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Roadmap for valorization of the digestate from a biogas plant

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ABSTRACT

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Digestate is the major product coming from the anaerobic digestion process, therefore, valorization of this stream is crucial for any biogas plant to be viable. Depending on digestate characteristics and local conditions, digestate might be a valuable by-product for agriculture, energy production, and other industrial applications. How to improve the quality and/or the value of the digestate in the market can be difficult to define since many variables are involved. In this thesis, a methodology (roadmap) was developed for selecting the valorization route for the digestate from a case study. The roadmap included: 1) Pre-treatment of raw digestate, 2) Decision tree evaluation of available uses and treatments, 3) Local conditions and demand of products in the market, 4) Definition of potential valorization routes, and 5) Calculations. The methodology was applied to full extent from steps 1 to 4. In step 5, the cost evaluation was not included.

For the case study, it was assumed a biogas plant processing only sewage sludge, producing 100,000 t/a of raw digestate, and located in the municipality of Hanko, Finland. In the pre-treatment, a centrifuge separated the raw digestate into solid (29,000 t/a) and liquid fraction (71,000 t/a). For the valorization of the products, alternatives with a final use in agriculture, a high maturity of technology TRL>6, and performed *on-site* were preferred over the others. Due to its high phosphorus content, the solid fraction was not valorized on site. It would be sent to an external composting facility or transported to other parts of the country with higher phosphorus requirements. For the valorization of the liquid fraction, it can be used to produce nitrogen–rich fertilizer (15,000 t/a), ammonium sulphate (2,572 t/a), or ammonium water (1,360 t/a). The areas and distances required for spreading these fertilizers were calculated for four scenarios depending on the demand of the products in the market (25, 50, 75, and 100%). A cost evaluation is needed to define the best valorization route for each fraction.

So far, the valorization of digestate has been mainly focused on overcoming technical and legislative challenges. There has been less discussion about the importance of the local market (including public acceptance). Not clarifying this aspect since the early phases of a project can result in unrealistic conclusions and unnecessary work. No biogas plant can predict and control all the factors affecting the valorization of digestate during all the operating years, but having a good understanding of the parameters considered in the roadmap might increase the chances to find a solution that is viable in the long-term.

Key words: anaerobic digestion, digestate, valorization, circular economy

CONTENTS

ABBREVIATIONS AND TERMS

Anaerobic digestion	Degradation process through which microorganisms break down organic material in the absence of oxygen.
Biogas	Mixture of gases, mainly methane and carbon dioxide, produced during the anaerobic digestion process.
CAPEX	Capital expenses. Investment costs for creating a future benefit. They can include paying for assets, equipment, buildings, land, upgrades, patents, etc.
Digestate	Residual material from the anaerobic digestion process. Everything that is not converted into biogas, goes into the digestate.
Fertilizer products	Products for enhancing the quality and/or growth of plants and crops.
Liquid fraction	Mechanically separated fraction from the raw digestate, which contains most of the water and the dissolved compounds.
OPEX	Operational expenses. Cost for the regular operation and functioning of a business (day-to-day).
Soil improver	Also referred as soil conditioner, it is a product added to preserve or improve the physical properties of soils. It can also boost the biological activity on it.
Solid fraction	Mechanically separated fraction from the raw digestate, which contains most of the solids and the insoluble compounds.
Substrate	Also referred as feedstock. It is the feeding material of a process. In anaerobic digestion, the substrates are waste or raw organic materials.
TRL	Technology Readiness Level. Method to evaluate how mature is a technology.
Valorization	Enhancing the properties of a product to increase its inherent value or price in the market.

1 INTRODUCTION

Anaerobic digestion (AD) is an established method for treating organic waste streams and producing energy in the form of biogas. The main advantages of this process include green energy production, valorization of organic residues, stabilization of organic matter, inactivation of pathogens, and reduction of greenhouse gas emissions (GHG) compared to fossil fuels and alternative treatments for organic waste handling (e.g., landfill or incineration) (Nkoa, 2014; Kuutti, 2020). Also, it has potential for the recovery and recycling of nutrients at a large scale.

The facilities using AD as the main operating process are also called biogas plants. In Europe, there were over 18,000 biogas facilities reported in 2018, more than double that in 2009 (Kuutti, 2020). Because biogas plants highly benefit from economy of scale, the capacity of the units has been increasing during the last decades (Rolamo et al., 2018). In Finland, the final disposal of organic waste into landfills was restricted since the beginning of 2016, which increased the volume of organic streams going to biogas plants (Vesilaitosyhdistys, 2017). The current trend in the country is building centralized and large biogas facilities for the municipal and industrial sectors (Rolamo et al., 2018).

During the AD process, microorganisms break down the organic material in the absence of oxygen, transforming it into biogas and digestate (Bamelis et al., 2015). Biogas is a mixture of gases composed mainly of methane (CH_4) (50 - 80% vol) and carbon dioxide (CO_2), but it may also contain traces of other elements such as hydrogen sulphide (H_2S), water, and siloxanes (Chen et al., 2015). Biogas is a renewable energy source produced from organic material that compared to fossil fuels reduces GHG up to 90% (Kothari et al., 2010; Sharma & Nema, 2013), making it one of the most promising energy sources in the transition towards circular economy (Fagerström et al., 2018).

Digestate is the residual solid/liquid material that was not transformed into biogas during the AD. Depending on the composition, it might be considered a valuable by-product (Vaneeckhaute et al., 2013; Khoshnevisan et al., 2018). Digestate is a stable mixture of microbial biomass and undigested material. It represents about 70-90% of the input volume to the anaerobic reactor and it contains most of the nutrients from the substrates (Fuchs & Drosg, 2013; Bamelis et al., 2015). Digestate contains macronutrients such as nitrogen (N), phosphorus (P), and potassium (K), and micronutrients such as iron (Fe), zinc (Zn), and copper (Cu) (Khoshnevisan et al., 2018). Because of its nutritional and organic matter content, digestate has been traditionally used for agricultural purposes as organic fertilizer and soil amendment (Nkoa, 2014).

As biogas production continues to grow, the handling and use of digestate are becoming more challenging due to more restrictive regulations, market challenges, and expensive handling, storage, and transportation costs (Rolamo et al., 2018). Using raw digestate (without post-treatment) is rather limited to farm-scale level. For large industrial and centralized facilities, further valorization of this stream is needed to improve the feasibility of the biogas plant. Digestate post-treatment also reduces and prevents the environmental impacts that large volumes of raw digestate may cause. (Eriksson & Runevad, 2016; Rolamo et al., 2018; Carucci et al., 2020). With a valorization route, the steps and resources needed to enhance the quality and/or market price of the digestate are defined.

1.1 Aim and research questions

Digestate volume represents about 70-90% of the input to the anaerobic reactor, therefore, valorization of this stream is crucial for any biogas plant to be viable (Fuchs & Drosg, 2013). In the literature, there are plenty of alternatives for improving the properties of digestate products, but to the best of the author's knowledge, there have not been attempts to create a methodology for selecting a valorization route. The reason for this is that many variables are involved in the process and most of them are context-dependent, which makes generalization and standardization rather difficult. However, the author considered that some initial guidelines and steps can be proposed.

A theoretical case study was constructed based on public information and then used as an example to develop the methodology. This thesis aimed to answer the following research questions:

1) What are the available valorization routes of digestate from biogas plants?
2) How to choose the valorization route of digestate?
3) What is the valorization route of digestate for a selected case study?
4) What are the expected quality and quantity of the digestate products for this case study?

1.2 Scope

It was decided to use a roadmap structure to have a visual representation of the developed methodology. A roadmap is a strategic planning tool that shows the desired outcome (goal) and the steps that must be done to get there (Chofreh et al., 2015). The roadmap in this thesis was developed based on the valorization alternatives found during the literature review (Appendix 1) and the local conditions of the case study. All the parameters considered were context-dependent, meaning the results are exclusive to the case study and generalizations should not be made. However, the methodology can be useful (to some extent) for other digestate valorization cases.

Even though the case study is theoretical, the methodology, calculations, and analysis presented in the document are relevant for a real scenario. The developed roadmap includes the following steps: 1) Pre-treatment of raw digestate, 2) Decision tree evaluation of available uses and treatments, 3) Local conditions and demand of products in the market, 4) Definition of potential valorization routes, and 5) Calculations. Due to the time constraint and the limited data available for the economic analysis, the methodology was only applied to full extend from steps 1 to 4. In step 5, the mass and energy balances were calculated, but the cost evaluation was not included. This thesis is not linked to any existing project or institution. The analysis and opinions presented on it are solely those of the author.

2 DIGESTATE VALORIZATION

2.1 Uses

Depending on the composition, digestate might be considered as a valuable by-product used in agriculture, energy, and other industrial applications. Digestate appearance is like mud (sludge) and typically is brown or black (FIGURE 1).

FIGURE 1. Digestate from an agricultural plant in the Czech Republic. Taken from (Rusin et al., 2017).

2.1.1 Agriculture

Digestate use in agriculture includes plant cultivation, gardening, and landscaping (e.g., construction of green areas, landfills covering, infrastructure) (Rolamo et al., 2018). In agriculture, digestate is used as an organic fertilizer and soil amendment due to its organic matter and nutrient content (Nkoa, 2014). It also improves the biological activity of soils (Tampio et al., 2016). The high quality and stability of the organic matter content restore the soil as a natural carbon sink while promoting soil health and fertility for higher crop yields (Tambone et al., 2017; Bhogal et al., 2018).

Agricultural use of digestate also promotes nutrient recycling back to the soils. The nutrient content in digestate comes from the substrates and its availability to the plants is improved during the AD process (Marshall et al., 2019). In the anaerobic reactor, the organic fraction of nutrients is mineralized, and complex organic compounds are degraded, which increases the availability of N, P, K, Ca, and Mg for the plants (Möller & Müller, 2012; Seadi et al., 2013). This effect is especially relevant for organic N and organic P, the two major nutrients in fertilizer products (Mehta & Batstone, 2013; Bachmann et al., 2016).

Digestate can be also processed to produce fertilizer products with concentrated nutrient content, e.g., ammonium sulphate, struvite, and phosphoric acid. These concentrated products also have other industrial applications (Rolamo et al., 2018). If digestate is transformed into biochar, it increases soil fertility while promoting carbon sequestration to combat climate change (Guilayn et al, 2020).

2.1.2 Energy production

Different types of biofuels can be produced from digestate after the water content is significantly reduced (Guilayn et al., 2020; Cesaro, 2021). Thickening, dewatering, and thermal drying processes could decrease the water content about 6, 30, and 95% respectively (Salamat et al., 2020). After increasing digestate density (up to 700 kg/m3) it is possible to produce pellets with a calorific value similar to wood (between 15-17 MJ/kg) (NAWROCKI, 2021). Combustion and incineration to produce heat and/or steam are then possible. Also, thermal conversion processes as hydrothermal carbonization, vapothermal carbonization, hydrothermal liquefaction, and hydrothermal gasification can be used to produce, among other products, bio-oil, syngas, and heat (Guilayn et al., 2020).

More novel and complex alternatives to using digestate as an energy source include fermentation, transesterification, and saccharification processes to produce, for example, biodiesel, bioethanol, and biohydrogen. These novel alternatives might not require significant water reduction as the alternatives mentioned before. (Sambusiti et al., 2016; Guilayn et al., 2020).

Producing energy from digestate reduces digestate volume, decreases storage and transportation costs, and offers new possibilities for using the products in situ when agricultural use is not viable or possible. However, energy consumption, CO_2 emissions produced by the hydrolysis of amino acids, the loss of N, and the complexity of the treatments should be considered (Salamat et al., 2020).

2.1.3 Other industrial uses

High-value products that can be obtained from digestate include bioplastics, biopesticides, biosurfactants, adsorbents, and construction materials (Guilayn et al., 2020). Also, biomasses such as fungal, insect, invertebrate, and algae can be cultivated using digestate as the growing media. From these biomasses, new materials can be extracted (e.g., volatile fatty acids, carbohydrates, alcohols) to produce special products (Fang et al., 2018; Cesaro, 2021). The novel alternatives for the industrial valorization of digestate are promising, but they still require further research and development (Rolamo et al., 2018; Guilayn et al., 2020).

2.2 Challenges

Although digestate can be a valuable material and there is a wide range of technologies to treat it, biogas plants must overcome several challenges to find the valorization route for this stream.

2.2.1 Technical

Digestate characteristics and quantity may vary considerably with time. Biogas plants might accept a wide range of substrates to keep biogas production stable throughout the year. Big changes in the type, quality, and/or quantities of the substrates used in the AD process, affect the final characteristics of digestate since it contains most of the nutrients and pollutants from the substrates (Fuchs & Drosg, 2013; Bamelis et al., 2015; Guilayn et al., 2020). Low-quality substrates (for example, with a high pollutant content) will result in low-quality digestates, which are more challenging to valorize. Major changes in the operating conditions affect as well the digestate characteristics (Guilayn et al., 2020).

Also, nutrient concentration in digestate is low compared to the concentration in inorganic products, which makes its marketability more challenging. Using pure and concentrated products is preferred because it decreases the risk of pollutant accumulation, undesired reactions, and requirements for storage and transportation. Because digestate is a complex mixture with a high water content (>70%) (Fuchs & Drosg, 2013; Guilayn et al., 2020), multiple treatments are required to produce pure and/or highly concentrated products. Moreover, storage of digestate products in Finland may require even 12 months since its use in agriculture is only possible on fields that are not frozen or covered with snow and according to the local demand (Rolamo et al., 2018). Long storage times may be problematic and expensive due to the large volumes and the gas emissions (Duan et al., 2020). Emissions of CH_4 and nitrogen in the form of N_2, ammonia (NH_3), and nitrous oxide (N_2O) are the most likely to occur, affecting the nutrient content of the product (Styles et al., 2018; Longhurst et al., 2019).

2.2.2 Legislative framework

In Finland, the operation of biogas plants is monitored by the Centre for Economic Development, Transport, and the Environment and the municipal environmental protection authorities (Rolamo et al., 2018). These institutions also approve some of the necessary permits for the biogas plants to handle digestate safely. To obtain those permits, the following aspects must be clarified: status of digestate as a product or as waste, source and volumes of the substrates used in the AD, pollutant content in digestate, processing treatments of digestate streams, and final use or disposal of all produced streams.

If the goal is to use digestate as a valuable product, its legal status should be changed from waste to product. To do it, the biogas plant should apply for an End-of-Waste (EoW) process (Kauppila et al., 2018). According to the Finnish Waste Act 5§, "*waste* means any substance or object which the holder discards, intends to discard or is required to discard" (Waste Act 646, 2014). A substance is no longer considered as waste if: it has gone under a recovery operation, there is a specific use for it, there is a demand for it, the technical and legal requirements for the specific use are met, and its use is not harmful or hazardous to people or the environment (Waste Act 646, 2014).

However, there is not a general EoW process in Finland for digestate products, thus the evaluation must be done case-by-case (Kauppila et al., 2018). Case-specific evaluations for getting environmental permits are more relevant when controlled substrates are used since they represent higher risks for humans, animals, and the environment. In those cases, special regulations apply. Examples of controlled substrates are animal by-products, sludges, and genetically modified organisms (GMO), which require special treatments for inactivating biological threats. For example, if more than 10% of the substrates in the anaerobic reactor are sewage sludge, the application of digestate products in agriculture is restricted to fields growing plants that are not consumed fresh by humans or animals. Also, hygienization at 70°C for 60 min with a particle size <12mm, or another approved thermophilic treatment, will be required for those substrates that might contain *Salmonella*, *Escherichia coli*, and root rot fungus. (MMM, 2011)

Pollutant content is monitored to avoid accumulation and contamination of the environment when handling and using digestate products. Finnish legislation limits the content of heavy metals and pathogens in agricultural products coming from digestate (Appendix 2). There are no limits for other contaminants such as microplastics, recalcitrant organic compounds, pharmaceutical product residues, and antimicrobial-resistant pathogens, but attention to these compounds is growing worldwide, which can lead to future restrictions (Longhurst et al., 2019).

Depending on the final use of digestate, more special regulations might apply. The Finnish Food Safety Authority, also called Evira, regulates the use of digestate products in agriculture. In the Type Designation List of Fertilizer Products, the pollutant limits and the minimum quality required in fertilizer products (e.g., nutrient content, stability, organic matter content) are established (Evira, 2017). Kuutti (2020) summarized the Finnish and EU regulations that apply for fertilizers produced from digestate (Appendix 3). Regardless of the digestate application, the final use or disposal of all produced streams should comply with the legislation. Odour control, emissions, discharges, wastewater treatment, restrictions on final disposal, nutrient leaching, and risk of accumulation and contamination of the environment should be considered. For example, if digestate is used for energy production, proper treatment of the by-products (i.e., condensate water, ashes, and exhaust gases) should be included to get the required environmental permit to operate (Vesilaitosyhdistys, 2017; Rolamo et al., 2018).

2.2.3 Market

Typically, biogas plants are intended for a lifetime of +15 years. Securing a place in the market during all those years is one of the most challenging parts of the digestate valorization process. Size of the market, product competition, public acceptance, marketing concept, and overall demand of the possible products should be clarified to define the valorization route of digestate (Barampouti et al., 2020; Cesaro, 2021). If the local market is small, products must be transported longer distances, which results in major costs for the biogas plant (Ojala, 2017). For example, Gasum, one of the biggest biogas players in the Nordics, gives and delivers for free the digestate products to the farmers near their biogas facilities (Gasum Oy, 2021), reducing the need for fertilizers in those areas.

Public acceptance is another critical factor to consider. The origin of substrates used in AD and the digestate post-treatments affect how likely customers are to accept digestate products. Quality variation and accumulation of pollutants (heavy metals, antibiotics, microplastics, pathogens, etc.) are among their main concerns. Customers are more sceptical of waste-derived products, for example, from municipal sewage sludge (Rolamo et al., 2018; Barampouti et al., 2020). Also, if digestate is used for agricultural purposes, it is expected that farmers would be more interested in receiving products that can be used and stored with the existing equipment and infrastructure. Typically, animal farms use compost-like and liquid-type fertilizers (e.g., slurry), while crop farms use solid-type fertilizers (e.g., mineral pellets; Singh, 2012). If a new type of fertilizer is used, farmers should consider the logistics and investment costs involved (Barampouti et al., 2020).

2.2.4 Costs

Handling and transportation of digestate are some of the most expensive aspects for biogas plants (Seadi et al., 2013; Ojala, 2017). High water content, long transportation distances to final users, and large storage capacities are among the reasons why, in most cases, expenses related to digestate are not fully covered even if digestate products are sold (Eriksson & Runevad, 2016; Rolamo et al., 2018). Additionally, the biogas plants that cannot take care of digestate logistics, marketing, and sales must hire a third party to do it, generating an extra cost for the operation.

Viable transportation distances depend on project location, means of transportation, fuel price, size of the plant, quality of the digestate products (water content), among other context-depended variables (Trombin et al., 2017). For each plant, there are maximum distances for which the transportation of digestate products (and substrates) does not affect the viability of the plant. After those limits, transportation costs jeopardize the economic feasibility of the entire project. Examples of transportation distances are shown in Appendix 4.

3 CASE STUDY

It was decided to locate the theoretical example in the municipality of Hanko, on the south coast of Finland. The biogas plant was assumed to be at a random distance of 10 km from the city center, next to a main road (FIGURE 2).

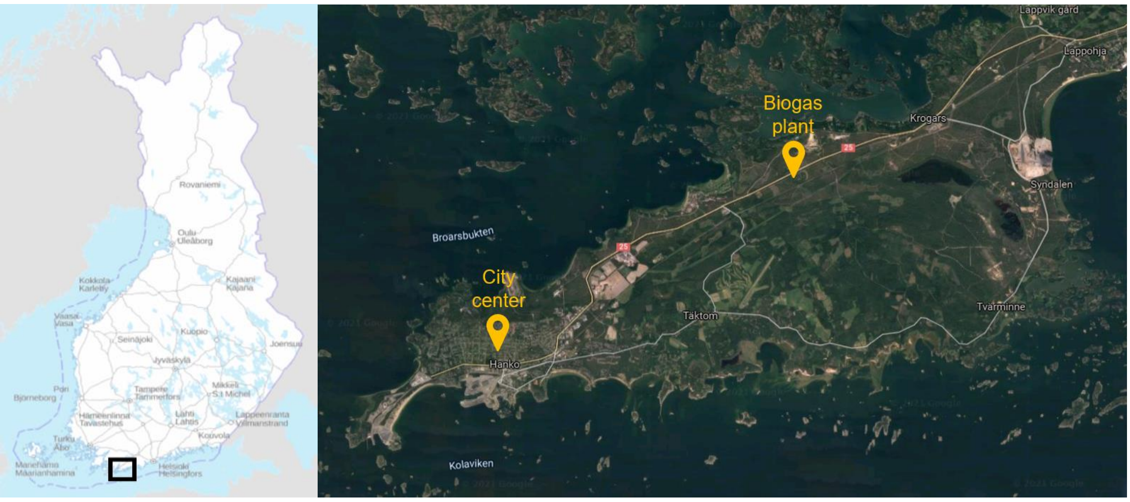

FIGURE 2. On the left, the map of Finland. The black square locates the municipality of Hanko. Image adapted from (LUKE, 2021). On the right, a zoom-in of the area shows the city center of Hanko city and the assumed biogas plant. Image adapted from Google Maps.

3.1 Digestate characteristics

In Finland, the total sewage sludge production for 2016 was about 832,000 tons. From this, 73% was treated in biogas plants (Vesilaitosyhdistys, 2017). According to The Finnish Water Utilities Association[1], the increment from 66% in 2015 could be due to the restriction on organic waste disposal into landfills that entered into force since the beginning of 2016 (Vesilaitosyhdistys, 2017). Since several biogas plants in Finland process some form of sewage sludge and the use of digestate from this substrate is strictly regulated, it was assumed that the digestate produced in the case study comes solely from sewage sludge. The idea was to analyze the valorization route for one of the most challenging but likely scenarios.

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[1] Vesilaitosyhdistys

Typically, biogas plants in Finland treating solely sewage sludge have a capacity under 120,000 tons per year. Some exceptions are Tampereen Vesi in Viinikanlahti (230,000 t/a), HSY[2] in Suomenoja (312,500 t/a), and HSY in Viikinmäki (878,400 t/a) (Rolamo et al., 2018). For the case study, a theoretical biogas plant with a digestate production of 100,000 tons per year was assumed.

The digestate characteristics were taken from the report of the Centre for Economic Development, Transport, and the Environment in the Finnish region of Pirkanmaa (Mönkäre et al., 2016). The values correspond to a digestate from the co-digestion of two sewage sludges (Table 1).

Table 1. Digestate characteristics for the case study. Adapted from (Mönkäre et al., 2016).

DIGESTATE	VALUE	UNITS
Amount	100,000	t/a
pH	7.5	
Temperature	37	°C
Total solids (TS)	9.5	%
Total nitrogen	65.4	g/kg TS
Soluble nitrogen	36.0	g/kg TS
Total phosphorus	33.6	g/kg TS
Soluble phosphorus	0.7	g/kg TS

It was assumed that after AD, digestate complies with all the limits established in the Decree for Fertilizer Products (MMM 24/11) of the Ministry of Agriculture and Forestry[3] (Appendix 2).

3.2 Pre-treatment before sludge valorization

The use of raw digestate (without post-treatment) from large biogas plants is challenging. For instance, when using it for agricultural purposes the nutrient load in

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[2] Helsingin seudun ympäristöpalvelut - Helsinki Region Environmental Services (HSY)

[3] Maa- ja metsälousministeriö (MMM)

raw digestate exceeds the nutrient requirements of the crops. Applying this excess of nutrients on the ground can penetrate the subsoil affecting both surface and groundwater (Nkoa, 2014; Lyons et al., 2021). Also, an excess of N in the raw digestate may increase the risk of NH_3 emissions into the atmosphere during long storage periods (Longhurst et al., 2019). Moreover, the high-water content in the material without post-treatment makes transport by land expensive, and its high content of solids (organic and fibrous material) makes transport by pumping challenging (Eriksson & Runevad, 2016).

To enable a safer and more efficient handling and use of the digestate, it can be mechanically separated into a liquid (LF) and a solid fraction (SF). The mechanical operation allows a better distribution of the nutrients and solids between the two fractions. Most of the water, N, K, and soluble compounds are concentrated in the LF; while most of the P, solids, and insoluble compounds are concentrated in the SF. Mechanical separation of raw digestate facilitates the handling, storage, and transportation because the SF has a higher bulking capacity, so the cost per journey is lower. In addition, the LF has a lower risk of clogging the pipes and equipment when being pumped, spread, or injected. Mechanical separation is required before almost any other valorization treatment (Guilayn et al., 2019). FIGURE 3 shows an example of how the material looks before and after the mechanical separation in a real biogas facility.

FIGURE 3. Raw digestate (left) and separated liquid and solid fractions (right) from an industrial biogas plant processing fish sludge. (Bellander, 2021)

The separation equipment is chosen according to the raw digestate quality (Aguirre-Villegas et al., 2019). The resulting SF is viable for subsequent processes such as compost, vermicompost, drying, pelletizing, or thermal conversion (Guilayn et al., 2019). The LF can be used to recover nutrients, dilute inputs, recycle water, or used as fertilizer. The most common equipment for mechanical separation are screw presses, decanter centrifuges, vibrating screens, and filter presses (Lyons et al., 2021). Guilayn et al. (2019) gathered data from various literature and reference sources to evaluate the performance of different mechanical separators (FIGURE 4). The results show that higher concentrations into the SF (except for N) are achieved mostly with centrifuges (with and without polymer addition) and are related to substrates with low fibrous content (e.g., slurries and sludges). Lower separation efficiencies are obtained, for example, with screw presses and are related with fibrous substrates (e.g., cow manure and silage).

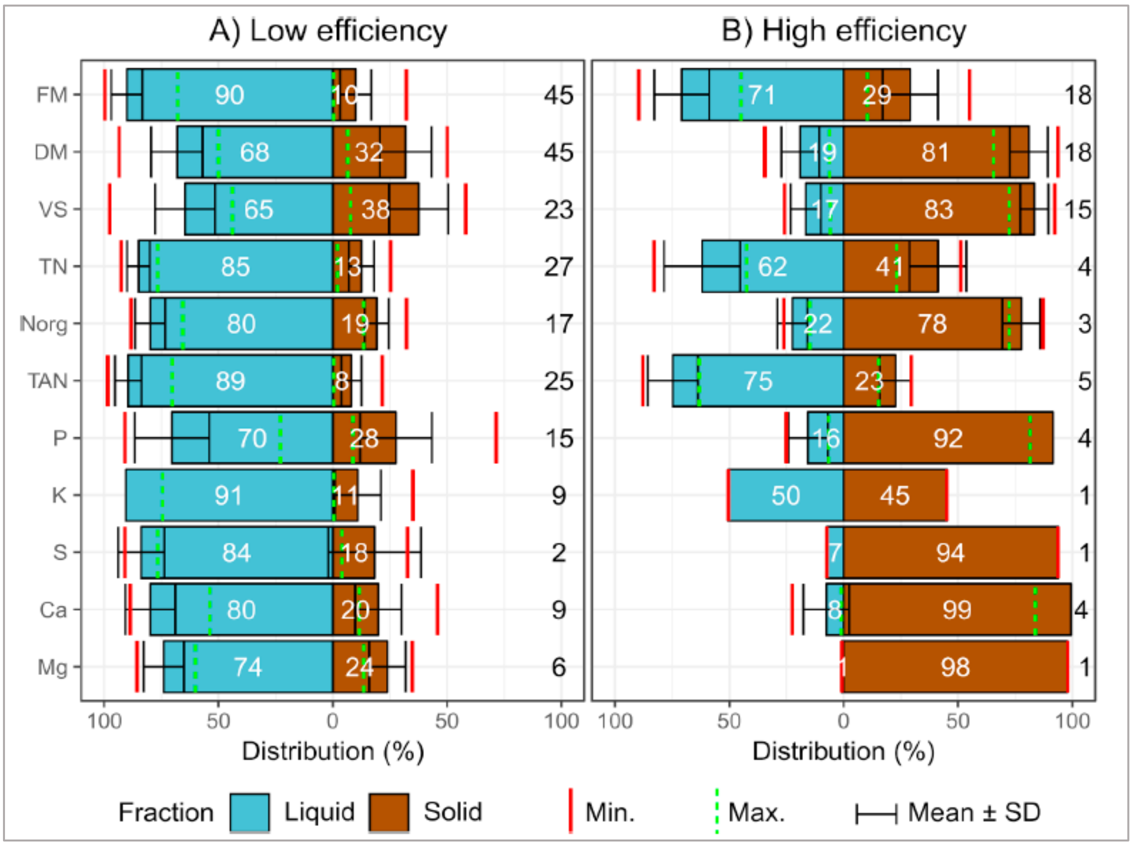


FIGURE 4. Separation of digestate components into the liquid and solid fractions according to the efficiency category. In the low-efficiency category, most of the separators were screw presses. In the high-efficiency category, most of the separators were centrifuges. The numbers on the right are the numbers of observations (data) among the consulted papers. FM: fresh matter. DM: dry matter. VS: volatile solids. TN: total nitrogen. Norg: organic nitrogen. TAN: total ammoniacal nitrogen. P: total phosphorus. K: total potassium. S: total sulphur. Ca: total calcium. Mg: total magnesium. Taken from (Guilayn et al., 2019)

Due to the above reasons, the first step required in the roadmap before any further valorization is mechanical separation. According to the results of Guilayn et al. (2019), the best equipment for separating the digestate from sewage sludge of the case study would be a centrifuge. The values in FIGURE 4 of the high-efficiency category were used in the calculations. Polymer addition was not considered.

3.3 Case-specific considerations

The developed roadmap and the final valorization route were affected by the following specific conditions and assumptions of the case study: the digestate production and quality were stable throughout the year, the biogas plant did not have any internal use for the raw digestate or its valorized products, the biogas plant had a limited footprint for building the digestate treatment, and when using a third party, the quality of the products was such, that the third party accepted them. Thus, the third party guaranteed the quality standards required for the final users.

4 METHODOLOGY

The replicability of this research, i.e., coming to the same conclusions under the same circumstances, was aimed through the strategies suggested by Sturnman (1997) such as: describing in detail the procedures for data collection, displaying the collected data so it can be reanalyzed if needed, reporting the negative findings, acknowledging biases or prejudices when doing the research, applying or creating appropriate methods to verify the quality of the data, and distinguishing between primary and secondary evidence, and between description and interpretation.

The visual summary of the methodology is presented in FIGURE 8 at the end of this chapter. That figure is also the roadmap for the valorization of digestate in the case study. The results of implementing this methodology are presented in Chapter 5.

4.1 Source data

A literature review was carried out to have qualitative and quantitative data for different digestate treatments and valorization alternatives. Scientific articles, thesis, and reports were consulted from databases such as ScienceDirect, Springer, American Community Survey (ACS), and Directory of Open Access Journals (DOAJ). Also, ongoing real examples (with a special interest in full-scale solutions) were consulted. The main keywords used for the search were “digestate” and “valorization”. Variations of these two words were used as well, e.g., “slurry”, “effluent”, “digested”, “residual”, “treatment”, “process”, “recover”, among others. For the considered treatments, typical values for operating thresholds, efficiencies, chemical, water, and energy consumptions were reviewed as well.

Among the consulted papers, Guilayn et al. (2020) was considered the most complete state-of-the-art inventory of digestate valorization alternatives. The authors included the alternatives mentioned by Fuchs & Drosg (2013), Monlau et al. (2015), Sheets et al. (2015), Bolzonella et al., (2018), Rolamo et al. (2018), and

Vondra et al. (2019). Guilayn et al. (2020) made an extensive literature review on digestate valorization alternatives from urban and centralized biogas plants. They verified 1362 papers, from which the first set of 520 publications was studied in greater detail. They also did a bibliometric study showing the patterns among the reviewed articles (e.g., most used substrate, most studied technology, preferred treatment goal). The summary of Guilayn et al., (2020) literature review and bibliometric study are found in Appendices A and B of their publication.

4.2 Decision tree

The decision tree methodology was used as the second step for constructing the roadmap for the valorization of digestate. This methodology classifies a large amount of information using a systematic evaluation of defined variables, and it serves also as a predictive model (Song & Lu, 2015). A decision tree is a flowchart-like structure and it has four main components: the root node, as the starting point that contains all the information (data set) before it has been analyzed; the decision nodes, which define how to evaluate the variables; the tree branches, which contain the chance of an event to occur or the values that a variable can have; and finally, the leaves, which show the outcomes/results for the given path.

A decision tree was developed to classify and evaluate the collected information from the literature review, taking into account the case study. Three decision nodes were considered: final use of digestate product(s), maturity of technology, and treatment location. For each one, two or more alternatives were compared qualitatively and/or quantitatively to determine the path to follow.

4.2.1 First node: final use

Digestate uses can be classified into three main categories: agriculture, energy, and other industrial valorization. The treatments included in each category and considered in this thesis are shown in Appendix 1.

So far, most of the biogas plants in Finland have used digestate for agricultural purposes (Rolamo et al., 2018). In this application, digestate improves the physical properties, biological activity, health, and nutrient availability of soils (Nkoa, 2014; Tampio et al., 2016). It promotes nutrient and carbon recycling and restores the soil as a natural carbon sink (Bhogal et al., 2018). If digestate is transformed into biochar, it increases soil fertility while promoting carbon sequestration to combat climate change (Guilayn et al, 2020). The technical treatments for agricultural use are rather robust and there are plenty of full-scale references. Moreover, closing the cycle of nutrients is of the greatest importance nowadays, especially for phosphorus, which is a scarce but vital resource. Interest and promotion for nutrient recycling have been growing during the last years at the EU level (European Commission, 2020).

Digestate use for energy production only applies to the separated solid fraction and it is not used in Finland due to the high energy consumptions to dry it, the low calorific value, the loss of N, the further treatment of the by-products (i.e., ashes and exhaust gases), gate fees, and the required environmental permit to operate (Vesilaitosyhdistys, 2017; Rolamo et al., 2018). Other industrial uses of digestate are rare at large scale and they would require further development before they can be competitive (Rolamo et al., 2018; Guilayn et al., 2020).

Considering the above, at the first decision node, agricultural valorization was favoured over the other two alternatives. Energy valorization was favoured when the agricultural option was not viable or sufficient.

4.2.2 Second node: maturity of technology

The list of available technologies for treating digestate is quite extensive and it can go even longer since combinations of different technologies are most likely to increase the overall treatment efficiency. Moreover, the same technology may be used for different streams of the digestate, e.g., raw digestate, liquid fraction, concentrated liquid fraction, and so on. Therefore, the performance of a specific technology will depend on the operating conditions and the material to be treated.

The maturity of a technology shows how ready such technology is to work under the environmental and operating conditions for which it has been developed. The more mature a particular technology, the fewer flaws and inherent problems will occur when using it; in consequence, access and use of such technology becomes more common. (MITRE, 2021).

There are various ways for assessing technical maturity, among which, the Technology Readiness Level method (TRL) has been the one extensively adopted by the European Union since 2010 (Héder, 2017). TRL is a measuring system at 9 levels (FIGURE 5). At each level, a technology is evaluated against proper technology requirements and demonstrated capabilities suitable for each case (NASA, 2012).

TECHNOLOGY READINESS LEVEL SCALE (TRL)

1. Basic principles observed
2. Technology concept formulated
3. Experimental proof of concept
4. Technology validated in lab
5. Technology validated in relevant environment
6. Technology demonstrated in relevant environment
7. System prototype in operational environment
8. System complete & qualified
9. System operational

FIGURE 5. TRL scale. Adapted from (European Commission, 2019).

A particular technology can have different levels of maturity depending on the application. For example, biofuel production via fermentation of cellulosic biomass has been developed more with side streams from the food industry, TRL ≥ 6, (Bacovsky & Sonnleitner, 2021), than with biomass that has been grown using digestate fertilizer products, TRL = 6, (Sambusiti et al., 2016). Therefore, it is important to highlight that the TRL values reported in this research are specific for digestate treatment.

Because of the size of the plant (100,000 t/a of digestate), the chosen technology (or combination of technologies) had to be robust and reliable. By considering only technologies with a high TRL > 6, the risk of technical bottlenecks during the operation was reduced.

4.2.3 Third node: treatment location

As mentioned in section 2.2.4, transportation distances have a big impact on biogas plants' feasibility. Volumes to be transported outside the facility, especially if they are intermediate products, should be minimized. In the decision tree, digestate treatments that are located at the biogas plant (*on-site*) were favoured over those which are performed in external facilities (*off-site*).

For the case study, treatments that were considered *off-site* were those with large area requirements, i.e., composting, vermicomposting, and ponds of microalgae and/or duckweed production (Guilayn et al., 2020).

4.3 Local conditions and demand of products for agriculture

As explained in section 2.2.3, a good understanding of the current market, future trends, and local conditions increase the chances for the valorization route to be viable in the long-term. In the third step of the roadmap, the local conditions and demand of the possible products were evaluated.

4.3.1 Nutrient limits in soils

Fertilization in agriculture depends on the type of soil (e.g., clay, mineral, organic), its physical characteristics (e.g., pH, organic matter, nutrient content), and the type of crop (e.g., cereals, potatoes, grasses) (Ylivainio et al., 2014). In Finland, the Nitrate Directive 91/676/ETY and decrees Vna 1250/2014 and 435/2015 set the limits for Soluble N between 30 – 250 kg/ha/a depending on the type of crops and fertility of the soil (Mönkäre et al., 2016; Rolamo et al., 2018). The Decree on Fertilizer Products MMM 24/11 and its modifications 12/12, 7/13, 12/15, 21/15, 5/16 set the limits for Soluble P at 325 kg/ha in 5 years (MMM, 2011). Also, the Finnish Agri-Environmental Program (FAEP) establishes fertilization ranges according to the type of crops and soils (Evira, 2020).

Ylivainio et al. (2014) analyzed more than one million soil samples from all over Finland with the soil test phosphorus (STP) to establish the P content at a municipal level. The researchers also calculated the P-index, which indicates the risk of P accumulation and eventual leaching into surface waters (FIGURE 6). The soils in Hanko municipality have a high STP and P-index values, 15 – 20 mg/L and 40 – 60, respectively, meaning that the addition of P must be avoided or restricted to the lowest fertilization values established by the FAEP (Ylivainio et al., 2014)

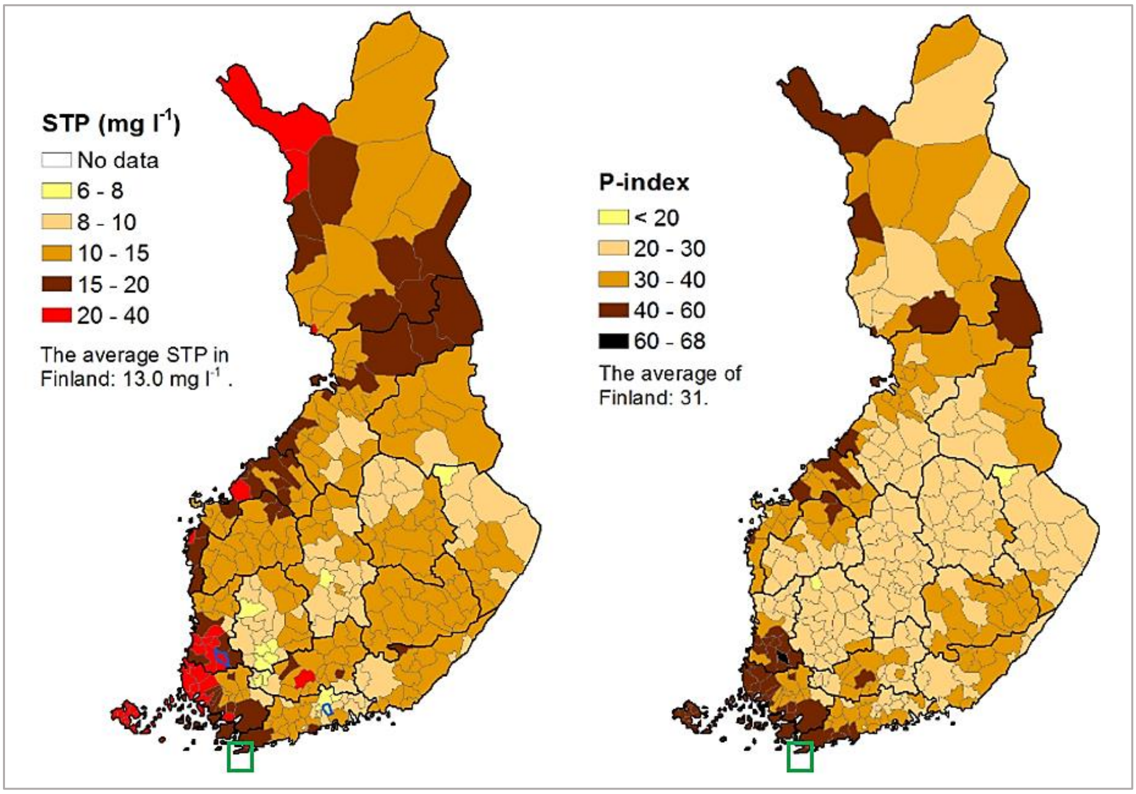


FIGURE 6. On the right, average STP in Finland. On the left, P- index in Finland. The green marks locate the municipality of Hanko. Image adapted from (Ylivainio et al., 2014)

For the case study, annual nutrient needs were assumed for all the fields to be 80 kg/ha of Soluble N and 5 kg/ha of Total P. Both values are under the maximum limits allowed by the legislation and the FAEP. Also, digestate treatments that allow the efficient separation of P from N were favoured. The separation of these two components might enable the more extensive use of N-rich digestate products in the Hanko area since P content is a limitation. For the solid fraction rich in P, transport to other parts of the country with higher P requirements and further treatment to make it suitable for the soils were favoured. It was assumed that the fields in the area used compost-like and liquid-type fertilizers. Therefore, the production of pellets was not considered for the case study.

4.3.2 Demand of products for agriculture

The total area required for applying the digestate products was calculated according to Equation (1).

$$Total\ area\ (ha) = \frac{Nutrient\ amount\ in\ digestate\ (kg/a)}{Nutrient\ need\ in\ the\ fields\ (kg/ha/a)} \tag{1}$$

According to the Finnish legislation, if more than 10% of the substrates in the anaerobic reactor are some form of sewage sludge, the application of digestate products is restricted to fields growing cereals, oilseed plants, sugar beet, and other plants that are not consumed fresh by humans or animals (MMM, 2011). Since the digestate from the case study was solely from the digestion of sewage sludge, only the area of suitable fields was considered.

As explained in sections 2.2.2 and 2.2.3, the demand for digestate products is affected, among other factors, by the fertilizer market, the nutrient needs, the presence of other biogas plants in the area, and the public acceptance. Ideally, this product demand is established through market research or negotiations with third parties and final users. The demand factor (DF) was defined as shown in Equation (2). A demand factor of 25% means that from all the suitable fields in the area, only 25% of them would receive the digestate products. For the case study, four demand factors were evaluated: 25, 50, 75, and 100%.

$$DF = \frac{Area\ of\ suitable\ fields\ using\ digestate\ products\ (ha)}{Total\ area\ (ha)} * 100\% \quad (2)$$

Using this equation, the required area of suitable fields was calculated for each demand factor considered.

4.3.3 Transportation distance

The distribution of the digestate products in the vicinity of the biogas plant was evaluated using the Biomassa-Atlas tool developed by The Natural Resources Institute of Finland. This online tool shows, among other data, the agricultural use of soils per type of field (LUKE, 2021). Iterations were done to find the transport distances to the required suitable fields. The central point was the biogas plant, and the distances were calculated along the available road network (FIGURE 7). More detailed explanation on how to use the tool and do the iterations is found in Appendix 5.

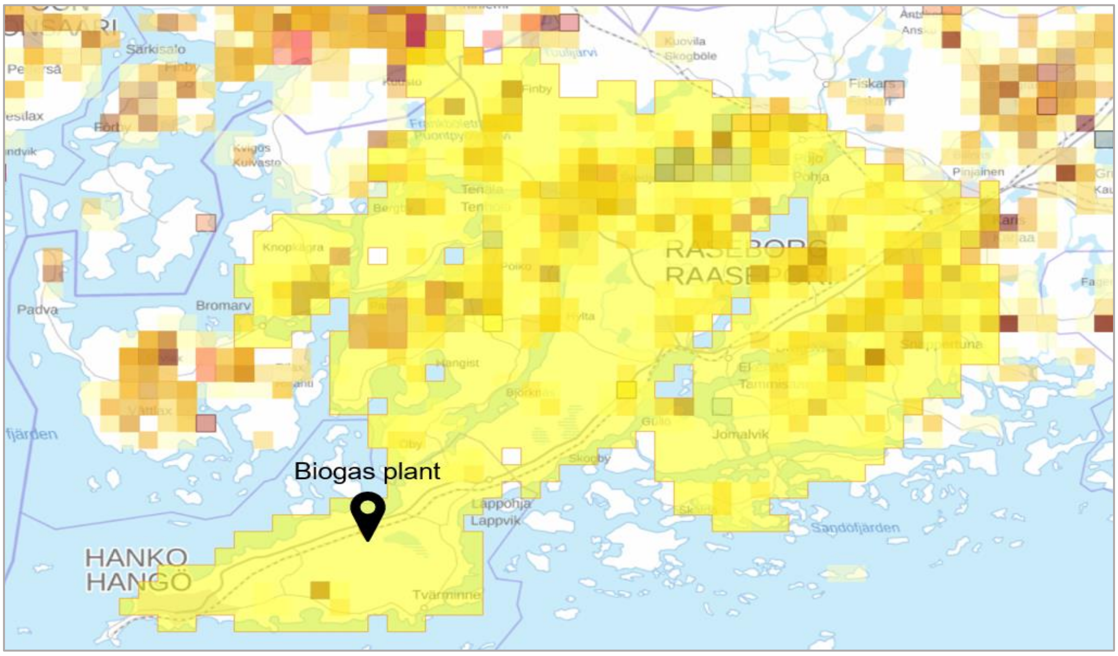


FIGURE 7. The brown squares are the suitable fields near the biogas plant (different shades of brown represent different types of fields). In yellow, an example of the area for distributing the digestate products if the maximum distance between the biogas plant and the suitable fields is 42 km, along the road network. Image adapted from (LUKE, 2021).

4.4 Potential valorization routes

The next step in the road map was to determine which of the pre-selected technologies from the decision tree were suitable for treating the digestate. For this, operation thresholds, efficiencies, and rules of thumb from literature and providers were consulted. Considering the size and the required long-term operation of the plant, other considered aspects were, for example, how complex was the technology to operate, how flexible it was for changes in the operation, the need for external experts to take care of the operation and maintenance, and the associated operational risks.

The suitable technologies can be used in different configurations to increase the overall treatment efficiency. At this stage, technical expertise is required to define which configurations are most likely to achieve the required quality of products, minimize associated risks, and decrease operation and maintenance needs. Moreover, from steps 1 to 3 of the roadmap, the uses, demand, and quality of potential products were clarified, which enabled to define the potential valorization routes.

For the case study, due to the time constrain, only one operation unit was considered for each stream after the mechanical separation. For the liquid fraction, the goal was to produce an N – rich liquid fertilizer with a dry matter content up to 12%, which is a common value for machinery spreading liquid fertilizers (ADAS et al., 2001). For the solid fraction, the goal was to adjust the P content to make the material suitable for agricultural purposes.

Further removal of water from the liquid stream was not included. This treatment depends on local conditions such as available discharge options (i.e., sewage system or body water), discharge limits, and local prices for fresh water and wastewater. Water removal also depends on how competitive or needed it is to recycle water back to the process. The recycled stream can be used to dilute the substrates in the biogas reactor or used as technical or potable water. This high-quality water can be achieved, for example, using membrane technologies (Fuchs & Drosg, 2013).

4.5 Calculations

The final step was to calculate the expected quality and quantity of all the streams produced in the potential valorization routes. These results are used to perform an economical evaluation, from which the final valorization route is decided. In this thesis, the cost evaluation was not included. Therefore, the final valorization route was not defined, only the potential routes and their corresponding mass and energy balances.

4.5.1 Mass and energy balances

In any physical, chemical, or biochemical transformation process, it is not possible to transcend nature's limits. Mass and energy balances are the natural boundaries from which the design conditions of a process are established. These balances are needed in any conceptual design to determine the pre-feasibility of the case (Peters et al., 2007). Without this, it is difficult for investors to find the project viable.

In section 4.4, technical operating thresholds and rules of thumbs were used to define the pre-selected alternatives. Now for the mass and energy balances, it is recommended to use values as close as possible to the real operating conditions. Data from an experimental phase and technical specifications from budget quotations are ideal. However, these data are not easily available if the project is in an early stage (e.g., concept definition or pre-feasibility). In that case, values from the literature, relevant references, or simulation programs can be used.

For the case study, stoichiometric values of the reactions were used. It was assumed that all Soluble N content was NH_4^+ and this was the only N compound reacting to pH changes. The undissolved N did not react. In a real operation, increasing the temperature and pH conditions promote hydrolysis of proteins, which might result in higher N – recovery than the original NH_4^+ content (Guilayn et al., 2020). Losses, chemical consumption of buffer compounds, possible consumptions of antifoaming, antiscalant, antifouling, washing, or cleaning chemicals were not considered. Calculations for *off-site* alternatives were not included. Separation efficiencies of the alternatives were taken from (LUKE, 2017). Energy integration was not included.

4.5.2 Cost evaluation

As expected in any business, the biogas plant must generate revenues for the project to become real. Even if the treatment line of digestate is not profitable, its impact must be minimized in such a way that the feasibility of the whole project is not threatened.

The investment costs (CAPEX) are the costs that the investors must assume to be able to start the production, e.g., the cost of the equipment, land, and the engineering, procurement, and construction of the project. The operation costs (OPEX) are generated from the regular operation and functioning of a business and they guarantee that the operation is, from the economic point of view, viable. OPEX usually includes the cost for salaries, services, chemical consumption, etc. It is important to highlight that handling and logistics costs are crucial when calculating the revenue of a biogas plant. Not including these costs may lead to unreal financial conclusions (Herbes et al., 2020).

The comparison of the CAPEX and OPEX costs is one way to recognize which of the pre-selected alternatives is the most suitable for the case based only on the economical aspect. If also the intangible benefits should be considered (e.g., social wellbeing, environmental advantages, economic growth, etc.), then a cost-benefit evaluation would be recommended. In that case, a monetary value should be assigned to each benefit (Palmer et al., 1999; Miraj et al., 2021).

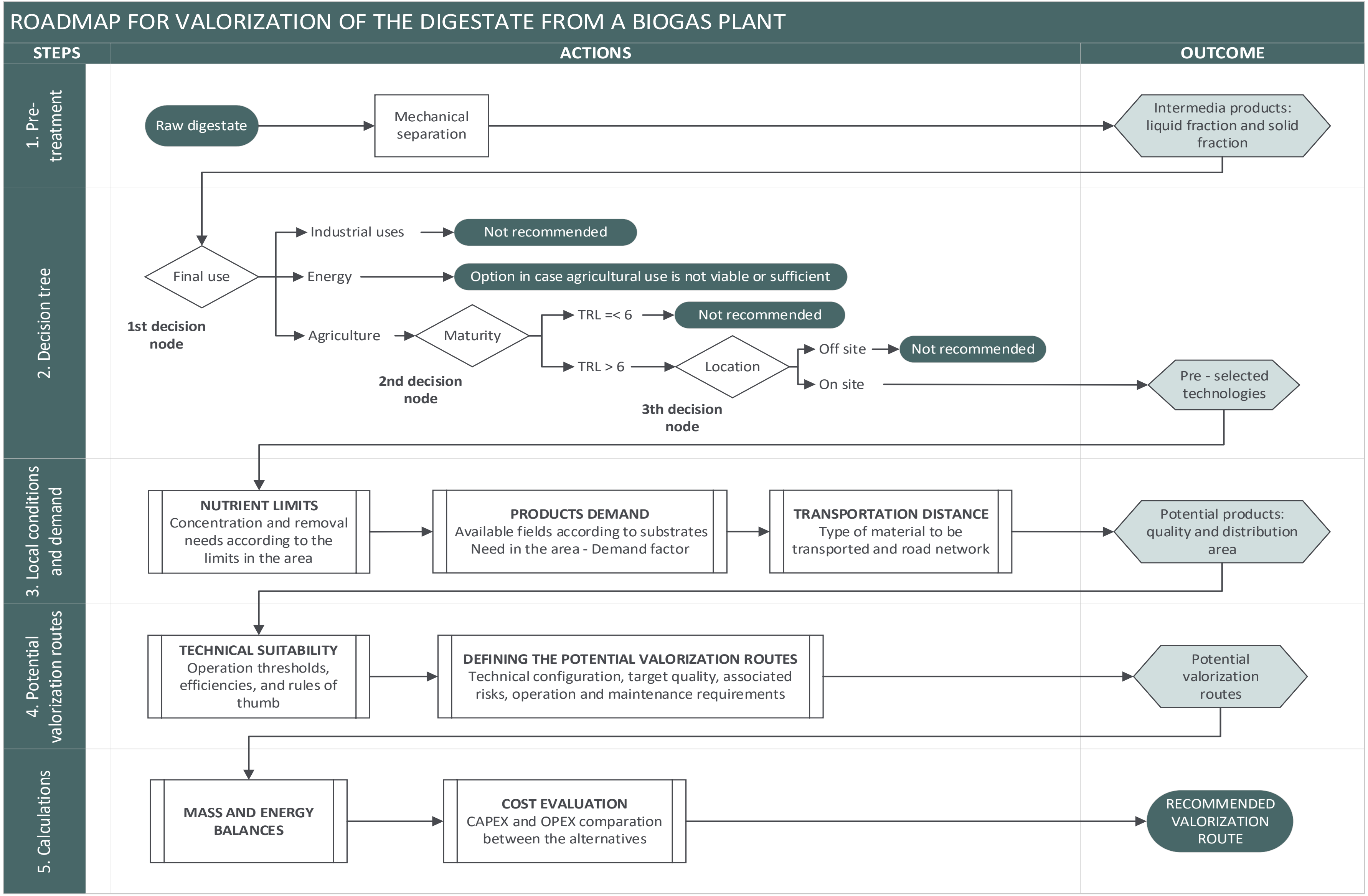
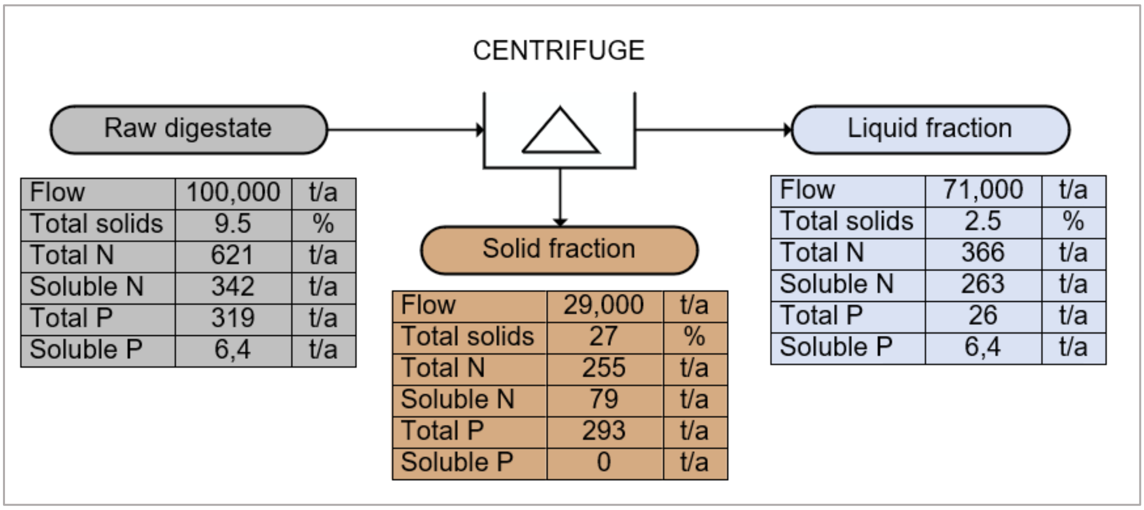


FIGURE 8. Developed roadmap for the valorization of digestate in the case study. Cost evaluation was not included in this thesis. This figure is also the summary of the developed methodology.

5 RESULTS

5.1 Pre-treatment

A centrifuge without polymer addition was used for separating the raw digestate into SF and LF (FIGURE 9). The biggest stream was the LF with a production of 71,000 t/a and high concentrations of N: Total N 366 t/a and Soluble N 263 t/a. Total P of the LF was 26 t/a, from which 6.4 t/a were soluble. The production of the SF was smaller, but still significant, with 29,000 t/a and high concentrations of both nutrients: Total N 255 t/a and Total P 293 t/a. Before sewage sludge is sent to biogas plants, most of the P is already precipitated due to the use of metal coagulants in the wastewater treatments. Thus, the digestate of the case study did not have a significant amount of soluble P compounds. For the case study, the Soluble P was concentrated in the LF since there was not further polymer addition to precipitate it.



Raw digestate

Flow	100,000	t/a
Total solids	9.5	%
Total N	621	t/a
Soluble N	342	t/a
Total P	319	t/a
Soluble P	6,4	t/a

Solid fraction

Flow	29,000	t/a
Total solids	27	%
Total N	255	t/a
Soluble N	79	t/a
Total P	293	t/a
Soluble P	0	t/a

Liquid fraction

Flow	71,000	t/a
Total solids	2.5	%
Total N	366	t/a
Soluble N	263	t/a
Total P	26	t/a
Soluble P	6,4	t/a

FIGURE 9. Mass balance for the mechanical separation of the raw digestate into liquid and solid fractions. Separation efficiencies taken from (Guilayn et al., 2019).

5.2 Valorization of the solid fraction

All the digestate treatments considered in this thesis (Appendix 1) were evaluated in the decision tree. In it, those alternatives using the digestate products in agriculture (node 1), with a high maturity of technology TRL>6 (node 2), and being performed *on-site* (node 3) were favoured over the other alternatives. After the decision tree, the remaining alternatives for the valorization of the SF were combustion, torrefaction, pyrolysis, gasification, and thermal drying. All of these are thermal treatments that increase the concentration of P in the final solid products (i.e., ashes, torrefied biomass, biochar, or dry digestate) and decrease the total volumes to be transported out of the biogas plant. Although this mass reduction has a positive impact in logistics and transportation, the challenge of applying the solid products in the area still remains due to the P content. Even though P is a valuable nutrient, as mentioned in section 4.3.1, there is a strict limitation for applying P in the soils of the Hanko area. Also, with these alternatives, the resulting solid products do not have a significant amount of nutrients that are easily accessible to plants, and most of the N and organic matter have been removed. Therefore, the final solid products would have low or no value for agricultural purposes near the biogas plant.

Because of the above, none of the alternatives from the decision tree was viable for the SF. Therefore, other alternatives that were not initially favoured during the evaluation must be considered: different final use (energy or other industrial uses), TRL= or <6, or *off-site* treatments. Considering that in Finland energy and other industrial uses from digestate are not common due to the reasons mentioned in section 4.2.1, and that, for a large facility, using alternatives with TRL= or <6 represents a high operational risk, it was decided to consider the *off-site* alternatives, i.e., composting and vermi-composting. From these two, composting is the most realistic alternative at a large scale in Finland. The mass and energy balances for *off-site* alternatives were not included in this thesis.

5.3 Valorization of the liquid fraction

After the decision tree evaluation, the remaining alternatives for the valorization of the liquid fraction were crystallization (of struvite, K – struvite, or Ca – P products), evapo-concentration, and the combination of stripping and scrubbing. The goal was to use one of these alternatives to produce an N – rich fertilizer with a dry matter content up to 12%, which is a common value for machinery spreading liquid fertilizers.

The crystallization alternatives are used for recovering mostly the Soluble P from the LF. In these treatments, complex P compounds are formed as crystals (e.g., struvite ($NH_4MgPO_4 \cdot 6H_2O$)) that precipitate to the bottom of the reactor, from where they are collected. An additional source of magnesium (Mg) and alkaline conditions might be required to favour the production of these crystals. According to some technology providers, the recommended operation thresholds for the crystallization alternatives are a maximum dry solid content of 1.0% TS and a minimum Soluble P content of 50 mg/l measured as orthophosphate (Driessen & Scheringa, 2021; Anwar, 2021). The LF of the case study had a higher solid content of 2.5% TS, so it was not suitable for crystallization since it would generate operational challenges. One option was to dilute the LF from 2.5 to at least 1.0%TS with the addition of 106,500 t/a of water. However, this would decrease Soluble P concentration under 36 mg/l, which is lower than the recommended values for a feasible operation. Thus, crystallization of struvite, K – struvite, or Ca – P products were not suitable for the LF of the case study.

There were not technical limitations for the alternatives of evapo-concentration and the combination of stripping and scrubbing. The evapo-concentration is a robust solution used to concentrate the volumes and amounts of different liquid streams, in this case the LF, up to 90% (Guilayn et al., 2020). The two main outputs of this treatment are the concentrated product and the evaporated stream (vapours and gases). In this case study, the concentrated product was the N – rich fertilizer to be sent out of the biogas plant. The evaporated stream was mostly water and it was condensated back to the liquid form in a heat exchanger. This water could be recycled to dilute the substrates in the biogas reactor or used as technical or potable water after, for example, a membrane treatment. The final use or further treatment of this condensated water was not included in the thesis. To keep N in the concentrated liquid phase, acid addition is required. At low pH and temperature conditions, most of the Soluble N is in the form of NH_4^+. At high pH and temperature conditions, NH_4^+ passes to the NH_3 form and evaporates with the water, which decreases the nutrient content of the fertilizer product. The production of the concentrated fertilizer was 15,000 t/a and it was rich in nutrients: Total N 366 t/a and Total P 26 t/a. The condensate water was 57,020 t/a and it might contain traces of soluble compounds. The amount of fertilizer (concentrated product) was about five times smaller than the original 71,000 t/a of the LF (FIGURE 10).

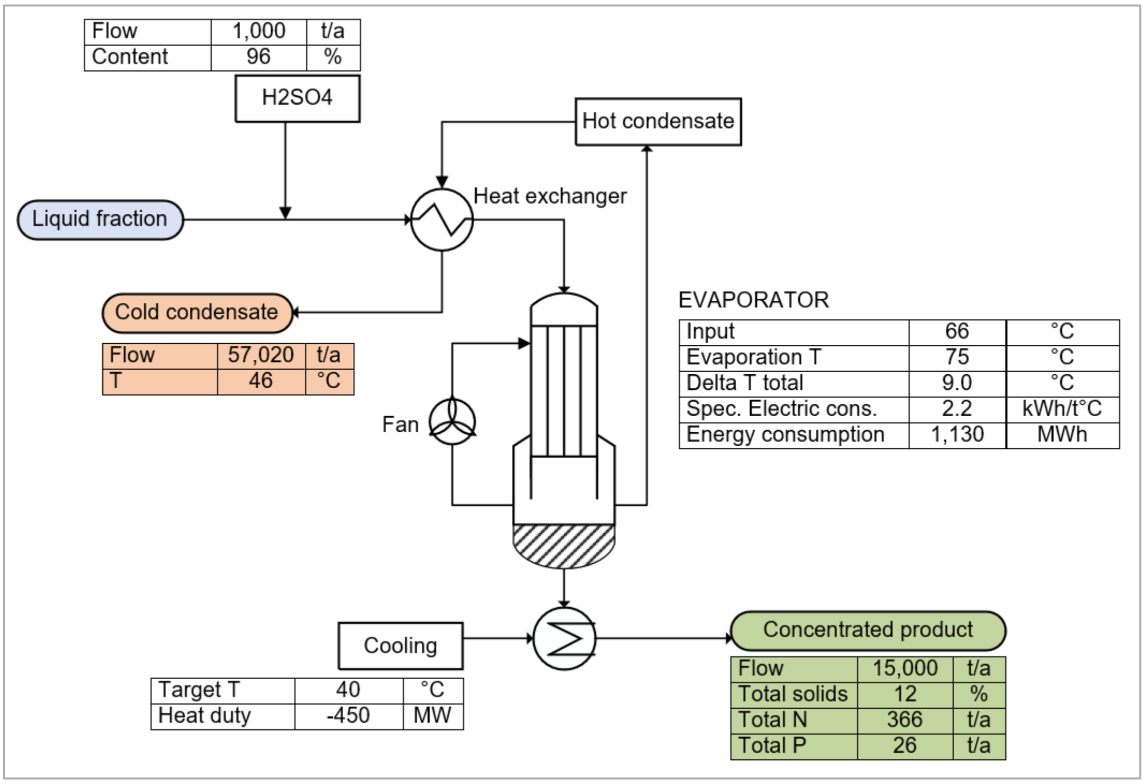


FIGURE 10. Mass and energy balance of the evapo-concentration alternative for the valorization of the liquid fraction to produce N – rich concentrate fertilizer. Sulfuric acid is added to keep the Soluble N in the liquid phase. Separation efficiencies were taken from (LUKE, 2017).

The combined option of stripping and scrubbing is used for nutrient recovery. In this case, the operating conditions (i.e., pH and temperature) are adjusted to favour the transfer of dissolved NH_4^+ to the gas phase as free NH_3. The separated NH_3 is then absorbed in the scrubber using an acidic solution or water. If sulfuric acid (H_2SO_4) is used to absorb the NH_3, the final product to be sent out of the biogas plant is ammonium sulphate. If water is used instead for the absorption, the final product is ammonium water (Styles et al., 2018). In both cases, about 94% of Total N was concentrated in the gas phase, and therefore, in the fertilizer products. P and the undissolved compounds remained in the bottom product of the stripping column. The production of ammonium sulphate solution was 2,572 t/a with a concentration of 38%, which is a common concentration for using this product in agriculture. In this case, the amount of fertilizer (ammonium sulphate) is 27 times smaller than the original amount of LF (FIGURE 11). Depending on the local conditions (i.e., regulations, discharge options, discharge limits, and treatment prices), the bottom product of the stripping column might require further nutrient recovery, water recovery, or final disposal. The final use of this stream was not included in the thesis.

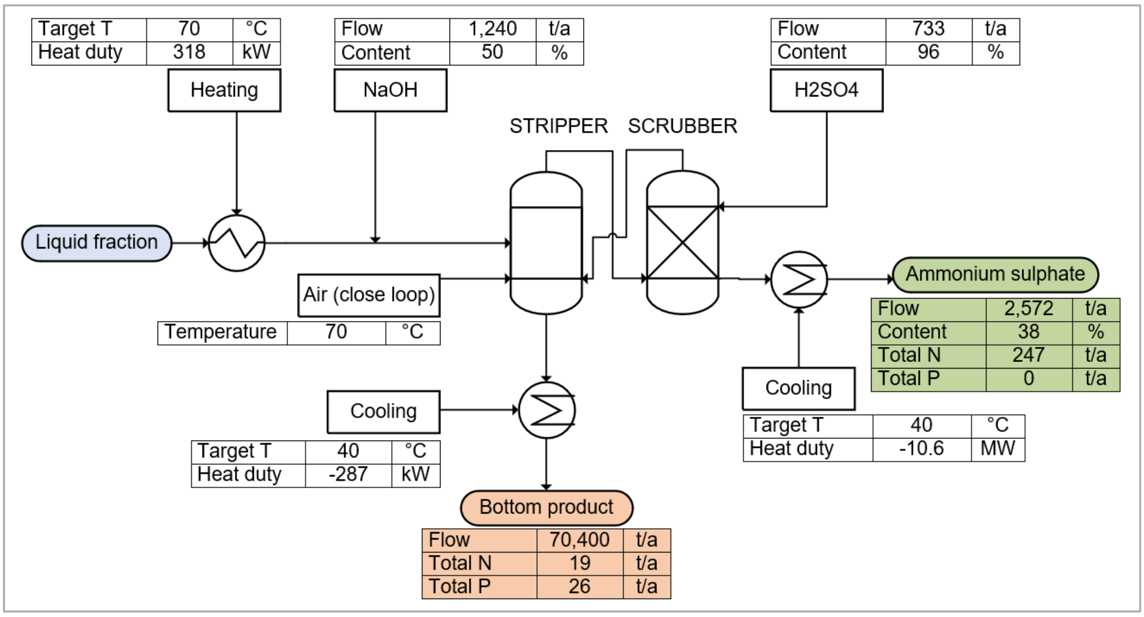


FIGURE 11. Mass and energy balance of the valorization of the liquid fraction to produce ammonium sulphate. Stripping and scrubbing are the main unit operations. Sulfuric acid is used as the absorbing media. Separation efficiencies taken from (LUKE, 2017).

For the production of ammonium water with the stripping and scrubbing, the total flow was 1,360 t/a with a concentration of 18%, which is common for this product when used in agriculture. The amount of fertilizer (ammonium water) is 52 times smaller than the original amount of LF (FIGURE 12).

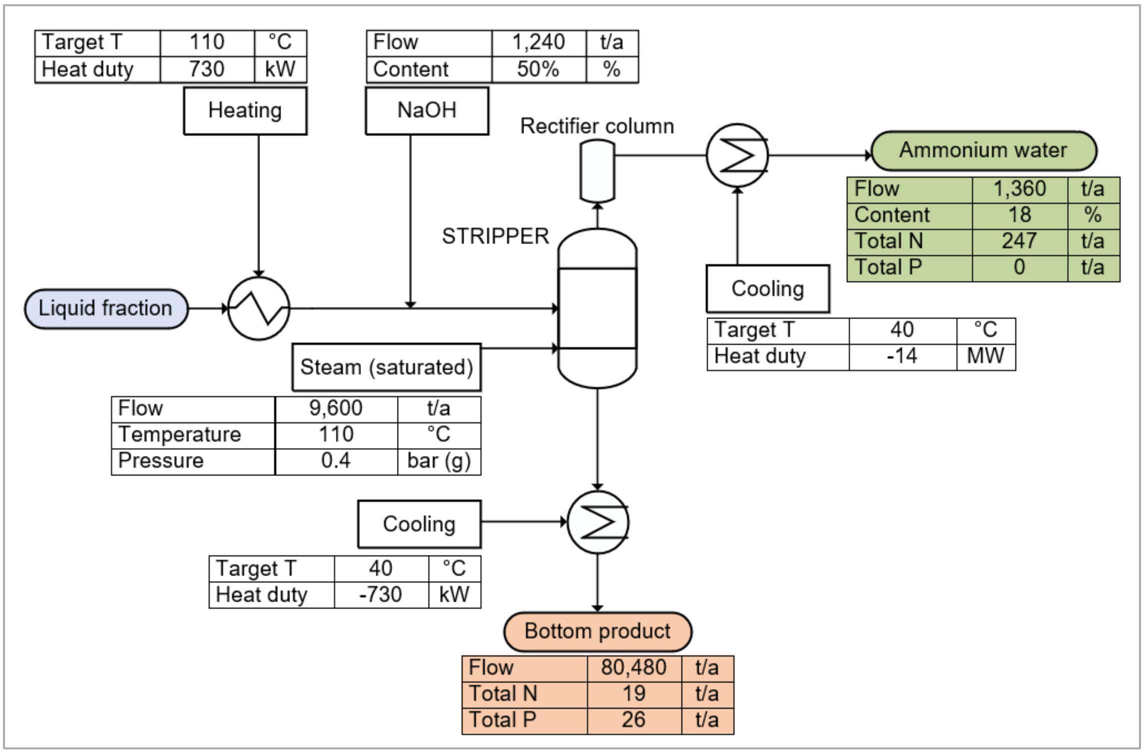


FIGURE 12. Mass and energy balance of the valorization of the liquid fraction to produce ammonium water. Stripping and a rectifying column are the main units. Condensated steam is used as the absorbing media. Separation efficiencies taken from (LUKE, 2017).

For the evapo-concentration alternative, P was the limiting nutrient to apply the N-rich fertilizer in the soils near the biogas plant. The required areas for using this product were calculated from Equations (1) and (2) using the annual nutrient need of 5 kg/ha of P tot (assumed in section 4.3.1), and the 26 ton/a of P tot in the N – rich fertilizer. With these values, iterations were done in the Biomassa-Atlas tool to find the transport distances to the required fields. Since the digestate was from the digestion of sewage sludge and this is a restricted substrate, only the area of suitable fields mentioned in Appendix 6 were considered. Four demand factors (DF) were evaluated to see the changes in the required areas depending on what percentage of the available fields would actually receive the products. For the DF of 25%, the required area was 20,416 ha. The maximum distance that the tool calculates along a road network is 65 km, which corresponds to an available area of 19,308 ha. Therefore, the exact distance for 25% DF was not found, but it is expected to be a bit higher than 65 km (FIGURE 13). The required areas for using the N – rich fertilizer product varied from 5,104 to 20,416 ha, with transportation distances between 42 and over 65 km.

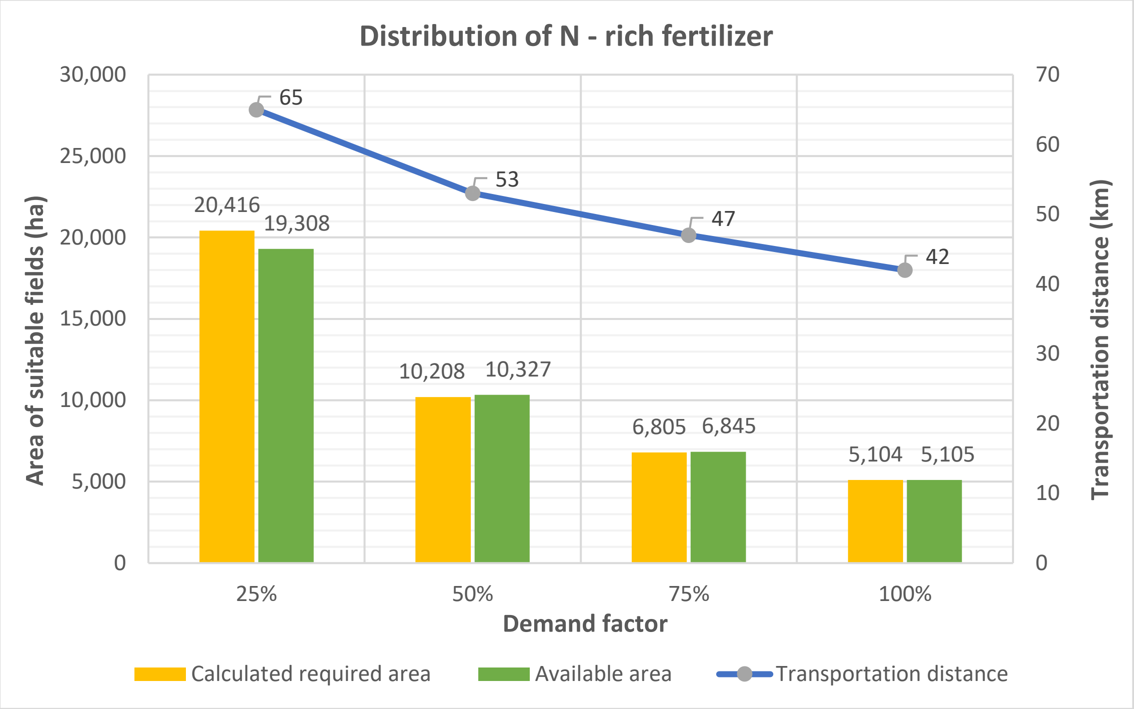


FIGURE 13. Areas of suitable fields required and available for spreading the N – rich fertilizer from the evapo-concentration alternative. The transportation distance is the longest a delivery truck would need to ride from the biogas plant to the suitable fields (one way). Four scenarios for distributing the products were calculated according to the demand of fertilizer products in the area. Areas of the suitable fields and transportation distances were consulted in the Biomassa-Atlas (LUKE, 2021)

For the ammonium sulphate and ammonium water production alternatives, there was not P in the fertilizer products, therefore, N was the limiting nutrient for using the products in agriculture. The required areas for applying any of these products were calculated from Equations (1) and (2) using the annual nutrient need of 80 kg/ha of Total N (assumed in section 4.3.1), and the 247 ton/a of Total N in the fertilizer. Please notice that the amount of Total N in the final product is the same in both alternatives, therefore, the area to be fertilized is the same in both cases. This is because the needs on the soils are specified in kg/ha of the nutrient, so the concentration or volumes of the fertilizers do not affect how much nutrients the soils should receive. As explained before, iterations were done in the Biomassa-Atlas tool to find the transport distances to the required fields. Also, four DF were evaluated (FIGURE 14). The required areas for using the fertilizer products varied from 3,088 to 12,350 ha, with transportation distances between 36 and 56 km.

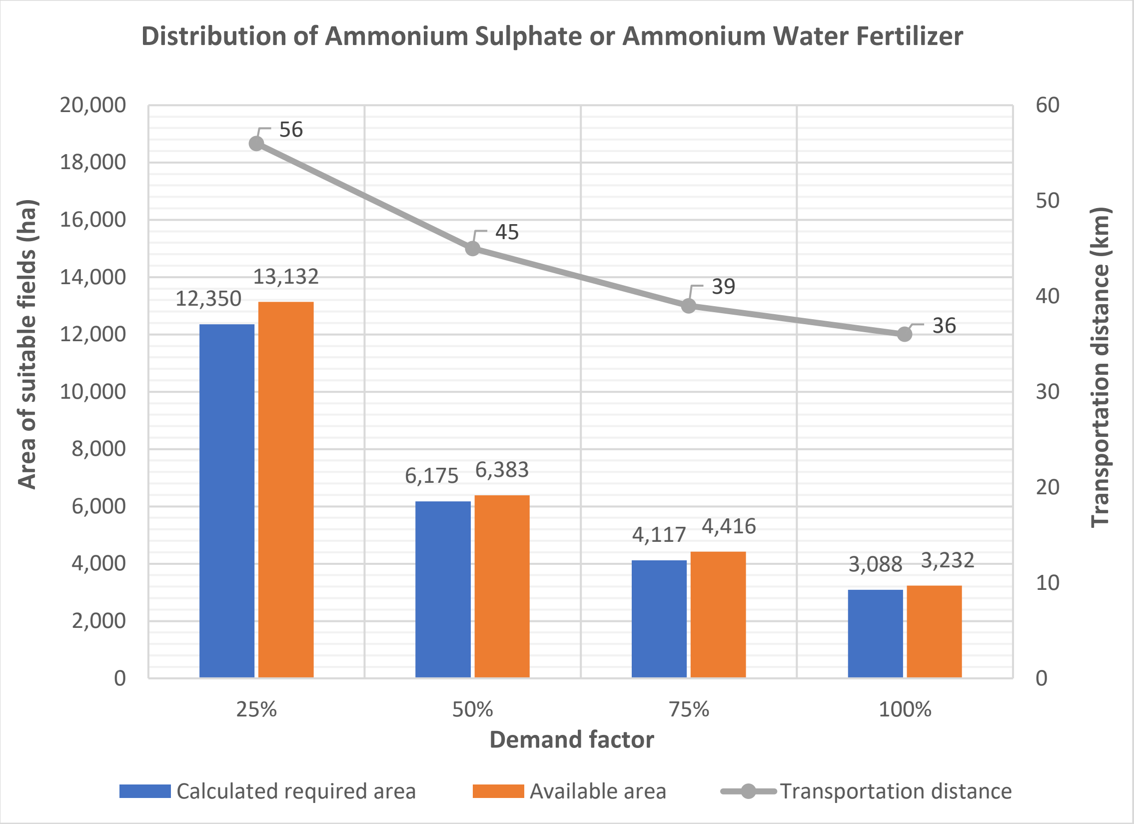


FIGURE 14. Areas of suitable fields required and available for spreading the produced ammonium sulphate or the ammonium water from the combined alternative of stripping and scrubbing. The transportation distance is the longest a delivery truck would need to ride from the biogas plant to the suitable fields (one way). Four scenarios for distributing the products were calculated according to the demand of fertilizer products in the area. Areas of the suitable fields and transportation distances were consulted in the Biomassa-Atlas (LUKE, 2021)

6 DISCUSSION

For the case study, in the valorization route of the solid fraction of the digestate, this would be sent to an external composting facility, where it would be mixed and treated with other co-substrates. The produced compost will comply with the Finnish legislation and can then be used in agriculture, for example, for landscaping (e.g., construction of green areas, landfills covering, infrastructure). This result is consistent with the growing use in landscaping of fertilizer products from sewage sludge (52% in 2016 (Vesilaitosyhdistys, 2017)). The increment is due to the less restrictive legislation than when applying the products in growing fields (Rolamo et al., 2018). Another possibility for the valorization of the solid fraction would be to transport it to other parts of the country with higher P requirements. Although the volumes to be transported are the same in both alternatives, distances and possible gate fees for receiving the solid fraction might vary significantly. The CAPEX and OPEX of the two alternatives should be compared to identify which is more beneficial from the economical point of view. If also the intangible benefits should be considered (e.g., social wellbeing, environmental advantages, economic growth, etc.), then a cost-benefit evaluation would be recommended.

The liquid fraction of the case study can be valorized to produce N – rich fertilizer, ammonium sulphate, or ammonium water. The fertilizer streams were 5, 27, and 52 times more concentrated, respectively, than the original LF input. The higher the concentration of the product to be transported out of the biogas plant, the more beneficial it is from the logistics point of view. The lowest transportation volumes and storage capacity required would be for the ammonium water alternative, followed by the ammonium sulphate, and the less beneficial from the logistics point of view would be the N-rich fertilizer (the less concentrated product). However, it is not possible to conclude that the production of ammonium water (the most concentrated product) would be the best valorization route for this case, because the associated costs for the treatments and the handling of the separated streams were not considered.

Although the tree alternatives were potential valorization routes for the liquid fraction, a cost evaluation would be required to compare and choose the best one.

For example, to the best of the author's knowledge, solutions of ammonium sulphate as the one produced in FIGURE 10 have almost no commercial value in this moment (November 2021) in Finland. According to some technology suppliers, the situation is the same in some parts of the Netherlands and it is due to an oversupply in the market (Driessen & Scheringa, 2021). In that case, it would be needed to calculate if the biogas plant operation is feasible, even when there is not any income from the digestate handling.

The most challenging part when applying the methodology was to clarify the local conditions and the legislation, since they might be interpreted in different ways. For example, according to legislation, it is possible to use digestate products coming from sewage sludge in crops growing beetroot and other plants that are not consumed fresh by humans or animals. However, beetroots are consumed fresh, canned, or frozen in Finland. So, it was not clear if these fields could be considered suitable or not for the case study, and therefore, they were not included in the area calculations. Another difficulty was that most of the information from real biogas plants in the country regarding the valorization of digestate is not public or updated, so comparing the results with current trends or relevant examples was rather difficult.

Contrarily to what was expected, the technical aspect was easy to resolve. During the literature review, several technologies for treating digestate were found and detailed information about them was easily available. From the inventory of technologies considered (Appendix 1), many alternatives were suitable for the raw digestate and the separated solid and liquid fraction of the case study. Once the information was systematically organized according to the decision tree structure, the decision-making process related to the technical aspect was easy and fast to perform.

For the case study, average nutrient needs were assumed for the whole Hanko municipality. Such values were established considering the maximum values permitted by the Finnish legislation and the recommended fertilization ranges from the FAEP. This approach gives a general idea of how the nutrients from digestate fertilizers can be distributed near the biogas plant. But it is also possible to create a more complex mathematical model if more specific data of the area is available, e.g., the areas per type of soils (e.g., clay, mineral, organic), the areas declared as organic farming (which has tighter restrictions for the use of fertilizers), and the available machinery. This will give a more precise idea of the nutrient needs in the municipality and the practicalities when applying the fertilizers, therefore, a better distribution of the products can be planned.

During the development of this thesis, it was noticed that most of the publications consulted were focused in overcoming the technical and the legislative challenges of utilizing digestate products. Less publications addressed the importance of the local market, and only few of them briefly mentioned the great importance of public acceptance. A good understanding of these market conditions is crucial for any biogas plant to find a valorization route that is viable in the long-term. Not considering these aspects since the early phases of a project can result in unrealistic conclusions. However, the drivers for utilizing digestate products do not seem to be heading in the same direction and it is not easy to understand the future of digestate in the country: on one side, digestate production continues to grow as biogas capacity expands. AD treatment is becoming more common for processing controlled substrates (e.g., sewage sludge) due to restrictions in final treatments such as landfilling and incineration. Also, there is a national interest in recycling nutrients and organic material back to the soils, and in promoting more environmental alternatives that improve soil quality and fight against the climate change. On the other side, the legislation for using digestate in agriculture is getting more restrictive, even though, recycled organic fertilizers such as digestate represent only a minor part (about 10%) of all the nutrients applied to the soils in Finland (Rolamo et al., 2018). And public acceptance is not easy to predict even when the final products comply with the legislation.

For example, a malt producer (Viking Malt) and a milling company (Fazer Mills) announced in 2017 - 2018 that they will not purchase grains that have been grown with fertilizer products coming from sewage sludge. They were concerned that these fertilizers might affect the purity (and therefore the image) of their food-grade products, due to accumulation of microplastics and organic pollutants. The decision was adopted during the following years by other mills and lead eventually to a ban of fertilizers from sewage sludge in feed-grain purchase agreements. (Haavisto, 2018). This information should be considered when deciding the final use of digestate that is produced from sewage sludge, because even if the final products comply with the legislation, their demand in agriculture might be quite low. It would be also interesting to consider what is the role of the biogas plant in improving the image of the digestate products among the public. Will this be only a responsibility of the government and the party in charge of placing the final products in the market, or should the digestate producer also help to improve this situation for its own benefit?

Biogas plants are constantly looking for solutions to overcome, also, the challenges of the market. For example, some biogas plants are implementing two processing lines: one for controlled substrates and the other for the rest of the biomasses. In this way, two digestates are produced. Two processing lines allow a major flexibility in the operation and facilitates the valorization of the digestate coming from the no-controlled substrates, since lighter restrictions apply to it. Some of the Gasum’s biogas plants are examples of this approach (Ojala, 2017). In the future, it is also expected a growing implementation of alternatives that recover nutrients in inorganic forms (e.g., ammonium sulphate, ammonium water, struvite pellets, etc.). This is also linked to the public acceptance because fertilizer products that have gone under many or more complex recovery processes are perceived as less risky, with higher purity and less pollutant content. These concentrated inorganic products also have other industrial applications, which makes these alternatives more attractive in the long-term. For digestate products coming from sewage sludge, final use in landscaping is expected to grow in the near future due to less restrictive legislation than when applying in growing fields.

7 CONCLUSIONS

Digestate is the major product coming from the AD process, therefore, valorization of this stream is crucial for any biogas plant to be viable. In this thesis, the methodology (roadmap) was developed for a case study and it included aspects the author considers critical when defining a valorization route. Even though for the case study, the steps of the roadmap were executed in their respective order, in a real case, more iterations among the steps would be required.

For the case study, the solid fraction would be sent to an external composting facility or transported to other parts of the country with higher phosphorus requirements for its valorization in agriculture. The liquid fraction can be used to produce N – rich fertilizer, ammonium sulphate, or ammonium water fertilizers. A cost evaluation is needed to define, among the options, which are the most economical valorization routes for the digestate of the case study.

So far, the valorization of digestate has been mainly focused on overcoming technical and legislative challenges. There has been less discussion about the importance of the local market (including public acceptance). How to interpret the legislation, the limited information available from other Finnish biogas plants regarding digestate, and understanding the market conditions, were the most challenging parts for finding the potential valorization routes for the case study. From the market conditions, public acceptance was especially difficult to clarify since legislation might not affect it, meaning that even if a product complies with the current regulations, final users might be sceptical to use it. Improving digestate image among the public is then crucial for the biogas industry. Performing a market research in the area is highly recommended to understand the case. Not clarifying the market conditions since the early phases of a project can result in unrealistic conclusions and unnecessary work.

The drivers for utilizing digestate products in Finland are at some points contradictory, so the future of digestate valorization in the country is unclear. What can be expected with some certainty is that digestate production will continue to grow and it will be concentrated in industrial and centralized facilities. No biogas plant can predict and control all the factors affecting the valorization of digestate during all the operating years. Nevertheless, having a good understanding of the parameters considered in the roadmap might increase the chances to find a solution that is viable in the long-term.

Some of the current trends for the valorization of digestate include the implementation of two processing lines for different types of substrates, recovery of nutrients in inorganic forms, and the use of digestate products coming from sewage sludge in landscaping.

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APPENDICES

(1/6)

Appendix 1. List of digestate treatments considered and the decision tree evaluation

Table 1. List of the digestate treatments considered in this thesis and the decision tree evaluation. The technology description, final uses, and TRL values were adapted from the inventory of (Guilayn et al., 2020). For the TRL values reported as a range, the average value was used. Location of the treatments was assigned according to the conditions of the case study.

TECHNOLOGY	**DECISION TREE EVALUATION**		
	1. FINAL USE	**2. TRL**	**3. LOCATION**
EVAPO-CONCENTRATION Robust solution to concentrate different digestate streams. Volume and amounts can be concentrated up to 90%. It can serve as hygienization step as well. Depending on the concentration of nutrients and OM[4], it can be used as fertilizer. **INPUT:** liquid fraction or membrane retentates **OUTPUT:** concentrated liquid and condensate	Agriculture	9	On-site
THERMAL DRYING For further water removal of the separated solid fraction. Solid content can be increased from about 15% up to 85%. It promotes TAN[5] volatilization, unless digestate is previously acidified. The dry digestate can be used as soil amendment or further treated for energy production. **INPUT:** solid fraction **OUTPUT:** dried digestate and steam	Agriculture or Energy	9	On-site
STRIPPING + SCRUBBING Used for nutrient recovery. Under favored conditions, the dissolved ammonium is transferred as free ammonia to the gas phase. The separated ammonia is then absorbed in the scrubber using an acidic solution or water. The final solution can be used in agriculture or in industrial processes. **INPUT:** liquid fraction or filtration retentates **OUTPUT:** ammonium salt acidic solution or ammonium water	Agriculture or Industrial uses	9	On-site

CONTINUES

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[4] OM: organic matter

[5] TAN: total ammonia nitrogen

(2/6)

TECHNOLOGY	**DECISION TREE EVALUATION**		
	1. FINAL USE	**2. TRL**	**3. LOCATION**
COMPOSTING Aerobic biological process to biodegrade organic material. It is performed by microorganisms and it requires different co-substrates to work. It generates heat, reaching even 70°C, so it may be used as a hygienization step. The final product is used in agriculture as soil amendment. **INPUT:** solid fraction **OUTPUT:** compost and leachate	Agriculture	9	Off-site
VERMICOMPOSTING Similar to composting, but the degradation is performed by earthworms. Temperature and pH conditions must be controlled so earthworms can survive. **INPUT:** solid fraction **OUTPUT:** vermicompost and leachate	Agriculture	9	Off-site
STRUVITE CRYSTALLIZATION Use to recover P from digestate by precipitating it as struvite ($NH_4MgPO_4 \cdot 6H_2O$). It can recover over 80–90 % of the soluble P and part of the ammonium 10–40 %. It may require an additional source of Mg and alkaline conditions to favor the precipitation of the crystals. The final product is used as fertilizer. **INPUT:** raw digestate or liquid fraction **OUTPUT:** struvite and liquid effluent	Agriculture	9	On-site
K - STRUVITE CRYSTALLIZATION Similar to struvite crystallization, but different operating conditions (pH, temperature, molar ratios, and competitive ions concentrations). **INPUT:** raw digestate or liquid fraction **OUTPUT:** K-struvite (KMgPO4·6H2O) and liquid effluent	Agriculture	9	On-site
Ca – P CRYSTALLIZATION Similar to struvite crystallization, but different operating conditions (pH, temperature, molar ratios, and competitive ions concentrations). **INPUT:** raw digestate or liquid fraction **OUTPUT:** hydroxy-apatite or calcium phosphate mainly and liquid effluent	Agriculture	9	On-site

CONTINUES

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TECHNOLOGY	DECISION TREE EVALUATION		
	1. FINAL USE	**2. TRL**	**3. LOCATION**
COMBUSTION (INCINERATION) This thermal conversion process concentrates the elements that are non-volatile at the applied temperature. Combustion may reach more than 1000°C. The process is used for reducing drastically the volumes of digestate and for producing energy (although the final energy balance can be negative). Moreover, the residual ashes can be used as nutrient source (P, K) for agriculture. **INPUT:** dried digestate (usually pelletized) **OUTPUT:** heat, steam, ashes	Agriculture or Energy	9	On-site
PYROLYSIS OR GASIFICATION Similar to combustion, pyrolysis and gasification are thermal conversion processes. Pyrolysis works in the absence of O_2 at temperatures of 350-600°C. Gasification works with a small amount of oxygen at 800 - 1200°C. The residual solid is called biochar and it can be used as a nutrient source for agriculture. **INPUT:** dried digestate **OUTPUT:** biochar/ashes, bio-oil, syngas, water (liquid phase), heat	Agriculture or Energy	9	On-site
TORREFACTION Similar to combustion, torrefaction is a thermal conversion that occurs in the absence of oxygen at 200-300°C. The residual solid is called torrefied biomass and it can be used as a nutrient source for agriculture or for energy production. **INPUT:** dried digestate **OUTPUT:** torrefied biomass	Agriculture or Energy	8	On-site
PRESSURE DRIVEN MEMBRANE FILTRATION: MF (micro filtration), UF (ultra filtration), NF (nano filtration), RO (reverse osmosis). To concentrate nutrients content from the liquid phase. Also, for cleaning or upgrading the separated water. **INPUT:** pre-treated liquid fraction **OUTPUT:** concentrated retentates and permeate	Agriculture	8	On-site

CONTINUES

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TECHNOLOGY	DECISION TREE EVALUATION		
	1. FINAL USE	**2. TRL**	**3. LOCATION**
DUCKWEED PONDS Ponds of duckweed are used to uptake the nutrients and organic matter from the liquid fraction of digestate. The biomass is then harvested to produce high- value products such as fertilizers and biofuels. **INPUT:** pre-treated liquid fraction **OUTPUT:** harvested biomass and effluent water	Agriculture or Energy	9	Off-site
MICROALGAE PONDS Similar to ponds of duckweed. **INPUT:** pre-treated liquid fraction **OUTPUT:** harvested biomass and effluent water	Agriculture or Energy	7	Off-site
ADSORPTION COLUMNS Used for separating selectively the soluble nutrients (especially TAN and orthophosphates). Nutrients flow through adsorbents mediums and then are recovered (desorption). **INPUT:** pre-treated liquid fraction **OUTPUT:** nutrient rich adsorbent or washing solution with released nutrients	Agriculture	6	On-site
TMCS: TRANSMEMBRANE CHEMISORPTION (Gas-permeable hydrophobic membrane contactors) For nutrient recovery using a hollow fiber membrane (hydrophobic). An acid solution absorbs and recovers the N compounds from the gas phase. **INPUT:** pre-treated liquid fraction **OUTPUT:** concentrated N – stream	Agriculture	6	On-site
EXTRACTION OF SOLUBLE ORGANIC MATERIAL Humic like substances are complex organic compounds generated naturally from the degradation and reorganization of OM. In the industry, they are commonly extracted from fossil sources. A strong alkalinization of digestate allows to solubilize these humic-like acids for subsequent recovery. **INPUT:** treated raw digestate (alkaline) **OUTPUT:** compost	Agriculture	6	On-site

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TECHNOLOGY	DECISION TREE EVALUATION		
	1. FINAL USE	**2. TRL**	**3. LOCATION**
ED: ELECTRODIALYSIS Nutrient recovery by the selective separation of negatively and positively charged molecules. **INPUT:** pre-treated liquid fraction **OUTPUT:** treated effluent, aniolitic effluent, catiolitic effluent	Agriculture	5	On-site
BES: BIO-ELECTROCHEMICAL SYSTEMS Nutrient recovery. Ammonium ions can migrate or diffuse across the ion exchange membrane. In theory, this ammonia recovery has a positive energy balance. **INPUT:** pre-treated liquid fraction **OUTPUT:** energy production	Agriculture or Energy	5	On-site
TURBULENT MIXING + SCRUBBING Nutrient recovery. A flow of air bubbles is injected to mix exhaustively the digestate for stripping out the N compounds. The separated ammonia is then absorbed in the scrubber using an acidic solution or water. **INPUT:** raw digestate **OUTPUT:** ammonium salt acidic solution or ammonium water	Agriculture	4	On-site
HTC (hydrothermal carbonization), VTC (vapothermal carbonization), HTL (hydrothermal liquefaction), HTG (hydrothermal gasification) Hydrothermal processes are divided into three: below 250°C, it is known as hydrothermal carbonization. The main product is a hydrochar which has a similar property to that of a low rank coal. Between 250 and 370°C, the process is defined as hydrothermal liquefaction resulting in the production of a liquid fuel known as biocrude. Biocrude is similar to petroleum crude and can be upgraded to the whole distillate range of petroleum derived fuel products. Above 370°C, gasification reactions start to dominate and the process is defined as hydrothermal gasification, resulting in the production of a synthetic fuel gas. The differences between hydrothermal and vapothermal carbonization are the reaction medium (liquid water and saturated vapor respectively). **INPUT:** raw digestate or solid fraction **OUTPUT:** biochar/ashes, bio-oil/biocrude, syngas, heat	Energy	8	On-site

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TECHNOLOGY	DECISION TREE EVALUATION		
	1. FINAL USE	**2. TRL**	**3. LOCATION**
TRANSTERIFICATION Digestate is used to grow lipid-accumulating biomass such as microalgae. Once harvested, vegetable lipids, oils, and fats inside the biomass are transformed to biodiesel in a transesterification reaction. **INPUT:** pre-treated liquid fraction **OUTPUT:** biodiesel	Energy	7	Off-site
SACCHARIFICATION After biomass harvesting, obtained OM is post-treated to release carbohydrates, which can be further use to energy valorization (bioethanol, biohydrogen, biogas). **INPUT:** pre-treated liquid fraction or pre-treated solid fraction if rich in residual fibers **OUTPUT:** precursors for biofuel production via fermentation or anaerobic digestion	Energy	7	Off-site
FERMENTATION PROCESSES Residual carbohydrates in the digestate (normally in recalcitrant compounds such as lignin) are treated so there is access to the monomer sugars. Alkaline, enzymatic, or thermochemical treatments are used before fermentation to hydrolyze the residual fibers. Depending on the inoculation, biofuels can be produced (e.g., methanol, ethanol). **INPUT:** pre-treated raw digestate **OUTPUT:** biofuels	Energy	6	On-site
FERMENTATION PROCESSES Same as before. Depending on the inoculation, high – value products can be developed (e.g., bioplastics). **INPUT:** pre-treated raw digestate **OUTPUT:** depending on the inoculation	Industrial uses	3	On-site
SIMULTANEOUS SACCHARIFICATION AND FERMENTATION After biomass harvesting, obtained OM is post-treated to release carbohydrates, which can be further use to produce sugars, alcohols, and other high-value products. Depending on the inoculation, high – value products can be produced (e.g., biopesticides or biosurfactants). **INPUT:** pre-treated raw digestate **OUTPUT:** depending on the inoculation	Industrial uses	3	Off-site

Appendix 2. Limits for fertilizer products in Finland

Table 2. Limits for harmful metals and hygienic quality in fertilizers according to the Finnish legislation (MMM, 2011).

LIMITS	ANALYSIS	VALUE	UNIT
Heavy metals	Arsenic (As)	25	mg/kg DM
	Cadmium (Cd)	1,5	mg/kg DM
	Chromium (Cr)	300	mg/kg DM
	Copper (Cu)	600	mg/kg DM
	Mercury (Hg)	1	mg/kg DM
	Nickel (Ni)	100	mg/kg DM
	Lead (Pb)	100	mg/kg DM
	Zinc (Zn)	1,500	mg/kg DM
Hygiene	*E. Coli*	1,000	CFU/g
	Salmonella	Not detected	

Appendix 3. EU and Finnish regulations for fertilizer products

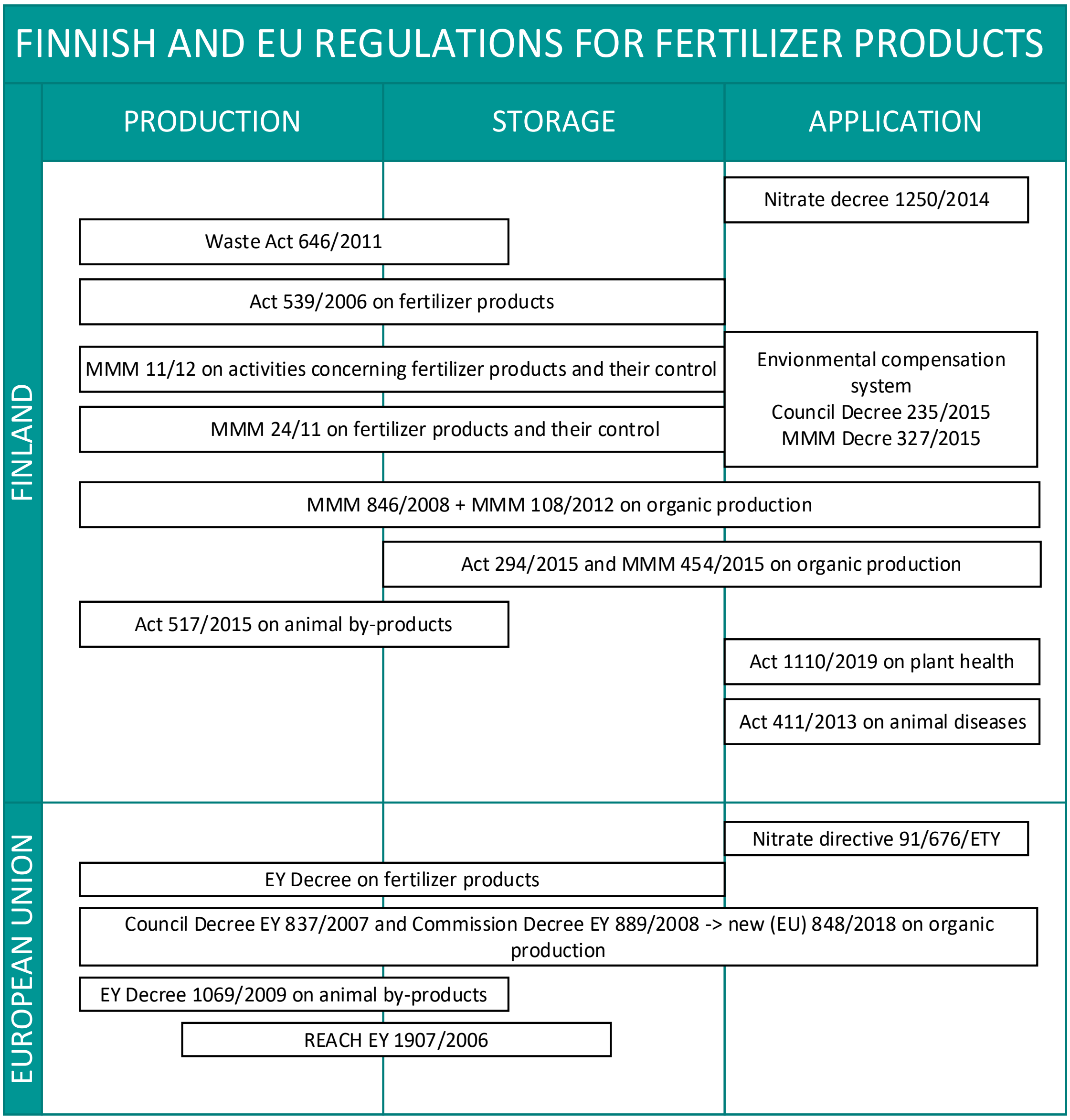

FIGURE 1. Summary of Finnish and EU regulations that apply for fertilizer products according to the scope in the supply chain. Figure adapted from (Kuutti, 2020).

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Appendix 4. Examples of transport distances of digestate products

Table 3. Examples of transportation distance of digestate products.

EXAMPLE	SCOPE	DISTANCE	REFERENCE
Viikinmäki WWTP	Solid fraction to Metsäpirtti composting field in Sipoo	• 40 km	(HSY, 2018)
Mäkikylä biogas plant, Finland	Solid fraction to Kymenlaakson Jäte Oy	• 15 km	(Ojala, 2017)
Case study of a full-scale biogas plant in Greece	Liquid fraction pumped by pipeline to local farmers and solid fraction transported to nearby fields	• 4 km LF[6] • 10 km SF[7]	(Spyridonidis et al., 2020)
Case study of centralized biogas plants in Croatia	Maximum viable distance for digestate products and manure	• 10 km	(Pukšec & Duić, 2012)
Case study of two biogas plants near Regensburg, Germany	Maximum viable distance for liquid fraction transported with 90 kW tractors	• 6,0 km[8] • 7,5 km[9]	(Möller et al., 2010)
Case study of two biogas plants near Regensburg, Germany	Maximum viable distance for solid fraction transported with 70 kW tractors	• 7,0 km[10] • 8,5 km[11]	(Möller et al., 2010)

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[6] LF: liquid fraction
[7] SF: solid fraction
[8] Dry matter content 5%
[9] Dry matter content 10%
[10] Dry matter content 20%
[11] Dry matter content 25%

EXAMPLE	SCOPE	DISTANCE	REFERENCE
Case study of a biogas plant in Netherlands	Maximum viable distance for raw digestate	• 15 – 25 km	(Poliafico & Murphy, 2007)
Study of forest wood and manure transport chains in Switzerland	Raw, liquid, and solid fractions transportation distances. The higher the dry matter content of the material, the longer the transportation distance	• 3 – 10 km	(Schnorf et al., 2021)
Technology provider	Maximum viable distance for raw digestate	• 5 – 10 km	(NAWROCKI, 2021)

Appendix 5. Procedure to use the Biomassa-Atlas tool

1. Go to: https://biomassa-atlas.luke.fi/?lang=en#
2. Open the *Biomasses* menu
3. Choose the *Potential* tab
4. Chose the *Land cover* option
5. Scroll down until the title *Field land use 2018, ha.* Open the drop-down menu *Utilized agricultural area*.
6. Choose the suitable fields that apply according to the case
7. Close the main menu (*Biomasses*) to return to the map
8. Go to the menu *Region selection tools* and choose the option *The centre of a circle or road network*
9. Select the reference point in the map (location of the project)
10. Choose the option *Distance along a road network (accessibility)*
11. Write the distance to be evaluated (maximum distance along roads in the tool can be 65 km)
12. Click in *Calculate* button
13. The report is shown in the screen and can be printed in other formats if needed (i.e., sheet of Excel)
14. Press *Quit* to start a new iteration

Appendix 6. Areas and transport distances for distributing the N – rich fertilizer

Table 4. Areas and transport distances required for using the N – rich fertilizer from the evapo-concentration alternative, according to the demand factor. Areas of the suitable fields and transportation distances were consulted in the Biomassa-Atlas (LUKE, 2021)

	UNITS	**DEMAND OF PRODUCTS FOR AGRICULTURE**			
Demand factor	%	25	50	75	100
Calculated required area	ha	20 416	10 208	6 805	5 104
Suitable fields					
Winter wheat	ha	908	613	283	229
Spring wheat	ha	6488	3044	1993	1370
Spring rye	ha	3	0	0	0
Rye	ha	1271	903	700	499
Other barley	ha	3300	1760	1165	940
Malting barley	ha	3906	2208	1414	1123
Oats	ha	3262	1705	1224	880
Mixed cereals	ha	93	28	0	0
Whole crop cereals	ha	24	13	13	13
Other oil crops	ha	0	0	0	0
Fiber and energy plants	ha	53	53	53	51
Available area	**ha**	**19 308**	**10 327**	**6 845**	**5 105**
Transport distance	**km**	**65**	**53**	**47**	**42**

Appendix 7. Areas and transport distances for distributing ammonium sulphate or ammonium water

Table 5. Areas and transport distances required for using the ammonium sulphate or the ammonium water from the combined option of stripping and scrubbing, according to the demand factor. Areas of the suitable fields and transportation distances were consulted in the Biomassa-Atlas (LUKE, 2021)

	UNITS	**DEMAND OF PRODUCTS FOR AGRICULTURE**			
Demand factor	%	25	50	75	100
Calculated required area	ha	12 350	6 175	4 117	3 088
Suitable fields					
Winter wheat	ha	750	264	229	217
Spring wheat	ha	4024	1772	1186	799
Spring rye	ha	3	0	0	0
Rye	ha	1054	652	423	341
Other barley	ha	2275	1082	792	520
Malting barley	ha	2725	1361	964	654
Oats	ha	2173	1186	760	640
Mixed cereals	ha	62	0	0	0
Whole crop cereals	ha	13	13	11	11
Other oil crops	ha	0	0	0	0
Fiber and energy plants	ha	53	53	51	50
Available area	**ha**	**13 132**	**6 383**	**4 416**	**3 232**
Transport distance	**km**	**56**	**45**	**39**	**36**