Figure 1

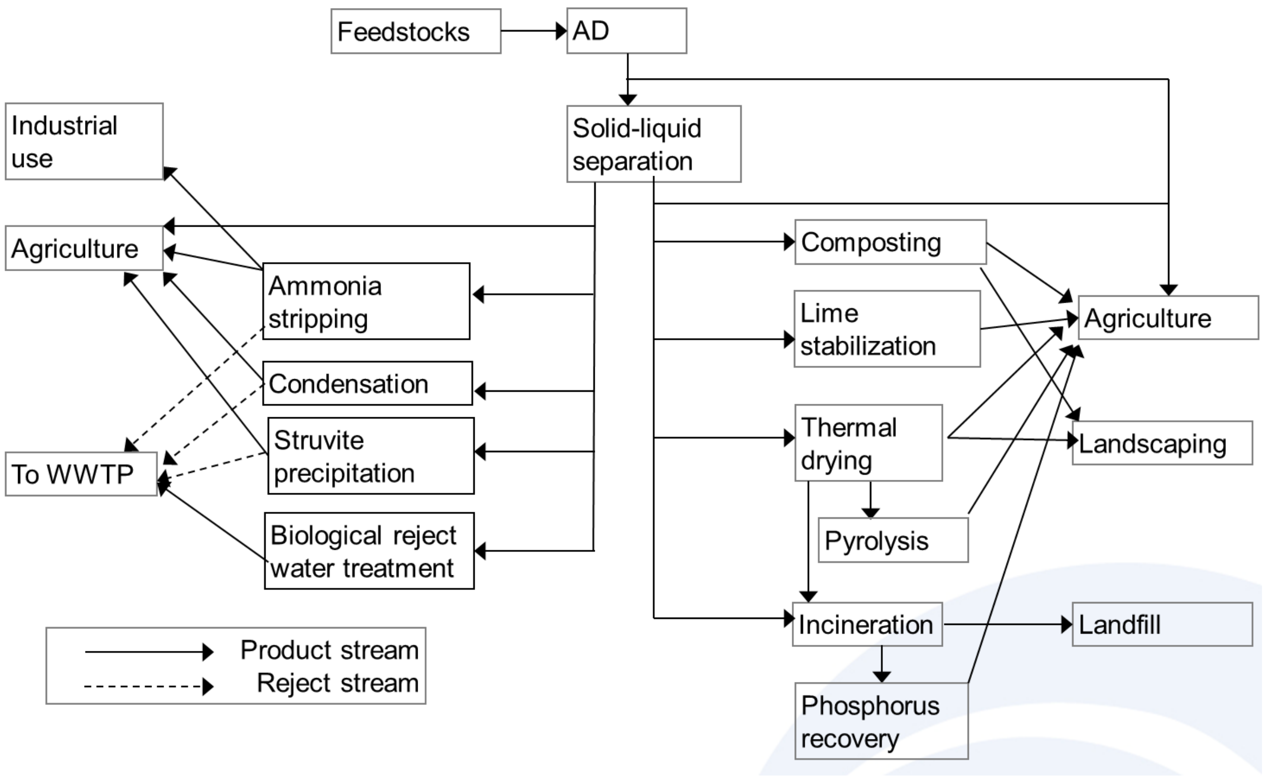


Figure 1. Digestate treatment methods and end use

The treatment technologies used for sewage sludge as percentage of sewage sludge are shown in Figure 2. The proportion of different fertilizer products produced from sewage sludge based on sewage sludge solids mass is shown in Figure 3. It should be noted that the data shown is only for sewage sludge. Furthermore, the data includes all sewage sludge, even though only 73 % of sewage sludge was treated anaerobically in 2016 [30]. However, the data gives an indicative estimation of the proportions of produced fertilizer products from biogas plant digestate.

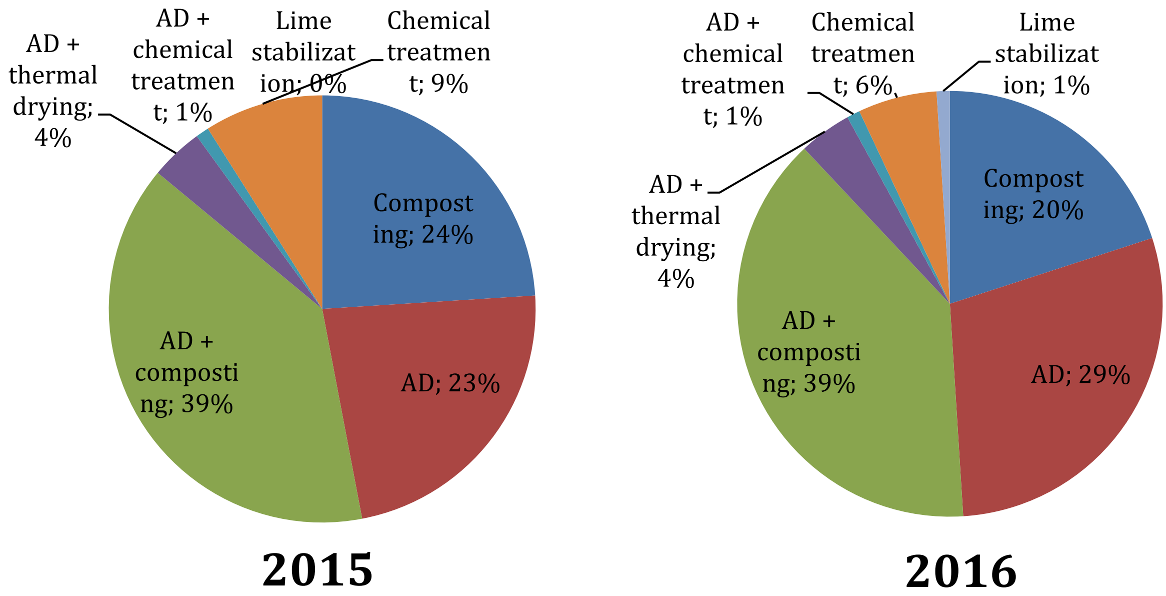


Figure 2. Treatment technologies used for sewage sludge in 2015-2016 [30]

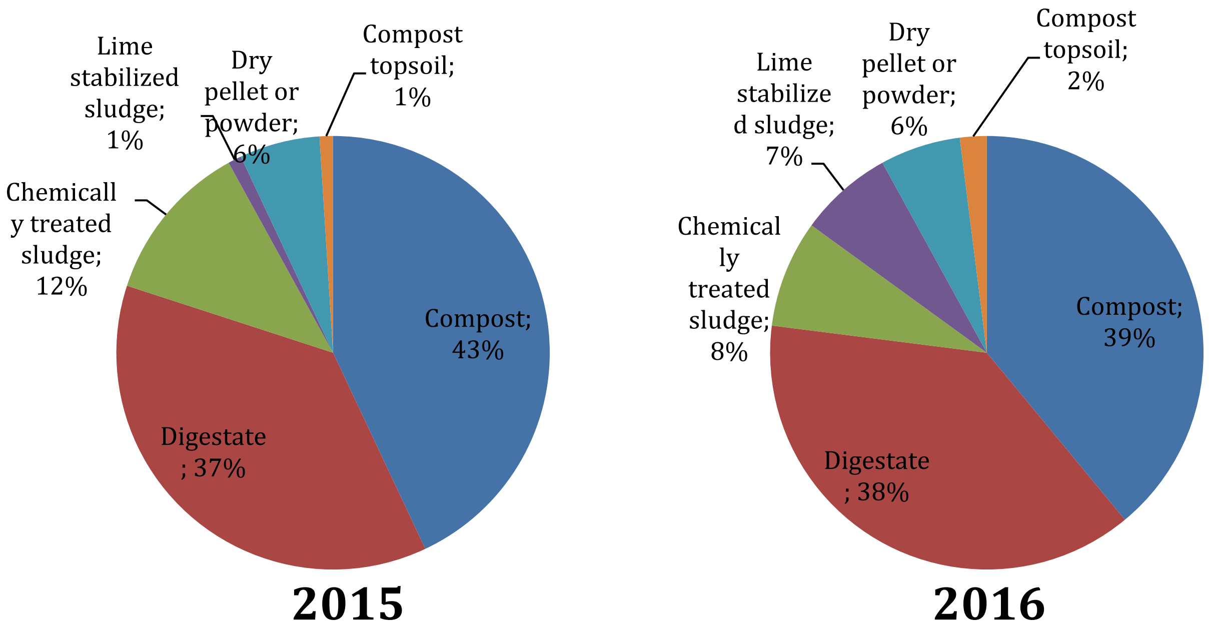


Figure 3. End products derived from sewage sludge in 2015-2016. [30]

2.3.1 End use without liquid-solid separation

In most cases, utilization of digestate without further treatment is, in principle, possible. As discussed in Chapter 5.1.1 , the digestate can be used as a soil additive according to Fertilizer type name list [37] by Evira. The digestate can be classified as fertilizer digestate (class 3A5/2), or as manure mixture (class 3A2/2) if feedstock to AD process consists solely of manure. These products are both classified as soil additives and can be used e.g. in agriculture or landscaping as such.

At larger plants, however, direct use of digestate is complicated due to challenges in controlling mass and nutrient flows. Digestate has great volume and mass, making its use less attractive due to high transportation costs.

2.3.2 Liquid-solid separation

At most biogas plants with wet process, the digestate is separated into liquid and solid fractions by mechanical separation equipment. Solid-liquid separation aims to decrease the water content in the solid fraction, thus improving the possibilities for further use and transportation. Typically, separation of phosphorus into the solid fraction is also targeted. Most common technologies for liquid-solid separation are centrifuge, belt press or screw press, centrifuge being the most commonly used. If digestate is very dilute, e.g. solids content is less than 3 %, also settling by gravity can be used as first separation process. Liquid-solid separation is often enhanced by using polymer chemicals. [39]

Screw press can produce very solid product, but its drawback is that some fine solids are lost in the reject water, decreasing the solids separation efficiency and significantly affecting the nutrient separation efficiency. Separation efficiency with screw press is the better the higher is the fibre content of digestate. Operation of belt press is affected by the separation properties of solid and liquid fraction. Typically, belt press cannot achieve as high solids content as screw press or centrifuge. In terms of nutrient separation, centrifuge is the most efficient technology. It is also robust technology and works well even with very fine solids and low fibre content. [39]

The solid fraction of dewatered digestate from wet AD process comprises typically about 10 - 30 % and liquid fraction about 70 - 90 % of feedstock mass [33][36]. The amount of nitrogen depends on the amount of soluble nitrogen and phosphorus in the digestate. When organic matter disintegrates in digestion, soluble nitrogen and phosphorus are released into the water phase. Typically, sewage sludge from Finnish WWTPs includes very little soluble phosphorus, because most WWTPs remove phosphorus by chemical precipitation, and the chemical bond between metal ions and phosphate ions is not broken in digestion. On the other hand, digestate from a plant treating manure or sidestreams from food industry may include significant amounts of liquid phosphorus. Therefore, the feedstock greatly affects the nutrient composition in the solid and liquid fractions. As discussed before, also the separation technology has an impact on nutrient separation rates. As an example, for a digestate from wet process treating mainly pig manure, typically about 70 % of nitrogen is retained in the liquid fraction, while only about 1/4 of phosphorus is retained in the liquid fraction [36]. For a wet process treating only sewage sludge, it is estimated that 81 % of nitrogen and only 10 % of phosphorus is found in the liquid fraction and the rest in the solid fraction [33].

2.3.3 Treatment of reject water

At most plants, the reject water is delivered to a WWTP without further treatment. This increases the flow and load, especially nitrogen load to the WWTP. Reject water may have nitrogen concentrations of up to 30 times higher than municipal wastewater [39]. Therefore, when designing biogas plants it is important to consider the ability of the available WWTP to treat the reject water. At some WWTPs, AD of reject waters have caused operational problems. In any case, the additional load to WWTP increases the energy and chemical costs of the WWTP, and a study on the available capacity of the WWTP should always be conducted when designing a biogas plant. A recommendation exists to pre-treat the reject waters at the biogas plant itself. [28]

At plants treating less than 10 % sewage sludge, reject water can be used as a fertilizer product as such. The concentration of nutrients in reject water is typically low in comparison to solid digestate and other fertilizer products, and therefore further treatment methods to improve the quality of liquid fertilizer product can be used. Possible treatment methods include ammonia stripping, evaporation (a.k.a. condensation), biological treatment methods and crystallization (e.g. struvite precipitation). [39]

Ammonium nitrogen (NH_4-N) can be separated from reject water by stripping it to the gas phase as ammonia (NH_3) and by scrubbing it to a liquid product. This kind of a product may be classified as inorganic nitrogen fertilizer (1B1/1) as discussed in chapter 5.1.1 [37]. Nitrogen in gaseous ammonia form can be recovered in utilizable form either by scrubbing or condensating ammonia-containing steam back to liquid form. Nitrogen separation efficiency in stripping depends on water temperature and pH, as they affect the chemical equilibrium between ammonium ion and ammonia. Volatile ammonia form is promoted by high pH and temperature, enhancing stripping efficiency. The pH in digestate is typically 7,5-8, while temperature may vary significantly depending on the process configuration; if treatment is undergone directly after AD, temperature is higher than after storage. Typically pH and temperature are adjusted prior to stripping. The ammonia-containing steam is turned into liquid form in recovery unit, which typically uses acids such as sulfur or nitrogen acid for scrubbing or by condensation. Optimally, recovery rates of 80-95 % as ammonium nitrogen have been achieved with stripping. Produced nitrogen concentrate can be used as fertilizer or in industrial applications to replace e.g. urea. Due to additional investment and operational costs, ammonia stripping is regarded applicable at plants which are of larger scale. Reject water stripping is in use for instance at Gasum Topinoja plant in Turku and Envor plant in Forssa. [39]

Reject water can be fed to condensation as such or after ammonia stripping. In condensation process, pH of reject water is lowered to 5 – 6 and condensation is performed in under-pressurized conditions by boiling water at a temperature of about 80 ºC. Commonly used condenser type is a falling film (FF) condenser, which consists of a large vertically oriented pipe, which includes hundreds or thousands of thin pipes. Reject water is pumped to the top of the condenser and let flow down along the pipe surfaces. Part of the water is recirculated back to the top from the bottom of condenser in order to achieve desired solids content in the condensate. The maximum solids content is limited by the increasing viscosity of water. Condensers typically achieve solids content of 10 – 30 %, depending on the properties of treated water. The evaporated steam from condenser is condensated back to liquid form. This side stream water includes organic acids and ammonia and can be utilized at the plant as technical water (partially treated wastewater) e.g. in polymer solution or dilution of AD feedstock. The side stream water is low in nitrogen content and can be added to the AD process without risk of excessive ammonia load to AD, which would cause inhibition. If not needed at the plant, the side stream water can be delivered to WWTP, if the process tolerates very dilute water, or treated on site for discharge to environment by e.g. membrane filtration. [39]

If fertilizer use of reject water is not targeted, microbiological treatment of reject water can be applied. Reject water is relatively highly polluted, especially in terms of nitrogen load, compared to typical municipal wastewater. Aerobic treatment of reject water is typically used as a pre-treatment prior to discharge to WWTP. In the design phase of a biogas plant, additional nitrogen load to receiving WWTP must be considered, if reject water is delivered to the WWTP. Various aerobic treatment methods, such as activated sludge process, biological filters and biofilm carrier processes can be applied in reject water treatment. Typically, biological processes aim to total nitrogen removal by transferring it into nitrogen gas form. Nitrogen removal may be achieved by traditional nitrification-denitrification processes, or utilizing alternative nitrogen removal processes such as deammonification, a.k.a anammox. Deammonicifation refers to direct oxidation of ammonia nitrogen to nitrite and reduction of nitrite to nitrogen gas using ammonia ion as electron acceptor, under anaerobic conditions. The best-known commercial applications are Demon, ANAMMOX and AnitAMOX. Deammonification is applied in full scale for instance at Lakeuden Etappi Biogas plant, and it has been piloted in full scale at Helsinki Viikinmäki WWTP. Alternative nitrogen removal processes typically require less organic carbon, consume less energy and produce less sludge than treatment with traditional activated sludge process. These processes are especially well suited for reject water treatment, making use of its high nitrogen content, low organic matter to nitrogen ratio and high temperature. [39]

Struvite precipitation is a chemical treatment method, which can be used to precipitate nitrogen and phosphorus from a solution to solid struvite ($MgNH_4PO_4 * 6\ H_2O$), which can be used as a fertilizer. For struvite formation, suitable concentrations of magnesium, ammonium and phosphorus, and a pH of 8 – 10 are needed. Struvite production from digestate reject water could be applied due to the relatively high ammonium content in reject water. For struvite precipitation, the phosphorus needs to be in soluble form. In digestate from sewage sludge digestion, typically soluble phosphorus content is low, as phosphorus is chemically precipitated at most WWTPs in Finland. In such case, addition of e.g. phosphoric acid would be necessary. For digestate treating sewage sludge from WWTPs with biological phosphorus removal, biowaste or manure, the soluble phosphorus content may be better suitable for struvite precipitation. In most cases, magnesium needs to be added as magnesium oxide due to typically low magnesium content in reject waters.

2.3.4 Treatment of solid fraction

The solid fraction of digestate can be used as such as soil additive e.g. in agriculture or landscaping. It can be classified as fertilizer digestate (class 3A5/2), or as manure mixture (class 3A2/2) if feedstock to AD process consists solely of manure. Typically, the dried digestate is stored in stack prior to end use. If desired, it can be cured actively prior to further use by mixing it with organic matter, such as woodchips, sand or peat. In curing, the digestate becomes less odorous, and it can be used in landscaping or raw material in composting. The solid fraction can also be further treated by composting or thermal treatment, such as thermal drying, carbonization or incineration.

Composting is the most widely used treatment method for solid fraction of digestate. In composting, organic matter is degraded aerobically under mesophilic (about 35 - 45 ºC) and thermophilic conditions (50 – 70 ºC), further stabilizing and hygienizing the matter and decreasing its volume. Composting may be carried out in stacks, tunnels or reactors. With sufficient retention time and temperature, composting can be used for hygienization of the material, if no specific hygienization step is included in AD process. Besides the digestate, additive materials, such as woodchips, garden waste, or peat, are needed to make the structure of the material more porous, ensuring aerobic conditions within the compost. In addition, the composting process needs additional organic matter, as the degradable organic matter content is low in digestate.

Composting of digestate can be used to produce high-quality soil additive especially for landscaping and gardening purposes. Compost can be used also in agriculture for fertilizer and soil amendment purposes. In composting, the composition of the product may be adjusted based on the end use by using additives, such as micronutrients. In composting, a significant proportion of nitrogen in digestate is turned into ammonia gas and lost from the end product. In stack composting, the formed ammonia causes emissions to atmosphere. After composting in tunnels or reactors, post-composting in stacks is typically needed. [39]

Thermal treatment technologies include thermal drying, pyrolysis and incineration. The advantage of thermal treatment methods is decrease in digestate volume and mass. On the other hand, thermal treatment technologies require high energy input due to high water content of digestate. Thermal drying methods also serve as a hygienization step.

Thermal drying of mechanically dried digestate can be used to produce dry pellet or powder with solids content of > 80 %. Thermally dried pellets, granules and powders can be classified as organic soil additive (3A2/5). During or after the drying process, the material can be granulated or pelletized to produce homogeneous and stabile product.

Pyrolysis of organic matter, such as biowaste or sewage sludge may be used to produce carbonized solid product, biochar, pyrolysis oil and/or pyrolysis gas. Pyrolysis oil and gas can also be used in energy production. In many organic waste pyrolysis applications, pyrolysis oil and gas are burned to produce energy for the thermal drying and pyrolysis processes. Pyrolysis of digestate is not applied in full scale in Finland, but technology is currently being studied and tested by several companies.

Incineration of organic waste, such as digestate, can be used to decrease the amount of waste material and to destroy the harmful organic substances and plastics. However, heavy metals remain in the incineration ash. Most of nitrogen is lost in the incineration, but phosphorus is mainly retained in the ash. Incineration of sewage sludge is not widely applied in Finland, and digestate incineration is not applied at all. In 2015, Fortum Riihimäki and Vapo Haapavesi power plants used sewage sludge, and it consisted only minor fraction (1- 10 %) of total fuel feed [30]. Digestate incineration may be regarded as less attractive option compared to direct sludge incineration due to high investment cost of consecutive treatment steps and lower calorific value of digestate.

However, in some European countries, incineration is applied after digestion of sewage sludge. As incineration ash includes significant amouts of heavy metals, it cannot be used as a fertilizer without further treatment. In Central Europe, technologies for phosphorus separation from sewage sludge ash are being implemented. In Finland, products derived from sewage sludge ash are not yet included in the type name list and therefore the product needs to be validated and accepted in the classification before such product can be used as a fertilizer product.

2.4 End use

The main means of utilization of organic fertilizer and soil additive products are agriculture and landscaping. Besides these, concentrated nutrient products may be used in industry to replace fossil nutrient products such as ammonium sulphate, urea or phosphoric acid. Concentrated nitrogen-phosphorus-solution is used in treatment of wastewater from forest industry. Ammonium sulfate produced by stripping can be used in glass wool production. Other industrial applications, such as use as a flue gas treatment chemical is currently being studied. Besides direct fertilizer use, concentrated nutrient products can be used as additives for liquid manure fertilizers to increase the nitrogen-phosphorus ratio. [39]

Despite the industrial applications, the vast majority of digestate is used in agriculture and landscaping. Agriculture involves the use at farms, but also other means of plant cultivation, such as gardening. Landscaping is used as a broad term describing both urban and rural uses that do not include agriculture or gardening. In fertilizer use, both liquid and solid product can be used. The products vary significantly in solids and nutrient content, as discussed in Chapter 4.1 . Plant- and animal-based products can be used as fertilizers in all agriculture, including grass and root vegetables. Fertilizers for organic farming have additional requirements for the feedstocks. Sewage-sludge based solid products, such as compost and topsoil products, are not widely used in agriculture due to limitations in agricultural use.

According to the latest report by VVY (The Finnish Association of Water Utilities), sewage sludges are used in agriculture more widely than expected by official statistics, such as the VAHTI-database [30]. Figure 4 present the utilization of sewage sludge in 2015-2016. It should be noted that the data is for sewage sludge only, and thus does not represent all digestate. It is estimated that use in landscaping is favoured for sewage sludge based products [39], and therefore the shown share of landscaping may be greater than for digestate in general. At the moment, similar data for all digestate in Finland is not available. In Figure 4, landfill refers to landscaping in covering e.g. landfills or mines.

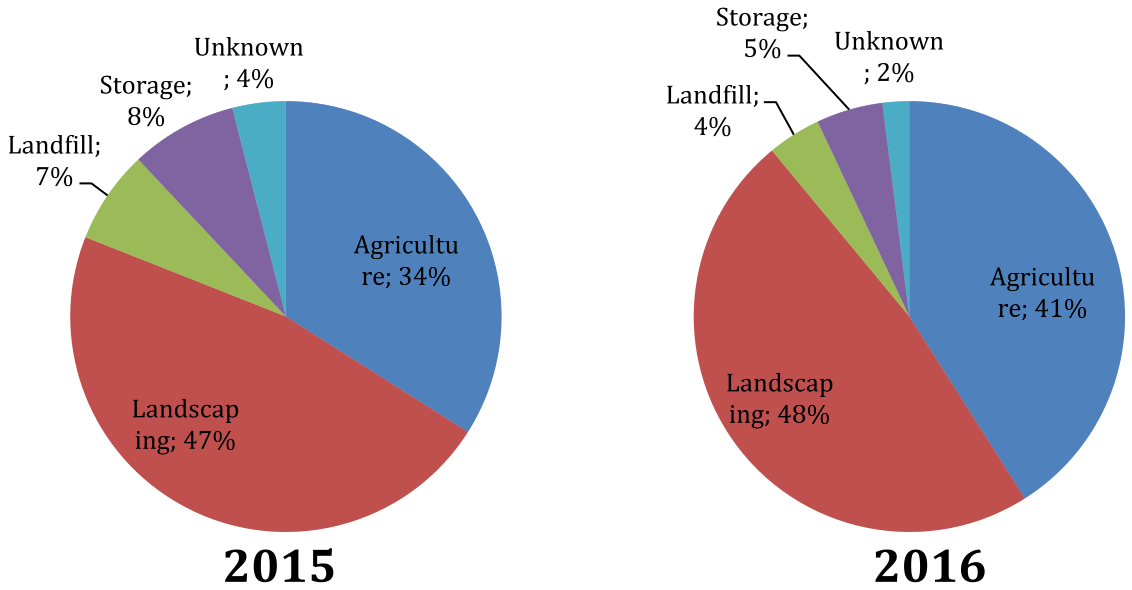


Figure 4. Utilization of wastewater-based sludges in 2015 and 2016

2.4.1 Use in agriculture

Digestate use in agriculture has increased in the past few years due to incentives to increase the nutrient recycling into food chains. There is widely accepted agreement on the fact that phosphorus is a scarce material and the phosphorus should be recycled rather than losing it in surface waters or dumping the phosphrous-rich material.

Recently, however, significant actors in the food industry, such as mill companies, have refused to use crops grown with sewage sludge based fertilizer products [10]. Due to this change in the market, utilization of sewage sludge based fertilizer products in agriculture has decreased rapidly. This has caused problems for biogas plants and WWTPs in finding end users for the digestate. At the moment, there is uncertainty about the future of agricultural use of sewage sludge based fertilizer products. Some experts from the agricultural producers' and water utilities' side see that the only option is technological development of sewage sludge treatment for instance with thermal treatment technologies, such as incineration or pyrolysis.

At the moment, similar development is not seen for other waste-based fertilizer products, and for instance biowaste-based fertilizer products are still used in agriculture. This has led to biogas plants to turn into separate treatment of sewage sludges in order to be able to sell the end products of e.g. biowaste digestion in agriculture. The legislation and requirements for fertilizer product use in agriculture are discussed further in Chapter 5.1.2 In Finland, heavy metal concentrations in sewage sludge and biowaste are generally low, and digestate products usually are well within the limits for agricultural use.

Typical amount of solid organic fertilizer products applied on fields is around 20 t/ha at one time. This is due to the maximum nitrogen amount of 170 kg/ha/a for manure based products as discussed in 5.1.2 Even though this limitation does not apply to other organic fertilizers, this is a relatively good estimation of applicable amount also for other solid organic fertilizer products [39]. The limitations for fertilizer application in agriculture are discussed in detail in Chapter 5.1.2 .

2.4.2 Use in landscaping

Digestate based products may be used in landscaping, e.g. in infrastructure projects, such as highway embankments, and in the construction of green areas. The products must meet the requirements of Fertilizer product law (539/2006), and the Evira Fertilizer type name list [37]. Soil additive products containing sewage sludge are widely used in landscaping due to limitations in agricultural use. As these limitations have recently even tightened from the side of food industry, use of digestate containing sewage sludge in landscaping is likely to increase in near future, at least until new treatment technologies are implemented and fertilizers without risk of harmful substances can be produced from sewage sludge.

At municipal and industrial landfills, landfill covering is typically required immediately after filling. The uppermost fertile layer, with a thickness of about 20 cm or as individually dictated by the environmental permit, should serve as a fertile layer promoting plant growth on the covered site. Typically during the landfill operation, rainwater from the covered area is treated as landfill leachate, but after the covering is completely finished, the rainwater from the covering is discharged to environment, thus causing the risk of nutrient leakage to surrounding waters and soils. Landfill covering may be regarded as one type of landfilling, and the requirements for materials are typically similar as in other types of landscaping. Similar covering as for landfills are used for landscaping of used mines and adjoining rock storage areas.

2.4.3 Storage

A biogas plant produces fertilizer products all year round, while the demand, especially in agriculture, varies during the year. Therefore, products have to be stored at least for periods of few months. Liquid products are typically stored in concrete basins or at the site of utilization in rubber mat covered containers. Solid matter is typically stored in covered stacks at either storage areas or fields. [39] Typically, the facilities are required to be able to store the digestate produced within one year of operation. In treatment of agricultural feedstocks, the digestate is often stored by the farms. Waste can be stored for a maximum of 3 years prior to end use as discussed in chapter 5.1.4 .

3 Biogas plants in Finland

The biogas installations in Finland can be roughly divided into four main groups by the feedstock and plant purpose. The plant types are 1. Biogas plants for sewage sludge (WWTP), 2. Centralized (co-digestion) biogas plants, 3. Industrial biogas plants and 4. Agricultural biogas plants. A summary of these plant types is shown in Table 3. The production figures are from the year 2015 and 2016, unless otherwise noted. In cases of unavailable data from these years, the latest available data is used as an estimate [1][4]. Most of the large biogas facilities in Finland operate as continuously-fed mesophilic wet reactors, while large plants with dry process exist [4]. Landfill gas recovery plants are not included in this listing.

Table 3. Biogas plants in Finland by plant type [1]

Installation	**Feedstock**	**Treatment capacity (m3/a of feedstock)**	**Biogas production (1000 m3)**
WWTP biogas plant	Sewage sludge	2 299 200	36 925
Centralized biogas plant	Biowaste, sewage sludge, sidestrams of food industry, and/or agricultural sidestreams	930 700	59 228
Industrial biogas plant	Industrial sidestreams and waste products	88 500	10 224
Agricultural biogas plant	Manure, agricultural sidestreams, energy crops	97 765	2 777
Total		**3 416 165**	**109 154**

*The summary is done for volumetric biogas production since complete electricity / heat production figures were not available.

In terms of biogas production, about 88% was due to large WWTP biogas plants (34 %) and centralized biogas plants (54 %). This quite clearly demonstrates the current situation, in which majority of biogas production is in large, centralized units. The data in Table 3 is visualized in Figure 5. Based on this, the study will be focusing mostly on centralized biogas plants. Majority of these centralized plants are located on the coastal region of Finland, which might have compounding implications to nutrient leakages. The distribution of Finnish biogas installations is shown in Figure 6.

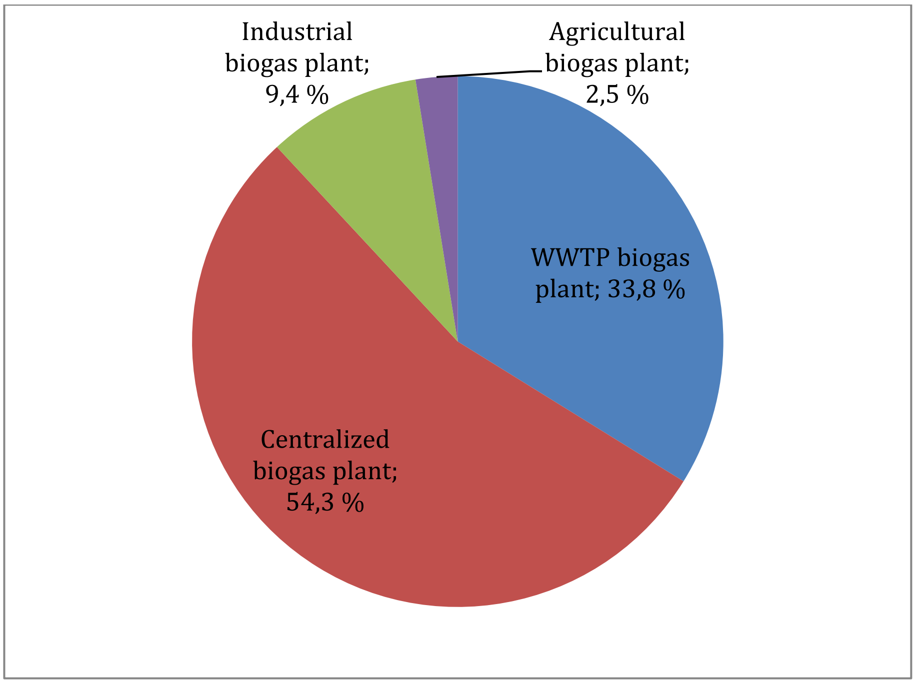


Figure 5. Proportion of major biogas plant types based on biogas production as of 2016

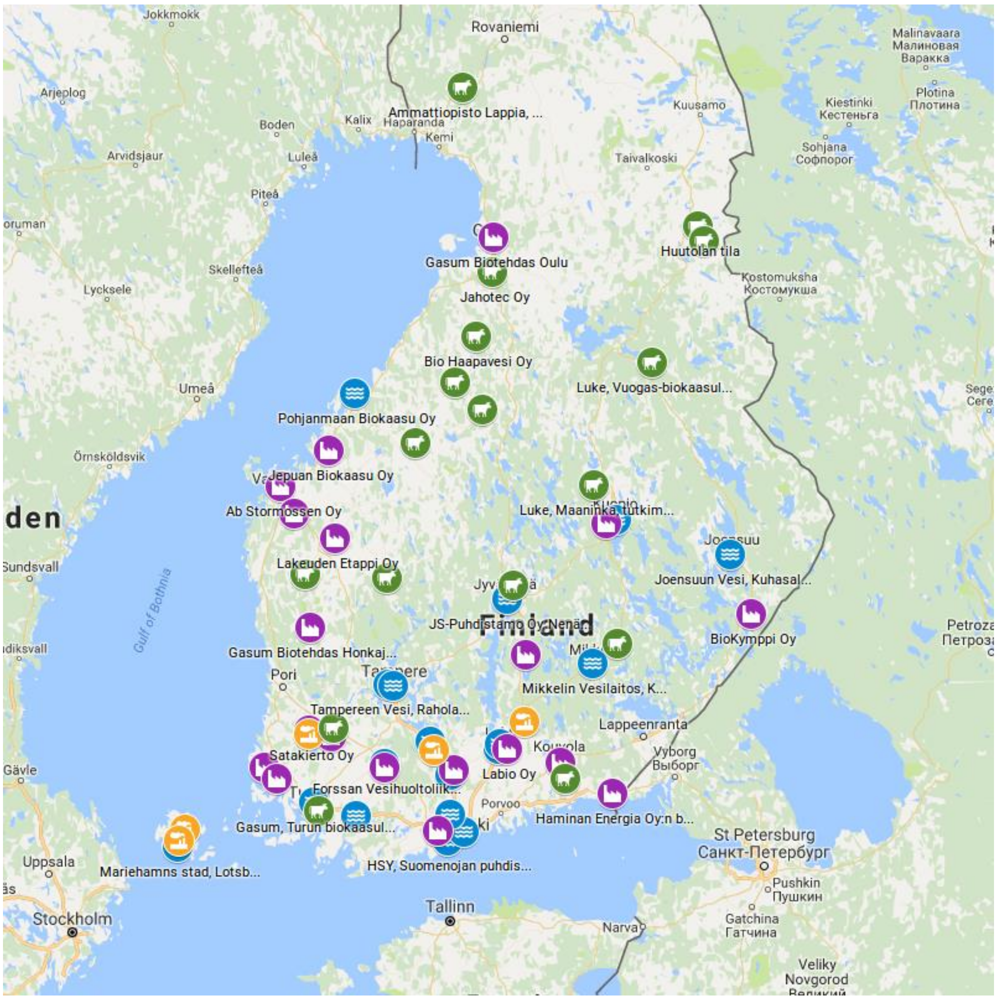


Figure 6. Biogas installations in Finland

As can be seen from Figure 6, most of the biogas plants, especially the municipal ones are located on the coastal region, which has the greatest population density and also the greatest density of animal husbandry. The effect of this will be discussed in greater detail in Chapter 7 .

3.1 WWTP biogas plants

Table 4 presents the biogas plants that are built for the purpose of sewage sludge treatment and treat solely sewage sludge. In many instances, the plants are located at the WWTP and owned by the WWTP, but this is not always the case. The capacity and produced biogas amount and also the amount of produced heat and power are given when applicable. All of the plants listed in Table 4 use wet AD process.

Table 4. WWTP biogas plants in Finland (2015) [1]

Installation	**Capacity (m^3/a)**	**Year of deployment**	**Biogas produced (1000 m^3)**	**Electricity (GWh)**	**Heat (GWh)**	**Biogas usage**
Forssan Vesihuoltoliikelaitos, Sortohaka treatment plant	18300		680 (2015)	1.392	1.989	CHP
Gasum, Turku biogas plant	75000		4507 (2015)	0.492	26.970	CHP
HS-Vesi Oy, Paroinen treatment plant	53000		577			Heat
HSY, Suomenoja treatment plant	312500		4136	0.023	23.507	Sold to Gasum
HSY, Viikinmäki treatment plant	878400		13412	24.528	41.870	CHP
Joensuun Vesi, Kuhasalo treatment plant	82000		1193	0.241	5.366	CHP
JS-Puhdistamo Oy, Nenäinniemi treatment plant	174500		2201 (2015)	2.606	8.742	CHP
Kuopion Vesi, Lehtoniemi treatment plant	87000		1199 (2015)	2.227	3.273	CHP
Lahti Aqua Oy, Ali-Juhakkala plant	22000		910		7.962	Heat
Lahti Aqua Oy, Kariniemi plant	110000		1730			Heat
Mariehamns stad, Lotsbroverket treatment plant	20300		411	0.317	1.161	CHP
Mikkelin Vesilaitos, Kenkäveronniemi treatment plant	36000		350	0	1.386	Heat
Nurmijärven Vesi, Klaukkala treatment plant	6500	2005	90 (2014)	0	0.357	Heat

Pohjanmaan Biokaasu Oy	51000		575 (2016)			CHP
Riihimäen Vesi, Riihimäki treatment plant	27400		600 (2009)	1.464	2.091	CHP
Salon Vesi, Salo central treatment plant	36500		440	0	2.296	Heat
Tampereen Vesi, Rahola treatment plant	78800		1073	2.311	3.302	CHP
Tampereen Vesi, Viinikanlahti treatment plant	230000		2081 (2015)	2.354	3.362	CHP
Total	**2 299 200**		**36 925**			

3.1.1 Case example: Viikinmäki WWTP

Viikinmäki treatment plant is the largest wastewater treatment plant in Finland by treatment capacity. Anaerobic digestion is used as part of the treatment process, and the produced biogas is used for combined heat and power. The biogas produced covers about 70% of electricity consumption and all of the heat energy required by the whole treatment process. [6]

The digestate from anaerobic digestion is separated into solid and liquid parts. The liquid part is fed back into the wastewater treatment process. Reject water treatment by deammonification is being piloted at the moment. The phosphorous-rich solid part is first separated mechanically and then transported to Metsäpirtti composting facility in Sipoo. The end product of the treatment chain is nutrient rich soil, which is primarily used for landscaping and bought by private and public sectors. Agricultural use of the soil is limited.

3.2 Centralized biogas plants

The centralized biogas plants are large biogas units used to treat a variety of materials including biowaste, sewage sludge, industrial waste streams and, in some cases, limited amounts of agricultural waste streams or manure. Plants with both wet and dry processes exist. The largest plants are owned by Gasum and HSY. Gasum uses the digestate to produce digestate and reject water based fertilizer products as discussed in chapter 4.1 . HSY utilizes the digestate as a raw material for compost and topsoil products.

Table 5 presents centralized biogas plants in Finland as of 2016. The capacity and produced biogas amount and also the amount of produced heat and power are given when applicable.

Table 5. Centralized biogas plants in Finland (2016) [1]

Installation	**Capacity (m^3/a)**	**Process type (wet/dry)**	**Year of deploy ment**	**Biogas produced (1000 m^3)**	**Electri city (GWh)**	**Heat (GWh)**	**Biogas usage**

Ab Stormossen Oy	60000	Wet		1580			CHP, fuels, industrial
BioKymppi Oy	35000	Wet		1763	2.408	5.620	CHP
Biolinja Oy Uusikaupunki	18000	Wet	2013	Unknown			Unknown
Envor Biotech Oy	84000	Wet		5725 (2015)	4.189	26.164	CHP, fuels, industrial
Gasum Biotehdas Honkajoki	60000	Wet	2014	4600			CHP ?
Gasum Biotehdas Huittinen	60000	Wet		4600			CHP ?
Gasum Biotehdas Kuopio	60000	Wet	2014	4600			Power, industrial
Gasum Biotehdas Oulu	19000	Wet	2015	2300			Industrial
Gasum Biotehdas Riihimäki	75000	Wet	2017	7700	2.347 (2011)	7.062 (2011)	Fuels, network
Gasum Vehmaa	120000	Wet		5061	9.585	26.164	CHP
Haminan Energia Oy’s biogas plant, Virolahti	19000	Dry	2015	Initialisation in progress			Fuels, network
HSY Ämmässuo biogas plant	44000	Dry	2015	5000 (2016)			CHP
Jepuan Biokaasu Oy	90000	Wet		3180	0	17.081	Heat, fuels, industrial
Joutsa Ekokaasu Oy	5000	Wet		260 (2015)	0	1.506	Heat, fuels
Labio Oy	80000	Dry		7390 (2015) 7800 (2016)	0	37.377	Fuels, network
Laihia municipal biogas plant	3700	Wet		247	0	0.269	Industrial
Lakeuden Etappi Oy	55000	Wet		2255	0	10.266	Heat
Mäkikylä biogas plant (Kouvolan Vesi Oy)	19000			1600 (2016) 2121 (2015)	1.835 (2015)	10.375 (2015)	Power, fuels, network
Satakierto Oy	24000	Dry, wet		270 (2011)	0	1.516	Heat

Total	**930 700**			**59 228**			

3.2.1 Case example: HSY Ämmässuo biogas plant

The HSY Ämmässuo biogas plant plant treats municipal and commercial organic waste in Helsinki region, Southern Finland. The plant is used for combined heat & power production, where most of the heat is being used by the process. Figure 3 presents the operating principle of the Ämmässuo biogas plant and the following digestate treatment into compost products [18].

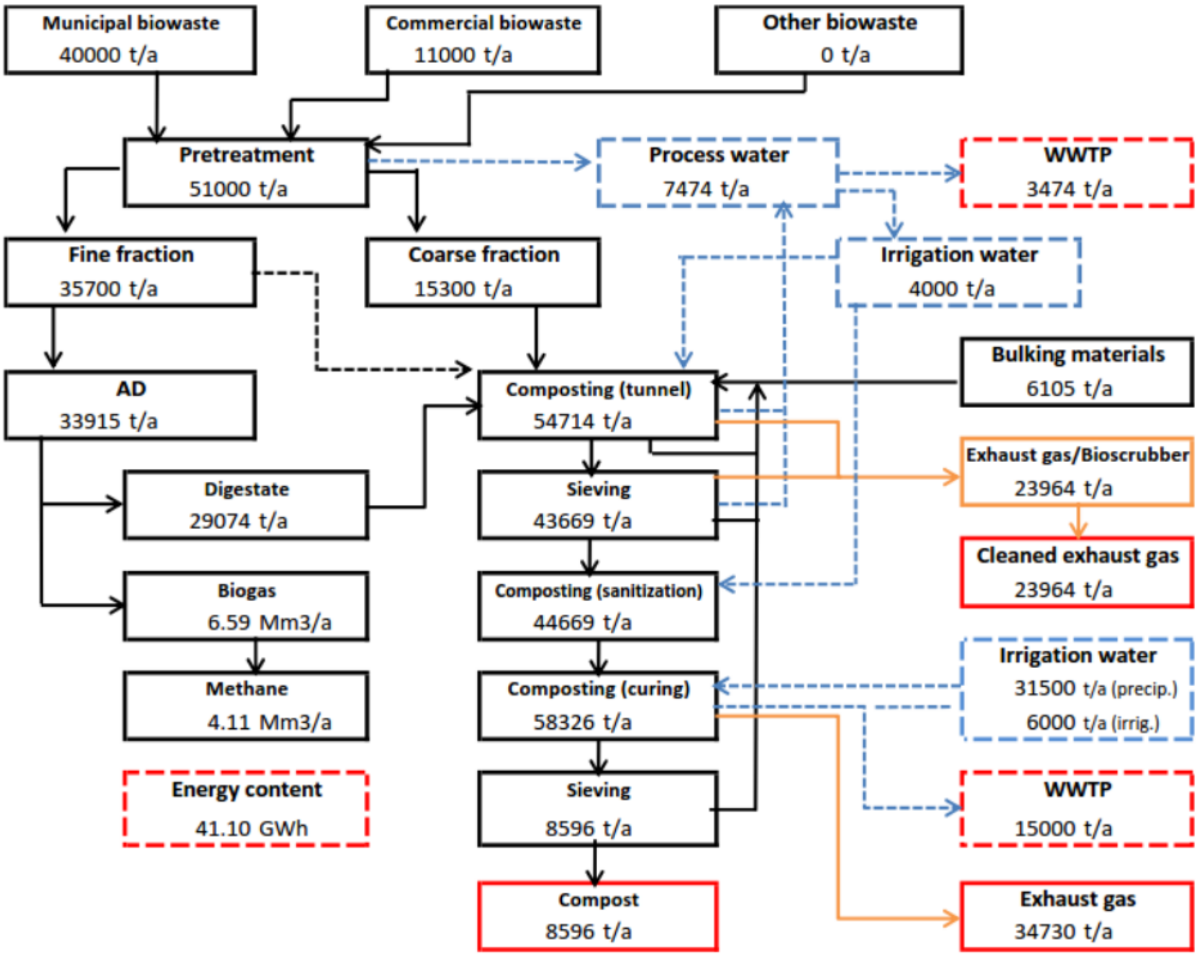


Figure 3. Systemic mass flow diagram of the Ämmässuo (SWTP) biogas plant

Feedstock is sorted by 80 mm sieve into fine and coarse fractions, which are fed to anaerobic digester and composting respectively. The anaerobic digestion itself operates in mesophilic dry process, and the digestate is fed to the composting process for further processing. The end product of the plant is compost, which is used for landscaping. The dry digestion process does not produce a significant wastewater load; wastewater from pre-treatment and composting is directed to Suomenoja wastewater treatment plant.

3.3 Industrial biogas

Table 3 presents the operational industrial biogas plants in Finland as of 2016. The capacity and produced biogas amount and also the amount of produced heat and power are given when applicable.

Table 6. Operational industrial biogas plants in Finland in 2016 [1]

Installation	**Capacity (m^3/a)**	**Year of deployment**	**Biogas produced (1000 m^3)**	**Electricity (GWh)**	**Heat (GWh)**	**Biogas usage**
Apetit Oyj, Säkylä	10500		440		1.688 (2015)	CHP indirect
Chips Ab, Godby, Ahvenanmaa	Unknown		484	0	2.661 (2009)	Heat, otherwise unknown
St1 Biofuels Oy, biogas plant integrated to bioethanol plant	19000		2100			CHP, industial
Stora Enso, Heinolan Fluting factory	10000		2530			Heat
Ålandsmejeriet, Jomala, Ahvenanmaa	13000		670			Unknown
EcoEnergy SF, Äänekoski	36000		4000		24.0 (2017)	Biomethane (fuel), solid biofuel
Total	**88 500**		**10 224**			

Industrial biogas plants are typically built to handle waste streams from an operating factory or industry and as such are quite difficult to categorize in terms of treatment methods. However, due to relatively low number and capacity, individual cases were not pursued.

3.4 Agricultural Biogas

Agricultural biogas plants in Finland typically do not post-treat the digestate, but typically apply it to the fields as such. In some cases the digestate may be separated into liquid and solid fractions. The biogas plants treating manure and obsolescent animal fodder from the farm itself can omit the hygienization treatment if the produced fertilizers are used within the farm. Table 7 presents the operational agricultural biogas plants in 2016. The capacity and produced biogas amount and also the amount of produced heat and power are given when applicable.

Table 7. Agricultural biogas plants in Finland (2016) [1]

Installation	**Capacity (m^3/a)**	**Year of deployment**	**Biogas produced (1000 m^3)**	**Electricity (GWh)**	**Heat (GWh)**	**Biogas usage**
Professional school Livia	2000		107	0.060	0.398	CHP, fuels
Bio Haapavesi Oy	9000		Unknown			Unknown
BioSampo -research center	365		9			Power
Emomylly Oy	19000		300			CHP
Professional school of Haapajärvi	3000	2007	10 (2015)	0	0.051	Heat, fuels
Heusala farm	1000		50			CHP
Huutola farm	3000		68 (2014)	0.136	0.196	CHP
Juntula farm	1600		16 (2013)	0	0.098	CHP
Juvan Bioson Oy	19000		1500			CHP, industrial
Kalmari farm	4000		270	0.166	1.253	CHP, fuels, network
Koivunen, Virrat (farm)	4000		200 (2009)	0.402	0.574	CHP
Kotimäki (farm)	9000		150	0.177	0.600	CHP
Luke, Maaninka, Research farm	3800	2009	62	0.024	0.275	CHP
Luke, Vuogas-biokaasulaitos, Sotkamo, research farm	1000	2008	Initialisation in progress			Unknown
Professional school Lappia, educational farm, Tervola	3000		65			Unknown
Jahotec Oy	10000		unknown			Unknown
Professional institute of Suupohja, educational farm	5000		Initialisation in progress			Unknown
Total	**97 765**		**2 777**			

In addition to the listed plants, some 15 new agri-scale biogas plants were under construction in 2015, However, the information on these was rather scarce and could not be established during the scope of the study [1].

3.4.1 Case example: Livia Vocational school biogas plant

The Livia test facility operates in two stages; The slurried digestate from the primary reactor is mechanically separated into liquid and solid fractions. The solid fraction is used similarly to solid manure in the research farm. The liquid fraction undergoes a post-fermentation process where the hydraulic retention time is at least 30 days. The residual gas is collected and added to the biogas produced by the main reactor. This arrangement is quite typical of the farm-scale biogas plants in Finland. However, it is more complicated than a single-container reactor and as such more expensive to build.

4 Commercial end products

The main product of biogas plants is biogas, which can be used in energy production, or alternatively as material in chemical industry. The most important side product is digestate and fertilizer products derived from digestate. After certain treatment steps, digestate products can be used in industrial applications to replace chemicals such as urea. In addition to digestate, several side products, such as carbon dioxide (CO_2), hydrogen (H_2), Sulfur (S) and Nitrogen (N_2) could be extracted from the biogas [39]. However, industrial applications are rare, and practically all digestate from commercial biogas plants is used in production of different fertilizer products. Therefore, the focus in this chapter is in fertilizer products.

4.1 Fertilizer products

The most common product types are digestate, reject water, composts and topsoil products, and nitrogen fertilizer liquids. Fertilizer products differ significantly in their properties. The solids content may be anything between about 1 – 90 %; there are products of both liquid and solid forms. Digestate products may comprise either untreated digestate, i.e. no liquid-solid separation is applied, or solid fraction of digestate. The former is typically, in the case of a wet process, a liquid product and the latter a solid product.

The amount of main nutrients remain mainly unchanged in AD process, and therefore the total amounts of nitrogen (N), phosphorus (P) and potassium (K) are relatively similar in the product as in the feedstock. If solid-liquid separation is used, most of nitrogen is found in the liquid fraction and most of phosphorus in the solid fraction, especially in the case of sewage sludge.

Dried digestates have typically a total solids (TS) content of about 20 – 30 %, and untreated digestates, as well as reject water, a TS content of about 1.5 – 20% depending on the type of product. In solid products the amount of total nitrogen is typically 25 – 100 g/kg TS, and amount of phosphorus 5 – 40 g/kg TS. Nitrogen-phosphorus ratio is typically about 0.7 - 4. The liquid (reject water based) products have varying amounts of nutrients, but nitrogen content is typically high (typically 90 – 300 g/kg TS) and N:P –ratio high (typically 8-15). The phosphorous-nitrogen ratio can be adjusted by mixing applicable amounts of liquid and solid fractions. The nutrient density in fertilizer products may be significantly more than that of manure, in which the phosphorous content is on average around 1.1 kg/t and nitrogen content about 4.3 kg/t. (Table 12).

Soluble nitrogen and phosphorus content vary widely. Typically soluble nutrient contents are high in reject water products (soluble N > 70 % of total N; soluble P > 50 % of total P). In solid fraction of digestate, 10-55 % of nitrogen is soluble and 0 – 20 % of phosphorus is soluble. Compost products, topsoil products and thermally dried products have low soluble nitrogen (4 – 14 % of total N) and very low soluble phosphorus (0.1 – 0.3 % of total P) content. The properties of studied fertilizer products are summarized in Table 8.

Table 8. Properties of commercial fertilizer products

Product (Type name, facility)	Raw materials	End use	TS %	VS/TS (%)	N (g/kg TS)	soluble N(g/kg TS)	P (g/kg TS)	soluble P(g/kg TS)	N (kg/m3)	P (kg/m3)	N:P
Reject water (1B4/4) products											
Gasum Voimakas (Vehmaa)	Manure, industrial organic side products	All fertilizing excluding organic farming	17.6 %	72.0 %	120	87.8	13	7.3	24.0	2.5	9.2
Gasum Moniravinne (Vehmaa)	Manure, industrial organic side products	All fertilizing excluding organic farming	1.8 %	63.4 %	284	222	20	18	5.7	0.4	14.2
Digestate (3A5/2) products											
Gasum perus (Honkajoki)	Source-separated biowaste, biowaste from retail sector, industrial organic side products of class 3 , sewage sludge	Grain and energy plants fertilizing, lawn founding, topsoil production for landscaping	5.6 %	55.0 %	110	54	22	0.043	6.3	1.3	5.0
Gasum humusvoima (Oulu)	Source-separated biowaste, biowaste from retail sector, industrial organic side products of class 3 , sewage sludge	Grain and energy plants fertilizing, lawn founding, topsoil production for landscaping	28.4 %	42.0 %	41.1	5.5	43	0.18	7.0	7.3	1.0
Gasum Biotehtaan maanparannuslannos (Huittinen)	Source-separated biowaste, biowaste from retail sector, industrial organic side products of class 3 , sewage sludge	Grain and energy plants fertilizing, lawn founding, topsoil production for landscaping	31.3 %		31	7.9	26	0.3	6.2	5.1	1.2

BioKymppi LuomuKymppi A	Source-separated biowaste, biowaste from retail sector, slaughterhouse waste, cattle manure	All fertilizing, also organic farming	5.3 %	72.8 %	113	63.4	14	2.9	5.9	0.7	8.1
BioKymppi LuomuKymppi B	Source-separated biowaste, plant-based waste, biowaste from retail sector, slaughterhouse waste, cattle manure	All fertilizing, also organic farming, topsoil production for landscaping	22 %	87.7 %	25.3	4.46	6.1	0.66	3.8	0.9	4.1
BioKymppi PeltoKymppi A	Source-separated biowaste, sewage sludge, grease sludges, plant-based waste, biowaste from retail sector, slaughterhouse waste	Grain and energy plants fertilizing	5.4 %	64.4 %	90.2	49.1	34	1.4	4.8	1.8	2.7
Dry granulate or powder (3A2/5)											
RANU Maanparannusrae	Sewage sludge, biowaste	Fertilizing especially in the fall and for plants and soil requiring high amounts of phosphorus	90 %	53 %	34	1.5	32	<0.1	27	26	1.0
Compost products (3A2/1, 3A2/3)											
HSY Metsäpirtin maanparannuskomposti (Soil additive compost 3A2/1)	Sewage sludge, peat	Gardening, agriculture, topsoil production, landscaping	30 %	60 %	22	3	20	0.018	3.9	3.3	1.1

HSY Metsäpirtin tuorekomposti (Fresh compost 3A2/3)	Digestate from sewage sludge, fibre-/biosludge, peat	Gardening, agriculture, topsoil production, landscaping	30 %	60 %	22	2	22	0.05	4.0	4	1.0
Topsoil products (5A2)											
Stormossenin nurmikkomulta (Compost topsoil 5A2/2)	Sewage sludge, biowaste	Landscaping and gardening, lawn founding	77.0 %	13.0 %		0.03		0.001	2.8	4.0	0.7
Metsäpirtin nurmikkomulta (Compost topsoil 5A2/2)	Compost containing sewage sludge, sand, peat, biotite	Landscaping and gardening	55.0 %	19.0 %		0.82		0.075	0.34*	0.031*	10.9
Metsäpirtin puutarhamulta (Compost topsoil 5A2/2)	Compost containing sewage sludge and horse manure, sand, peat	Landscaping and gardening	55.0 %	19.0 %		0.66		0.1	0.26*	0.06*	6.6
Nitrogen Fertilizers (1B1/1)											
Envor Typpineste	Biowaste, sewage sludge, side streams from food industry	All fertilizing, industrial use	liquid						90.0		
Gasum Typpiravinne	Sewage sludge	All fertilizing, industrial use	liquid						30.0		

*Soluble fraction

4.1.1 Reject water products

Gasum Voimakas is a reject water product manufactured by Gasum Vehmaa biogas plant. It is manufactured from animal manure and industrial by-products. It is classified as Reject water (1B4/4), but the solids content is increased to about 18 %. Total nitrogen and phosphorous contents are slightly higher at 24 and 2.5 kg / m3 respectively, making this primarily a nitrogen fertilizer. As Gasum Voimakas does not contain sewage sludge, it does not have the same limitations a product with sewage sludge. [13]

Gasum Moniravinne is a liquid product with total solids content of only 1.8 %. At Vehmaa plant it is made from manure and industrial sidestreams, and thus does not have the limitations that are due to products including sewage sludge. Being much more dilute than Gasum Voimakas, its nutriet concentrations are quite low, nitrogen content being 5.7 kg/m3 and phosphorus content only 0.4 kg/m3.

4.1.2 Digestate products

Gasum Perus is a liquid product manufactured by several Gasum biogas plants that treat biowaste, sewage sludge and industrial waste and manure. The product is classified as Digestate (3A5/2). The water content is about 94 % and total nitrogen & phosphorous content are 5.7 and 1.7 kg / m3 respectively. As dictated by the fertilizer produce law, this type of product is only approved for grains, sugar beet, oil plants and other plants not aimed for human or animal consumption. Root vegetables cannot be produced within 5 years after using the product. [13]

Gasum Humusvoima is a solid product with solids content of about 30 %, and is classified as Digestate (3A5/2). At Gasum Turku plant, Gasum Humusvoima is produced from digestate of solely sewage sludge. The total nitrogen and phosphorous contents are 7.1 and 6.7 kg / m3, respectively. The usage limitations are similar to those of Gasum Perus. [13]

Biotehtaan Maanparannuslannos is a solid product classified as Digestate (3A5/2). The solid matter content is about 29 % and total nitrogen and phosphorous contents are 5.9 and 5.7 kg / m3, respectively. Biotehtaan Maanparannuslannos is produced from biowaste, sewage sludge and industrial waste, and thus similar limitations apply as for Gasum Perus and Gasum Humusvoima

LuomuKymppi A by BioKymppi is liquid digestate product with solids content of about 5 % . It does not contain sewage sludge and can be used in organic farming. BioKymppi Luomukymppi B is a solid product, made of the solid fraction of digestate. Its solids content is 22%. Alike Luomukymppi A, it does not contain sewage sludge and can be used in organic farming. PeltoKymppi A, like Luomukymppi A, is a liquid digestate product with solids content of about 5 %. Sewage sludge is used as one of the raw materials.

4.1.3 Dry granulate or powder products

Dry granulate or powder products are made by thermal treatment, and thus the solids content is very high. Phosphorus content is high, whereas nitrogen content is relatively low. Soluble nutrients content, especially soluble phosphorus content, is very low. RANU pellet product by Lakeuden Etappi is the only dry granulate or powder product currently sold in Finland as of 2015 [42].

4.1.4 Compost products

Compost products are solid products with relatively high solids content. Compost products by HSY Metsäpirtti are made using solid fraction of anaerobically digested sewage sludge in a mixture with peat. Metsäpirtin tuorekomposti has lower maturity level and is therefore classified as fresh compost (3A2/3), while Metsäpirtin maanparannuskomposti is classified as soil additive compost (3A2/1). Both have nitrogen and phosphorus content of 20-22 g/kg TS or 3-4 kg/m3. N:P –ratio is low, close to 1. Soluble nitrogen and phosphorus content is relatively low.

4.1.5 Topsoil products

Topsoil products are made from compost products by mixing them with e.g. peat or sand. They have high solids content, but nutrient content is low. Topsoil products are mainly used in gardening, and therefore their volumes are smaller compared to digestate and compost products.

4.1.6 Nitrogen fertilizers

Nitrogen fertilizers are products derived from reject water by ammonia stripping or condensing. They typically have very low solids content and have nitrogen content of at least 3 %. Soluble ammonium nitrogen makes up a significant proportion of total nitrogen. Phosphorus content is typically very low, but other elements such as Sulphur may be present in significant amounts. Envor Typpineste has high nitrogen content (9.0 %) mostly consisting of ammonium nitrogen, but also includes 10.2 % of Sulphur due to Sulphur acid scrubbing.

4.2 Case examples of advanced circular economy concepts

At the time of writing, there were several examples of partial circular economy regarding nutrients in Finland. The oldest and most well-established chain is the one where sewage sludge from wastewater treatment plants is digested, post-stabilized by composting and applied to farmland.. However, due to legal limitations and prejudice from both farmers and the food industry, the adoption of wastewater-based fertilizer products has been slow and sometimes even moving backwards. Currently most of the composted slurry is mixed with peat moss or similar organic material and sold as fertilized soil, mainly to landscaping works and private gardeners. Several more advanced concept-level circular economy businesses exist in Finland. In this chapter, an example of such case is described.

4.2.1 Sybimar

Sybimar has been developing a closed-cycle concept for fish farming, hydroponics and energy production for ten years. A greenhouse produces vegetables and oxygen, the fish in turn consume oxygen and release carbon dioxide for the plant life. Waste streams from the process will be treated with a biogas plant, which is currently being built. This kind of closed loop fish farming system, is a possible solution for nutrient release from the traditional fish farming industry, since all wastewaters are treated and returned to the cycle. The concept is visualized in Figure 7.[31]

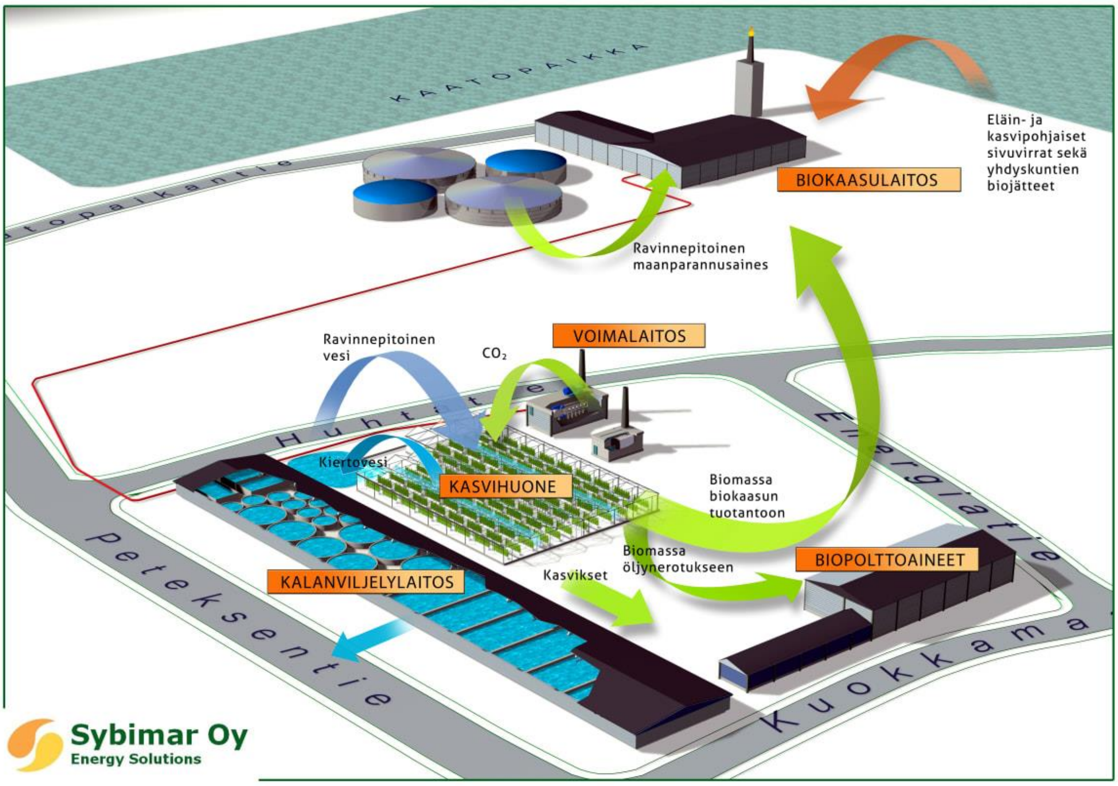


Figure 7. Sybimar closed loop circular economy concept [31]

5 Legislative framework

This chapter reviews the legislative framework for biogas plant operations in Finland. Operating biogas plants and their environmental permits are monitored by the Centre for Economic Development, Transport and the Environment (ELY-keskus) and Municipal Environmental Protection Agencies [24].

5.1 Legislation regarding end product use

5.1.1 Evira product classification system

Based on Fertilizer product law (539/2006), all commercially sold products have to be classified according to the national type name list for Fertilizer type name list by Evira [37]. In addition, the facilities producing these products have to be validated by Evira.

Organic fertilizer products are divided into organic fertilizers and organic soil additives based on their raw materials and nutrient content. All products with more than 10 % of sewage sludge or equivalent raw material, or do not fit other categories, are classified as soil additives. [39]

Digestate can be used as raw material in several type classes. Two categories, Reject water (1B4/4) and Digestate (3A5/2), are applicable to digestate without any further treatment or after liquid-solid separation. The products of class 1B4/4 may be produced from digestate of plants in which less than 10 % of feedstock is sewage sludge [41]. Other categories are applicable to digestate after certain type of treatment, as listed in Table 9. As discussed in Chapter 2.2 , a hygienization step, e.g. thermal hygienization for 1 hour at 70°C or an approved thermophilic process, is required for facilities treating sewage sludge or animal-based feedstocks such as biowaste. If ammonia stripping is used for reject water, the product can be classified as inorganic nitrogen fertilizer (1B1/1). Inorganic fertilizer can thus be produced from organic waste material by a suitable treatment method.

Table 9. Fertilizer product types that are applicable for digestate [37]

Class	Class name	Subclass	Subclass name	Treatment after AD*	Digestate (without liquid-solid separation)	Solid fraction	Liquid faction	AD feedstock requirement	
1B1	Inorganic mono-nutrient fertilizers	1B1/1	Nitrogen Fertilizer	Ammonia stripping			X	Any	
1B4	Organic fertilizers as such from side products	1B4/4	Reject water	Solid-liquid separation			X	Feedstocks accepted for organic fertilizer production	
3A2	Organic soil improver	3A2/1	Soil improver compost	(Solid-liquid separation), Post-composting	X	X		Manure, sewage sludge, plant waste, biowaste or equivalent	
		3A2/2	Manure mixture	(Solid-liquid separation)	X	X		Manure	
		3A2/3	Fresh Compost	(Solid-liquid separation), Post-composting	X	X		Manure, sewage sludge, plant waste, biowaste or equivalent	

		3A2/5	Dry pellet or powder	(Solid-liquid separation), Thermal drying (e.g.80°C, 2 h), pelletizing or other equivalent and approved thermal treatment	X	X		Any	
3A5	Soil improver as such	3A5/2	Digestate	(Solid-liquid separation)	X	X		Any	
5A2	Topsoil mixture	5A2/2	Compost topsoil	(Solid-liquid separation), Composting and mixing with other topsoil ingredients	X	X		Any	
		5A2/4	Packaged flower topsoil	(Solid-liquid separation), Composting and mixing with other topsoil ingredients	X	X		Any	
		5A2/5	Packaged topsoil mixture	(Solid-liquid separation), Composting and mixing with other topsoil ingredients	X	X		Any	

* Treatment methods in brackets are optional

5.1.2 Agriculture

There are several legal documents, which control the use and manufacturing of organic fertilizer products. The Nitrate directive (91/676/ ETY) and corresponding decrees (Vna 1250/2014, 435/2015) controls the use of organic fertilizers with respect to nitrogen. Fertilizer product decree (Lannoitevalmisteasetus, MMMa 24/11 and changes 12/12, 7/13, 12/15, 21/15, 5/16) defines the maximum limits for soluble phosphorus and cadmium addition. In addition to this legislation, the fertilizer amounts are limited by the Requirements for Environmental compensation (Ympäristökorvauksen sitoumusehdot, [32]) for farms receiving this subsidy.

In the aforementioned regulations, the following limits and restrictions regarding nutrient amounts are defined:

- The Nitrate directive (91/676/ ETY) and corresponding decrees (Vna 1250/2014, 435/2015) define the following:
  - Maximum amount of soluble nitrogen is 30 - 250 kg/ha/a depending on the crops and fertility level of soil, including all fertilizers
  - The amount of total nitrogen from manure and fertilizer products containing manure is limited to 170 kg/ha
  - For other organic fertilizers the total nitrogen limit does not apply since application of decree Vna 435/2015.
  - The total amount of total nitrogen may be higher than 170 kg/ha, as, in addition to manure-based fertilizers, other organic and inorganic fertilizers may be applied until the limit for soluble nitrogen is met [33].
- Based on Fertilizer product decree (MMMa 24/11 and changes 12/12, 7/13, 12/15, 21/15, 5/16)
  - Maximum amounts of water or ammonium citrate soluble phosphorus applied are 325 and 560 in 5 years in agriculture and gardening, respectively. This applies to all fertilizers.
  - Maximum amount of Cadmium is 1.5 g/ha/a or 7,5 g/ha in 5 years, which may limit the amount of Cadmium-rich fertilizer products and indirectly the amount of applied nutrients. However, typically in such cases, the maximum amount of nutrients will be applied by using e.g. mineral fertilizer
- The Requirements for Environmental compensation apply for farms that receive the Environmental compensation. The following limits are defined for the basic level of Environmental compensation [32].
  - The maximum amount of soluble nitrogen is 20 - 240 kg/ha/a depending on the crops and fertility level of soil, including all fertilizers
  - The maximum amount of total phosphorus is 0 - 63 kg/ha/a depending on the crops and fertility level of soil, including all fertilizers. However, this is a calculated value and may differ from the actual total phosphorus amount
  - In calculation of the phosphorus limit amount, 100 % of total phosphorus in the products is taken into account for manure, 60 % for sewage sludge and certain waste-based fertilizers (for details, see [32]) and 40 % for ash. Thus, for example with sewage sludge based fertilizers the actual maximum amount of phosphorus can be up to 63/0.6 = 105 kg/ha/a

- For grains and oil plants, additional amounts of soluble nitrogen (10- 50 kg/ha) or total phosphorus (3 – 6 kg/ha) may be applied if the achieved crops production level meets the requirements of high crop yield
- In 2015, the Environmental compensation corresponded to > 90 % of agricultural area and about 86 % of farms. Recently, however, there has been observed a decline in the amount of farms applying for Environmental compensation, as some farmers see that it limits the amount of nutrients too much and is not financially attractive enough.

As a conclusion, there are two cases with different nutrient limits in agriculture:

- For farms receiving subsidies, but not Environmental compensation, the following limits from legislation apply:
    - The amount of total nitrogen from manure and fertilizer products containing manure is limited to 170 kg/ha
    - The maximum amount of soluble nitrogen is 30 - 250 kg/ha/a depending on crops and fertility level of soil, including all fertilizers
    - Maximum amount of soluble phosphorus is 325 kg/ha in 5 years, including all fertilizers
- For farms receiving also Environmental compensation, in addition to the aforementioned limits from legislation, the following limits apply:
    - The maximum amount of soluble nitrogen is 20 - 240 kg/ha/a (+ 0 – 50 kg/ha/a) depending on the crops and fertility level of soil, including all fertilizers
    - The maximum amount of total phosphorus is 0 - 63 kg/ha/a (+ 0 – 6 kg/ha/a) depending on the crops and fertility level of soil, including all fertilizers. This is a calculated value, and the actual amount total phosphorus can be higher, as described above.

Several regulations restrict the fertilizer application methods:

- No fertilizers may be used within 5 m of a body of water
- It is recommended to not use any fertilizers within at least 10 m from a body of water [43]
- Nitrogen fertilizers may not be applied by surface spreading within 10 m of a body of water if land slope is greater than 2 %
- The field must be ploughed within 24 hours of solid fertilizer surface spreading
- Manure based products, including digestate, can be applied only during the period 1st April – 31st October and it is not allowed to apply these on snow or on frozen field.
- Storage of organic fertilizers (TS content higher than 30 %) in stacks on fields is allowed 1.4. – 31.10 for a maximum of 4 weeks
- Storage stacks may not be located within 100 m from water bodies and within 5 m from a ditch. Storage is forbidden in ground water areas and areas prone to flooding.
- The stack must have at least 20 cm thick water retaining layer and a watertight cover.

The Fertilizer product decree also provides the limits for different harmful elements as shown in Table 10. For comparison, the heavy metal content in sewage sludge in Finland are shown.

Table 10. Content and regulative limits of the heavy metals in fertilizers and their raw materials.

Element	Maximum content in organic fertilizers (mg/kg TS)	Maximum content in ash related products in forestry, (mg/kg TS)	Content in digestate, (mg/kg TS) , EU averages. [27]	Content in sewage sludge recycyled to agriculture in Finland (mg/kg TS) [40]
Arsenic (As)	25	40	-	-
Mercury (Hg)	1.0	1	0.1	0.4
Cadmium (Cd)	1.5	25	0.4	0.6
Chromium (Cr)	300	300	15.1	18
Copper	600	150	87.5	244
Lead (Pb)	100	150	5.8	8.9
Nickel (Ni)	100	150	6-11 [21]	30
Zink (Zn)	1500	4500	311	332

For agricultural use of sewage sludge based products with sewage sludge content of more than 10 % there are specific limitations [39]. As dictated by the fertilizer produce law, fertilizer products with sewage sludge as raw material are only approved for grains, sugar beet, oil plants and other plants not aimed for human or animal consumption. Root vegetables or grass cannot be grown within 5 years after using such product. In addition, heavy metal content in soil and the added heavy metal load need to be investigated. The maximun allowed heavy metal limits in soil and maximum load of heavy metals are defined [29].

5.1.3 Landscaping

According to earlier fertilizer product decree (12/07), the maximum amount of soluble nitrogen and phosphorus were defined as 1250 kg/ha and 750 kg/ha in 5 years, respectively [46]. However, the existing Fertilizer product decree (24/11) and its changes do not define such limits for landscaping. The fertile layer thickness in landscaping is 5 – 100 cm depending on the requirement of the vegetation as recommended by the Finnish Traffic Agency (Liikennevirasto) [43]. The recommended nutrient contents in landscaping materials are 1 – 100 g/m^3 for soluble nitrogen and 3 – 30 g/m^3 for total phosphorus depending on the vegetation type. As shown in Table 8, the concentration in commercial products may be higher than these recommended values. The products used for landscaping are typically required to meet the requirements of Fertilizer product law (539/2006), and the Evira Fertilizer type name list.

The amount and quality of fertilizer products used in landscaping for large scale units, such as landfills and mines, is regulated individually in the environmental permit. Typical fertile layer in environmental permits is defined as about 10 - 30 cm thick layer. Thus, the amount of digestate product used in such layer would be approximately 1000 - 3000 m3/ha.

5.1.4 Storage

According to the Waste taxation law (1126/2010), waste can be stored for a maximum of 3 years prior to end use. Otherwise, the storage will be regarded as a landfill without permit and the waste will be due to waste taxation. Furthermore, according to Landfill decree (VNA 331/2013), digestate cannot be landfilled as its organic matter content is well above the highest allowed (10 %) for landfilled waste. The storage capacity of the biogas plants depend on the environmental permit. Typically, the facilities with a composting plant are required to be able to store the digestate produced within one year of operation.

5.2 Permitting procedures

Opening a new biogas installation in Finland requires several permits and announcements. These are sub-mitted to several municipal, national and official instances. Below is a description of each requirement.

5.2.1 Environmental Impact Assessment (EIA)

For biogas plants with a capacity exceeding 20,000 tons per year, an environmental impact assessment (EIA) process is required. In EIA, the impact of the plant is compared to current situation and other potential alternatives are studied. The process is monitored by the Centres of Economic Development, Transport and the Environment (ELY-keskus). [39]

5.2.2 Environmental permit

According to the Finnish environmental law (FI 86/2003 and FI 169/2000), a biogas reactor treating waste products (including different manures, solid waste and sludges) needs to apply for an environmental permit before starting operations. The permit is granted by a local environmental authority or Regional State Administrative Agency (AVI), depending on the size of the biogas plant. [39]

The permit is applied by the manager of the plant or the company / community operating the plant. The application requires information on the plant operation, process used, location, environmental impact estimate and impact prevention measures. Also in the appendix the applicant needs to report possible other permits, agreements on sewage connections, a map and plan of the plant, accident & fire risk assessment and rescue plan as well as environmental impact monitoring plan and general operations monitoring plan. Furthermore, in accordance to the environmental protection act 12§, plants treating sorted (municipal) waste, also need to submit a document on what kind and where the waste is collected, how it is transported, utilized and how the process works in general. The plant operator also needs to show sufficient professionalism and knowledge, as well as ability for monetary guarantees or insurance.

Construction permit / Action permit

According to land use and construction law (FI 132/1999), all permanent structures and installations require a construction permit. This permit is granted by regular municipal authorities. When a plant construction is finished, a standard inspection by municipal and fire department officials is conducted.

5.2.3 Trade announcement

A trade announcement is required by the Finnish Food Safety Authority (Evira) if the biogas plant processes animal products, communal or industrial wastewaters or similar external waste products or if the biogas process residue is sold as fertilizer products. In practice, almost all biogas plants apply in this process, with the exception of farm biogas plants that only process their own waste and use the residue within the confines of their own farm.

5.2.4 Plant validation permit

Also granted by Evira, the plant validation permit is required for plants producing organic fertilizers or their ingredients for external use. For commercial fertilizer production, a plant needs to fulfill fertilizer produce law (FI 539/2006) requirements. Animal waste or animal products processing plants also need to conform with European Community by-product act (EC 1069/2009).

The plant operator needs to show the product is suitable and safe for fertilizer use. Evira will also inspect on the process, spaces, self-monitoring practices and bookkeeping [7].

5.2.5 Electricity delivery agreements

If the plant is producing electricity and a grid connection is desired, a delivery agreement is needed with the grid owner. If the generation set of the biogas plant needs the grid for synchronisation, but does not deliver any power to the grid, an agreement is still needed. Three different types of agreements are used, depending on the case.

When simply connecting the biogas plant to the grid with no electricity delivery, this agreement type applies. It can be done based on an existing subscription, but some changes might be needed regarding the wiring and main fuses.

In some cases, this agreement is needed with the local grid owner. It is used for electricity delivery and sales. This agreement is made with the electricity producing or sales companies. The producer can typically select the best vendor for his electricity, but only one agreement can be made at any time.

5.2.6 Wastewater delivery contract

The load to WWTPs from industrial sources, such as biogas plants, is usually regulated with industrial wastewater treatment contracts between the WWTP owner and the company discharging industrial wastewater to the WWTP. Typically in these contracts, the wastewater fee is defined based on wastewater flow and quality indicators. Also flow and quality limits and sanctions for violating them are defined.

5.2.7 Explosion protection documentation

An explosion protection documentation is required at sites where operators or employees may be exposed to a risk of explosion. Under certain conditions, methane and biogas can form an explosive mixture with air. Thus, most biogas plant operators are required to produce this documentation. [8] The document contains e.g. description of substances and conditions that may cause explosive air mixture, classification of explosive risk spaces and description of ventilation and cleanup procedures.

5.2.8 Rescue plan

A rescue plan must be produced in accordance to rescue law (FI 468/2003). It aims to decrease the risk and effect of emergencies and includes e.g. predictable risky situations with their effect as well as prevention measures, emergency exits, extinguishing and rescue efforts, safety personnel, and instructions for assessed risky situations.

5.2.9 Announcement to rescue department

The plant operator must inform the local rescue department on handling and storage of dangerous chemicals if the minimum limits for these chemicals are exceeded. The announcement must be delivered well before the operation is started. The safety officials will perform an inspection within three months of the beginning of operation and report any shortcomings. The announcement must include e.g. explosive, flammable and hazardous chemicals handled or stored at the biogas plant, a risk assessment regarding the handled or stored chemicals and an action plan for leakage control, fire prevention and accident avoidance

5.3 Monitoring

Operating biogas plants and their environmental permits are monitored by the Centre for Economic Development, Transport and the Environment (ELY-keskus) or local environmental authority based on the size of the plant. In addition, the quality of fertilizer products is monitored by Evira. In most cases, plant operations are monitored through self-monitoring and periodic inspections by the aforementioned officials. The self-monitoring is based on the monitoring plan approved by officials before opening the plant. [39]

The self-monitoring plan is a document that describes the operation of the plant, especially the critical steps of the process and the means to avoid problems in the critical process steps. The plan includes e.g. the following:

- Receiving of raw materials

- Traceability of products on a batch basis
- Production processes
- Quality control and analyses
- Storage and transportation

In addition to self-monitoring plan, the plant owner has to prepare a plan on monitoring the operation, emissions and impacts, which is approved by the monitoring official. The scale of monitoring is based on the environmental permit. A summary report of the monitoring results has to be prepared annually. The monitoring involves e.g. the following [39]:

- Quality and source of the raw materials used
- Quality, amount, and delivery location of end products
- Stored materials at the end of the year
- Quality and amount of wastewater produced
- Summary of environmental monitoring at the plant and assessment of plant's impacts on environment

In agriculture, the following regulations are defined about monitoring in MAVI Requirements for Environmental compensation:

- The actor/farmer has to obtain the composition analysis of the applied product every 5 years including total and soluble nitrogen and total phosphorus contents. This data needs to be available for inspection at any time and should be also included in the bookkeeping together with application dates and amounts.
- Bookkeeping has to include the amount of grown products that contains the amounts for applied nutrients for tracking the field balances.

Spot checks at farms receiving the agricultural subsidies are carried out by MAVI. The use of digestate-based fertilizer products in agriculture can thus be traced both from the producer and user end.

6 Subsidies and profitability

6.1 Subsidies

The Centre of Economic Development, Transport and the Environment (ELY-keskus) has listed several forms of public support for farm-scale biogas installations. The support originates from both regional, national and EU-level organisations, and the whole support framework is relatively complicated. Below is a simplified listing on public support available for farm biogas:

- **Design & planning:** The costs for design & planning can be included in the total supported budged of the initiative. Notably, the construction work should not start before the application has been accepted and support granted.
- **Farm-level investment:** It is possible to apply for 15% investing assistance and for a interest-supported loan that covers 70% of the total approved expense of the project. The limitation here is that the planned feedstock must come from within the farm itself.
- **Agricultural businesses:** A continuously open application, aimed at those biogas producers who would run a business selling energy or biogas or treatment of external materials. The support percentage is 10-35% and it is also possible to apply for development and initiation support.
- **Larger biogas facilities:** Aimed primarily at larger installations that are located in primary animal husbandry area and are treating external feedstocks. The typical support is about 35% and applied directly from the ministry of Agriculture and Forestry. Support for these plants is also available from the Ministry of Economic Affairs and Employment.

6.2 Profit creation

6.2.1 Gate fees

Typically, gate fees constitute the major income for the centralized biogas plants. In the case of WWTPs or other plants that produce feedstock for their own biogas plant, the major benefit from biogas process, besides energy production, is that the waste stream is turned to a more stable and utilizable product.

6.2.2 Heat and electricity production

Since 2011, it has also been possible for biogas producers to get tariffs for electricity fed into the grid. These tariffs have brought the price for sold electricity up to 13.35 cents per kilowatt-hour. However, in 2012, none of the farm biogas producers had applied for the system. The reason for this is probably the requirements for eligibility: Plants that have been built with public subsidies or from second-hand parts are not eligible. Furthermore, the minimum rated power must be at least 100 kVA, which is beyond the reach for most Finnish farms if only manure and hay were to be used as feedstock. [12]

Most of the reviewed material indicate the largest hindrance for adoption of farm biogas in Finland is the relatively small size of farm units. Smaller farms produce less feedstock, which in turn hinders the adoption of the tariff system for electricity. For farms aiming towards energy self-sufficiency, commercial products for farm-scale biogas are still too expensive and the return of investment with relatively low energy prices is still too long.

6.2.3 Fuel production

Biogas can be converted into biomethane and used as traffic fuel by methane upgrading technologies, which purify the biogas to 95 – 99 % methane. When upgraded to biomethane, biogas can be sold at higher price, which may be profitable at larger plants which are located close enough to adequate methane-powered vehicle population. The amount of both methane-powered cars and biogas filling stations are in rapid increase in Finland.

7 Risk assessment

The main risks of biogas production regarding nutrient leakages are related to amount of produced end products, their quality and end usage. This chapter focuses on the effects of AD process for end product quality with regards to nutrients, the nutrient flows of digestate products and their proportion of all nutrient flows, the geographical nutrient balance and risks related to specific end usages of digestate products. In addition to end usage of digestates, the risk of nutrient leakage related to increased nitrogen load to WWTPs due to reject water is discussed.

7.1 Effect of AD on nutrients in end products

Anaerobic digestion converts organically bound nitrogen and phosphorous into soluble compounds which are easier for plants to utilize, but also have higher risk of nutrient leakage. Especially in the case of nitrogen, the risk of washout is increased. For phosphorus, the effect is less strong, especially in the case on sewage sludge digestion if phosphorus precipitation with metal salt is used at the WWTP, because phosphorus bound to metal complexes is not solubilized in significant amounts in anaerobic digestion. Phosphorus bound to a metal salt is not rapidly available to plants, but from nutrient leakage perspective low soluble phosphorus content is beneficial.

Based on Table 12, the amount of soluble nitrogen contained in manure is on average about 43 %, in sewage sludge about 18 %, in organic waste about 6 % and in food industry waste about 40 %. In comparison, in digestate products without solid-liquid separation (Gasum Perus, Luomukymppi A, Peltokymppi A) soluble nitrogen fraction is about 45 – 60 % as can be found from Table 8. As organic waste and sewage sludge are the main feedstocks for the studied products, the soluble fraction of nitrogen can be estimated to increase in AD by about 25 – 50 %-units.

Information on the amount of soluble phosphorous in different biomasses is rather scarce at the moment [10]. In sewage sludge, the fraction of soluble phosphorus is typically less than 1 % [33][44] whereas in manure it is more than 40 % [30]. In solid in digestate products without solid-liquid separation the soluble phosphorus fraction is 0 – 5 % in products with sewage sludge (Gasum Perus, PeltoKymppi A) and about 20 % for a product without sewage sludge (LuomuKymppi A). According to Luke [30], the solubility of phosphorus is not significantly affected in AD.

Majority of phosphorus is typically found in the solid fraction of the digestate. In the case of compost and topsoil products, the quality of the added soil and binding agents such as peat and other organic matter may have greater impact on solubility than the treatment of digestate.

7.2 Nutrient flows

In a report by the Centre of Natural Resources (Luke)[10] is combined information from many sources in an attempt to draw a complete picture on P and N nutrient cycles in Finland. Table 11 presents a summary of these data.

Table 11. An estimate on phosphorous and nitrogen nutrient consumption in Finland

	Phosphorous consumption (t / a)	Nitrogen consumption (t / a)
Agriculture	**32 300**	**228 000**
Inorganic fertilizers	11 300	148 000

Manure	19 300	76 000
Recycled fertilizer products	1 700	4 000
Proportion of recycled fertilizers products(%)	5.3 %	1.8 %
Forestry	**259**	**3 560**
Inorganic fertilizers	113	3,560
Ash-based fertilizers	146	0
Landscaping & earthworks		
Recycled fertilizer & soil products	1 050	1 470
Fish farming	**210**	**1 600**
Traditional fish fodder	160	1 360
Fodders containing recycled nutrients	50	240
Total	**33 800**	**234 600**
Total recycled fertilizer products	2 800	5 710
Total proportion of recycled fertilizer products	8,2 %	2,4 %

From Table 11 it should be noted that the recycled fertilizer product responds to only 8.2 % of consumed phosphorus and 2.4 % of consumed nitrogen**. Therefore, the significance of biogas production, which corresponds to only a part of recycled fertilizers, is limited in comparison to other nutrient flows.** If the volume of biogas production increases significantly, the significance with regard to nutrients will obviously also increase. In the near future, however, the amount of organic fertilizer produced from digestate cannot practically become comparable to manure and inorganic fertilizers.

The data from Luke report [10] including the total amount of produced biomasses and their nutrient content including manure, surplus hay and grass, sewage sludge, biowaste, waste streams from food industry and sludges from forestry industry are shown on Table 12. In addition, estimated amounts of biomass and corresponding nutrients treated in AD are shown. The amount of biomass and nutrients treated in AD are based on proportional amounts shown in Table 1 [10]. The data in Table 12 is updated with regard to sewage sludge based on VVY report [30]. It should be noted that not all of the biomasses are treated and utilized as nutrient source. For instance, the data for biowaste includes both separately collected biowaste and biowaste ending up in municipal solid waste.

Table 12. An estimate on the available biomass, data from 2014 – 2016 [10]

Biomass	**Total amount (t/a)**	**Phosphorous (t/a)**	**Nitrogen (t/a)**	**Soluble nitrogen (t/a)**
Manure	17 300 000	19 300	75 600	32 400
Hay & Grass	1 510 000	2 540	7 060	420
Residential & Industrial sewage sludge [39]	832 000	3 590	4 670	840
Biowaste	809 000	730	5 340	320
Waste from the food industry	259 000	360	2 070	830
Sludges from forest industry	578 000	230	1 160	30

Total	**21 288 000**	**27 000**	**96 000**	**35 000**
All treated in AD (Table 1)	962 000	2 990	5 340	1 060
% treated in AD	5 %	11 %	6 %	3 %

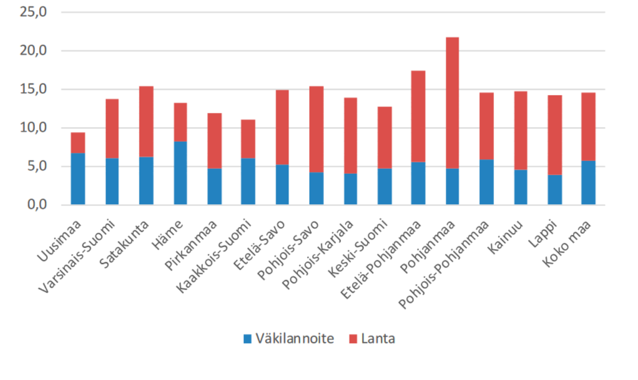
Based on data shown in about 11 % of P, 6 % of N and 3 % of soluble N of biomasses are found in biomasses processed by AD. Manure makes up about 71 % of total phosphorus, 79 % of total nitrogen and 93 % of soluble nitrogen in biomasses, while sewage sludge, biowaste and wastes from food and forest industries all together make up only about 18 %, 14 % and 6 % of total P, total N and soluble N, respectively.

The potential for organic fertilizer production, including manure, is about 96000 tons of nitrogen and 27000 tons of organic phosphorous annually. This can be compared to total consumption figures (Table 11), which were 235 000 t a nitrogen and 34 000 t/a phosphorus. From this overall balance it can be concluded that all organic nutrient sources could be used for current nutrient demand. However, use of inorganic nutrients makes the overall nutrient balance positive as discussed in the following chapter.

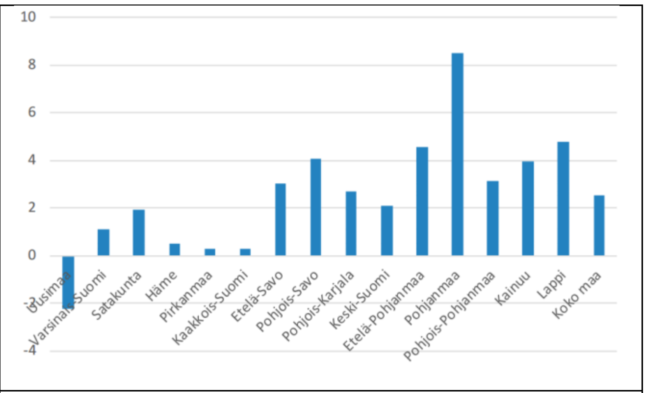
7.3 Geographical nutrient balance

According to various sources mentioned by Luke [10], Southwestern Finland has overproduction of phosphorous due to large amount of animal husbandry. A summary of regional nutrient consumption and balance are presented in Figure 8. **Both P and N balances are positive in most regions, which indicates risk of potential nutrient accumulation.**

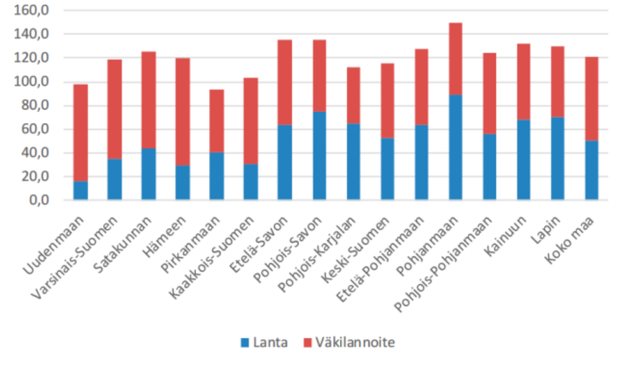
It is estimated that about 20% or 3500 tons of manure-based phosphorous is generated annually in areas that cannot utilize it in horticulture [10]. To correct the balance, transportation of more than 3 million tons of manure to other areas every year would be needed. The balance of manure-derived nitrogen is positive in all regions, thus making the transportation of nitrogen fertilizers between regions unnecessary. Nitrogen and phosphorous separation would be beneficial to produce phosphorus-rich fertilizers for transportation.



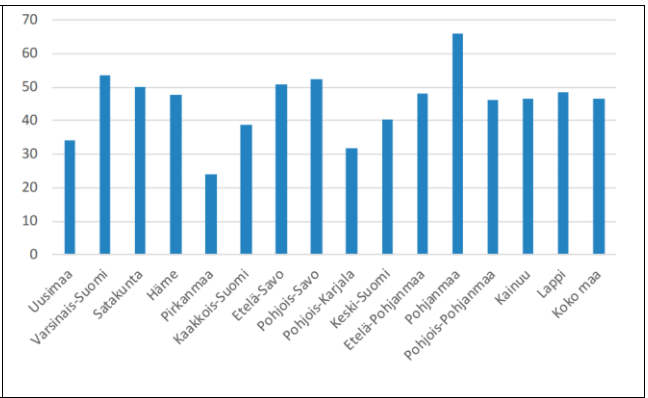
A. Amount of P applied 2013 in different regions in Finland, kg/ha. [20]



B. P balance 2013 in different regions in Finland, kg/ha. [20]



C. Amount of N applied 2013 in different regions in Finland, kg/ha. [20]



D. N balance 2013 in different regions in Finland, kg/ha. [20]

Figure 8. Nutrient consumption and nutrient balances by region in Finland as of 2013. [20]

Baltic Manure report [21] presented the soil samples at different countries around the Baltic Sea. It was found that there was excessive P fertilization carried out on many fields that received mineral products, based on the soil sampling. Thus, organic fertilization cannot be increased unless the amount of mineral fertilization is decreased. For Finland, the Luke report provides a more detailed picture [10]. As an example, Figure 8 shows the amount of manure based P available compared to surplus or shortage in kg / ha by municipal area.

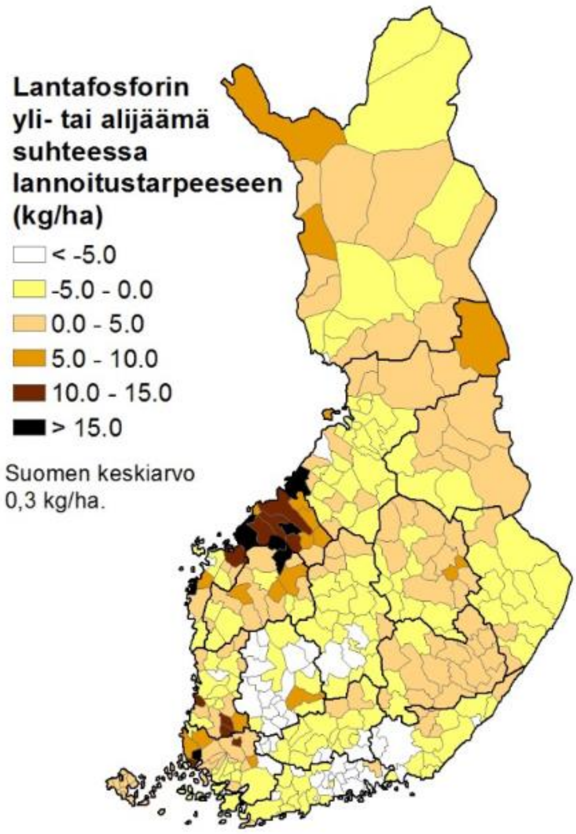


Figure 9. Relative amount of manure based P available in different regions in Finland (ELY keskukset). P available/P needed.

From Figure 9, it is clear that especially the west coast area has a significant over-fertilization risk if the manure is locally applied. If the nutrients cannot be utilized by the horticulture, there is a risk of nutrients accumulating in soils and leaking to waters and ultimately to the Baltic Sea.

As discussed in this chapter, the nationwide positive nutrient balance and regional imbalance in phosphorus pose risk of local or even nationwide nutrient accumulation. **However, the role of anaerobic digestion in the whole picture can be estimated to be of minor importance regarding its relatively small share of all nutrient flows.**

7.4 Risk considerations based on end use

7.4.1 Agriculture

A number of regulations limit the use of fertilizers in agriculture regarding the fertilizer amounts, time of application, spreading methods and storage as discussed in Chapter 5.1.2 . These regulations mainly aim to decrease the nutrient leakage to waters. In addition to legislation, MAVI Requirements for Environmental compensation applies to most agricultural land.

There are several contributing factors to agricultural nutrient leakages in Finland, but the two major ones are weather and climate conditions and soil quality [10]. On a typical winter, the topsoil gets frozen, and cannot absorb any nutrients. This also increases the risk of flooding of the fields and nutrient washout every spring. There's typically only one harvesting season per field per year, which limits the timing of fertilisation.

Another issue is soil quality; in Finland the depth of topsoil is very shallow and in many cases the soil consists of dense inorganic silts and fine sands that cannot bind nutrients very well [11]. Improved drainage generally decreases rain water retention, thus increasing the washout of particulate matter and nutrients. However, in some cases, the poor condition or total absence of drainage piping in fields may lead to flooding and consequent nutrient washout [11].

The time window for effective fertilization is rather narrow, making storage of fertilizers between seasons necessary. Solid organic fertilizer products can be stored on fields in covered stacks. Typically stacking is done from fall/winter until spring and lasts typically several months. The leachate from the stack typically includes ammonium and soluble organic nitrogen, which are partially retained in a filtrating layer below the stack. Soil additive composts may include nitrate nitrogen, which may be released in the leachate. Nitrogen that is flushed to soil under the stack and not used up during the next growing season is nitrified and can easily be flushed to groundwater. This nutrient leakage can be prevented by proper founding of the stack. [39]

Solid recycled fertilizer products are typically spread on the fields in similar manner as dry manure on the top of the soil, after which the soil is rebated. Liquid fertilizer products are usually spread by using different types of distributor, which place the liquid on the top or underneath the soil surface. Placing liquid below the soil surface is important in order to avoid ammonia loss to atmosphere. Ammonia losses are exceptionally high when using reject water products due to their high pH. However, surface spreading is still widely used as there is no requirement to use placing distributors. [39]

As a rough estimate, a typical amount of solid organic fertilizer products applied on fields is about 20 t/ha at one time. [39]. As an example, for solid digestate, assuming nitrogen content of 6 kg/m3, soluble nitrogen 27 % of total, total phosphorus content 3 kg/m3 and soluble phosphorus 10 % of total and density of 950 kg/m3, the applied amounts per hectare would be 126 kg N, 34 kg soluble N, 63 kg P and 6.3 kg soluble P. The applicability of this amount depends on the crops and fertility level of soil. In addition, Requirements for Environmental compensation affect the maximum amounts of nutrients if they are applied.

At farms that do not receive Environmental compensation, the fertilizer amounts are limited by legislation only, and can be higher than the limits in the Requirements for Environmental compensation. Especially the phosphorus limit of 325 kg/ha in 5 years for soluble phosphorus is high, and the amount of total phosphorus may be yet significantly higher. This can be the case especially when organic fertilizers with low soluble phosphorus content are used. Thus, if Environmental compensation becomes less popular among farmers, the risks of local nutrient leakages and accumulation of nutrients, especially phosphorus, may increase. However, the problem is mainly regulatory, and is not directly related to biogas production or to the use of digestate based products as fertilizer.

The biogas process may increase the soluble fraction of all utilized nutrients, but regarding the regulations and small proportion of digestate-based fertilizers in agriculture, the effect can be estimated to have minor importance in the whole picture of agriculture fertilization. An identified risk with regard to fertilization is related to insufficient regulation in terms of phosphorus when the Requirements for Environmental compensation are not applied.

7.4.2 Landscaping

Great amounts of fertilizer products are used in landscaping. The nutrients may be flushed with rainwater, especially before vegetation has been established well. Soluble nutrients are most prone to flushing, but in heavy rain events also particulate matter may be flushed, causing also insoluble nutrients to end up in surface waters.

The fertile layer thickness in landscaping is 5 – 100 cm depending on the type of plants as recommended by the Finnish Traffic Agency (Liikennevirasto) [43]. 5-30 cm is enough for lawn, while 100 cm is needed for large trees. Typically, at highway embankments, products with high nutrient content are not desirable due to excessive plant growth.

As an example, the fertile layer defined in environmental permits for landfill and mine covering may be about 20 cm in thickness. Thus, the amount of digestate product used in such layer is 2000 m3/ha. For example solid digestate described above, the applied amounts per hectare would be 12 000 kg N; 3240 kg soluble N; 6000 kg P; 600 kg soluble P. The amount of soluble nitrogen and phosphorus are roughly ten times higher than annual application in agriculture per year. However, typically for landscaping purposes the digestate products are mixed with less nutrient rich materials to get a product with lower nutrient content. For comparison, if compost product with 3 kg N/m3 and 3 kg P/m3, and soluble fraction of 10 % for nitrogen and 1 % for phosphorus was used, the nutrient loads would be 6000 kg N/ha, 600 kg soluble N/ha, 600 kg P/ha and 6 kg soluble P/ha.

It is worth noting, that in landscaping the fertilizer products may replace soil materials. By using fertilizer products in landscaping, the nutrient loads are significantly higher compared to soil materials. This may cause significant nutrient leakage risks, especially if digestate products are increasingly directed to landscaping instead of agriculture, while agriculture is still using the same amount of fertilizers from other sources.

The nutrient load from landscaping is by nature a single occurrence, as landscaping activities are not typically performed on a regular basis at same sites. This lowers the overall risk from landscaping, but the local risk of a single application should be considered.

7.4.3 Storage of digestate

Significant amounts of organic waste materials are stored at the biogas plants and their storage areas. The logistics and storage of large amounts of organic material and digestate may elevate the risk of accidental leakage. The storage capacity varies between plants. For instance, Labio and HSY Ämmässuo plants, which have compost facilities on site, have storage capacity for about one year of production.

Currently, there is no requirement for a proof of secured end use for the digestate products. Uncertainties in utilization of the digestate may cause risks related to logistics and storage of the products. In cases where the biogas plant does not have a clear end market for digestate products, accumulation in storage poses a risk of nutrient release.

There have been reported cases where digestate from a biogas plant could not be sold or delivered out from the plant. In the case of Envor biogas plant in Forssa in 2015, this resulted into on-site accumulation of digestate and an eventual release into a river close by when a flooding accident occurred due to weather conditions [16][15]. In this kind of case, it is clear that there has been problems in both organizing the end use and in the preparation for storage even under unexpected circumstances. Similar cases are possible in the future as well, especially regarding the challenges in agricultural use of digestate products containing sewage sludge.

7.4.4 Nitrogen load to WWTP

Due to low demand for nitrogen fertilizers and high cost of reject water treatment into high-quality fertilizer products, many biogas plants are forced to deliver the liquid part of the reject waters to wastewater treatment plants. This creates a risk of exceeding the WWTP capacity, if appropriate planning is not conducted. In an extreme case, this might cause a nitrogen overload at WWTP, decreasing nitrogen removal at WWTP and causing additional nitrogen discharges to receiving waters.

In early 2017, the wastewater treatment plant of Eura had several issues in the WWTP process due to high nitrogen influx. The probable cause for this has been identified as biogas plant owned by Satakierto waste treatment company [17]. This case underlines the importance of considering the effect of reject water delivery to WWTP.

The load to WWTPs from industrial sources, such as biogas plants, is usually regulated with industrial wastewater treatment contracts between the WWTP owner and the company discharging industrial wastewater to the WWTP. Typically, the wastewater fee is defined in these contracts based on wastewater flow and quality indicators. Also flow and quality limits and sanctions for violating them are defined

8 Conclusions and recommendations

Biogas production has gained a stable position in Finland as one step in treatment of many waste streams, such as sewage sludge, biowaste and side products of food industry. Most digestate products from biogas plants are used in agricultural and landscaping purposes, and these pose the greatest risk of nutrient leakages related to biogas plants.

Anaerobic digestion (AD) solubilizes the organic phosphorus and nitrogen of AD feedstocks. Therefore, the nutrients in digestate may be more prone to nutrient flushing. This effect is more important for nitrogen, part of which is converted to ammonia nitrogen. In typical biogas process, the soluble fraction of nitrogen after wet process is 45 – 60 %, and the increase in the process is estimated to be about 25 – 50 %-units. The fraction of soluble phosphorus is typically 0 – 20 %, and is not significantly affected in AD, rather depending mostly on the soluble phosphorus content in AD feedstocks.

By total nutrient amount, the most significant fertilizers used in Finland are manure and inorganic fertilizers. Recycled organic fertilizers, including digestate products, make up only about 8 % of phosphorus and 2 % of nitrogen consumed for fertilizing purposes. On the other hand, all biomasses treated by AD comprise 11 % of phosphorus and 6 % of nitrogen of all biomasses that could potentially be utilized as recycled fertilizer products. **Therefore, it can be stated that the biomasses being treated in AD constitute a small part (~10 %) of the total amount of nutrients applied to land, especially in comparison to manure and inorganic fertilizers.**

Agriculture is by far the biggest consumer of fertilizer products. Agriculture corresponds to about 97 % of all nitrogen consumption and about 96 % of all phosphorus consumption. The amount of all nutrients applied to agricultural soils, including manure, inorganic and recycled fertilizers alike, are quite strictly regulated and monitored. The legislation sets limits to soluble nitrogen and soluble phosphorus from all fertilizers, and for total nitrogen from manure. In addition, it defines the allowed application and storage methods and ways of operation. Moreover, the Requirements for Environmental compensation limit the amount of soluble nitrogen and total phosphorus at farms receiving this subsidy, i.e. > 90% of farms at the moment. As the number of farms receiving Environmental compensation is in decrease, the applied amount of nutrients may increase and cause local risks for nutrient leakages and accumulation. Especially the phosphorus limit in legislation is high. However, this issue is not directly related to biogas production or use of digestate-based products.

The soluble fraction of nitrogen in digestates may sometimes be higher than in manure. On the contrary, soluble phosphorus content is typically not significantly increased in AD, and the soluble phosphorus fraction in digestate products is typically notably lower than that of manure. **Thus, issues related to regulation, monitoring and nutrient solubility do not appear to make recycled fertilizers significantly more prone to nutrient leakages than manure or inorganic fertilizers. However, the regulation regarding phosphorus is lacking when the Requirements for Environmental compensation are not applied, causing potential risks of phosphorus accumulation and leakages regardless of used fertilizer type.**

The nutrient flows involved in landscaping are much smaller compared to agriculture. The total amounts of phosphorus and nitrogen used in landscaping are only about 1/30 and 1/150 of those used in agriculture, respectively. However, landscaping may have potential nutrient leakage risks locally. The amount of nutrient application can be up to about ten times higher than in agriculture, posing a risk especially in areas which are sensitive to additional nutrient flows. It should be noted that the nutrient load from landscaping typically happens as a single occurrence, whereas in agricultural areas the application of nutrients takes place each year. In conclusion, **use of digestate products in landscaping may create local risks, but their magnitude is probably minor and duration short.**

From the above, it can be concluded that **the risks of nutrient leakage related to AD may be locally significant, but in any case much smaller than those related to fertilization as a whole.**

Digestate product storage involves risks of nutrient leakages if end use and storage are not properly organized and monitored. **A requirement for secured end use of the products for new plants, as well as an end use plan for the existing plants, would help to avoid risks related to accumulation in storage and potential illegal dumping or excessive use of products.** Currently there are no such requirements. Storage on site is monitored in conjunction with plant inspections made by the local ELYs. The use of digestate products is monitored through bookkeeping at farms and inspections conducted by MAVI.

In Finland, the nutrient balance, i.e. the ratio of production and demand for nutrients, is positive with regard to both nitrogen and phosphorus. There is also a significant regional imbalance in phosphorus production and consumption. **This involves risks of both regional and nation-wide nutrient accumulation.** Further analysis of this issue is beyond the scope of this report. It can be stated, however, that biogas production has little effect on nutrient accumulation in comparison with manure and inorganic fertilizers. AD and subsequent digestate treatment into easily transportable fertilizer products can even be seen as one potential way to address the regional imbalance and enhance nutrient recycling.

Besides fertilizer product use, **biogas production may pose a risk of local nutrient discharge to surface waters from WWTPs, if the reject water causes excessively high nitrogen load at a WWTP.** This issue is most significant at small WWTPs, especially if the load from biogas plant(s) has not been taken into account in WWTP process design. Operational problems at biogas plants may cause nitrogen and solids load peaks in reject water, potentially exceeding the design loads. Reject water typically includes high amount of ammonium nitrogen, thus causing additional nitrogen load to WWTP. The additional nitrogen load may increase the nitrate nitrogen content in WWTP effluent and, in the worst case, interrupt the WWTP process, causing poor effluent quality or need for treatment bypassing. This issue seems to be easily forgotten when designing new biogas plants. **Proper planning and design of reject water treatment and discharge should be checked as a part of the environmental permitting process of biogas plants. When discharging into sewer network, appropriate industrial wastewater agreements must be made between the producer and the receiving water utility.**

In the future, biogas production is estimated to increase in Finland. Anaerobic digestion of manure and agricultural side streams has the highest potential for additional biogas production. However, the biogas plants are currently facing uncertainty about the digestate use in the future. Use of sewage sludge based products in agriculture has decreased rapidly due to critical opinions and bans by food industry and agricultural producers. To address this, the trend is towards separate treatment of sewage sludge and other feedstocks. Landscaping use of sewage sludge based digestate is likely to increase in the near future, until new end uses or treatment technologies are introduced. This trend may include the risk of additional nutrient influx as less recycled nutrients are used to fulfill the nutrient needs in agriculture.

9 Final summary

In conclusion, it seems that organic fertilizers originating from biogas plants do not, on a country-wide scale, pose a major risk of nutrient leakage to surface or ground waters – at least in comparison to other fertilizers, notably manure. The main justifications for this conclusion are:

- less than 10 % of all nitrogen and phosphorus applied in agriculture and landscaping originate from recycled fertilizer products containing solid or liquid rejects from biogas plants
- differences in application methods or in solubility of nitrogen and phosphorus do not make recycled fertilizer products more prone to nutrient release than e.g. manure and organic fertilizers
- building and operation of biogas plants is regulated through appropriate permitting and monitoring procedures
- all nutrients applied in agriculture are traced and monitored, including the nitrogen and phosphorus from recycled fertilizers

There is a potential risk related to insufficient regulation over phosphorus use in agriculture when the Requirements for Environmental compensation are not applied. The risk is likely to increase if the number of farms receiving Environmental compensation decreases.

Local effects from recycled fertilizers used in landscaping, inappropriately treated reject waters or leakage of digestate/reject accumulated in storage may be significant. These effects cannot, in practice, be quantified. However, they are mostly one-time occurrences and thus less important than the effects from continuous agricultural use.

Regulation considering biogas plants and the use of their end products is fairly inclusive. Individual loophole possibilities exist, such as the lack of requirement for a proof of secured end use of digestate products. It is recommended that an agreement for secured end use would be required in the permitting phase of a new biogas plant installation. Proper treatment of reject water is often neglected in design of biogas plants and should be better adhered to during the permitting procedure

Biogas production is expected to increase in the near future. However, at the same time, application of sewage sludge based fertilizers is expected to decrease due to increasingly negative attitude towards them and outright bans set by food industry and agricultural producer organisations. It is thus difficult to predict the development of biogas-related nutrient leakages, because the market is probably entering a transition phase.

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