VALORISING ORGANIC WASTE STREAMS FROM FOOD VALUE CHAIN BY ANAEROBIC DIGESTION

Lappeenranta–Lahti University of Technology LUT
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ABSTRACT

Lappeenranta–Lahti University of Technology LUT
LUT School of Energy Systems
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Circular Economy

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Valorising organic waste streams from food value chain by anaerobic digestion

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The purpose of this thesis is to increase understanding related organic waste and residue streams and their valorisation potential throughout the food value chain. Food value chain consists of large amount of organic material flows, which can be treated by using anaerobic digestion in order to produce biogas and biofertilizers. This research is written in order to increase knowledge about the potential of organic waste streams in the raw material of biogas and biofertilizers as well as the role of biogas and biofertilizers in green transition, and how fossil energy and mineral fertilizers can be replaced by renewable energy and recycled fertilizers.

The second key goal of this work is to assess the economic profitability of a biorefinery that produces biogas and recycled fertilizers from the waste streams of the food system, and the effect of different inputs on the plant's methane and nutrient yields, and on the other hand, the effect of the raw material used on the plant's profitability. Key finding of this study is that sales of biomethane and gate fees have essential role and on contrary, sales of biofertilizer has only a minor role in the profitability of biogas plant.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT
LUT Energiajärjestelmät
Ympäristötekniikan koulutusohjelma
Circular Economy

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Arvon luominen ruoka-arvoketjun orgaanisten jätevirtojen anaerobisella mädätyksellä

Diplomityö

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75 sivua, 15 taulukkoa ja 8 kuvaa

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Hakusanat: biokaasu, kierrätyslannoite, orgaaniset jätevirrat, jätehuolto

Tämän diplomityön tarkoitus on lisätä ymmärrystä ruoka-arvoketjun orgaanisista jäte- ja sivuvirroista sekä niiden hyödyntämispotentiaalista läpi koko arvoketjun alkutuotannosta ruokajätteeseen. Ruoka-arvoketju sisältää laajan määrän orgaanisia materiaalivirtoja, jotka voidaan käsitellä anaerobisella mädätyksellä biokaasun ja kierrätyslannoitteiden valmistammiseksi. Työn tarkoitus on lisätä ymmärrystä biomassojen, varsinkin jäteperäisten, potentiaalista biokaasun ja lannoitteiden raaka-aineena sekä biokaasun ja biolannoitteiden roolista fossiilisen maakaasun ja mineraalilannoitteiden korvaajana.

Tämän työn toinen keskeinen tavoite on arvioida biokaasua ja kierrätyslannoitteita ruokajärjestelmän jätevirroista valmistavan biojalostamon taloudellisen kannattavuuden arviointi ja erilaisten syötteiden vaikutus laitoksen metaani- ja ravinnesaantiin sekä toisaalta käytetyn raaka-aineen vaikutus laitoksen kannattavuuteen. Työn keskeisenä löydöksenä voidaan todeta, että biokaasulaitoksen kannattavuuden näkökulmasta biokaasumyynnillä ja porttimaksuilla on merkittävä rooli, kun lannoitemyynnillä on ainoastaan pieni merkitys.

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LIST OF SYMBOLS

CH_4	Methane
CO_2	Carbon dioxide
H_2S	Hydrogen sulphide
K	Potassium
N	Nitrogen
NH_3	Ammonia
P	Phosphorous

Abbreviations

AD	Anaerobic digestion
GHG	Greenhouse Gas
CHP	Combined heat and power
COD	Chemical oxygen demand
FM	Fresh matter
OFSM	Organic fraction of municipal solid waste
OLR	Organic loading rate
TS	Total Solids
VS	Volatile Solids
FM	Fresh matter

1 INTRODUCTION

This research is made in order to understand organic waste streams from food value chain, and their valorisation potential into renewable energy and biofertilizers by using anaerobic digestion. Other purpose of this thesis is to evaluate economic feasibility of biorefinery for treatment of organic waste from food value chain, recovering energy and close the nutrient loops by producing biofertilizers from the digestate into the Finnish markets.

1.1 Background

Fight against climate change needs rapid change towards more sustainable use of natural resources. Annual greenhouse gas emissions in 2019 were totally approximately 59 Gt, most of which consisted of carbon dioxide about 38 Gt and methane about 11 Gt and in addition smaller amounts of other greenhouse gases (IPCC, 2022). By replacing fossil fuels such as natural gas to biogas made from organic waste and residues, it is possible to mitigate carbon dioxide emissions and solve waste problem. On the other hand, more effective treatment of organic waste streams from food value chain, especially from agriculture, helps to mitigate amount of methane emissions. Mulvaney sees biological processes as a potential energy source for decarbonization (Mulvaney, 2020, 132). However, cultivation raw materials for biofuel purpose have negative impacts to land-use and water balance and this perspective is too often forgotten in the biofuel discussion. By using biogas made from waste and side streams, greenhouse gas emissions can be reduced by up to 90% compared to fossil fuels, when the entire value chain from biowaste to final use is taken into account. (Gasum, 2022). On the other hand, by using digestate as a biofertilizer, it is possible to close nutrient loops and decrease the need of mineral fertilizers in agriculture. Rockström et al. (2009) mentioned more than ten years ago that use of phosphorous and nitrogen is about on the limit of planetary boundaries. The focus of this research is on the anaerobic digestion of organic waste and residual streams in the food value chain for their utilization into biogas and biofertilizers.

Current geopolitical environment drives countries to be more independent related to energy and natural resources. Anaerobic digestion to convert organic waste and other biomass into biogas and biofertilizers can be one option to increase energy and food security and reduce dependence on fossil fuels and mineral fertilizers. In addition to renewable energy, in this case biogas, biofertilizer production from digestate brings additional income to the biorefinery and, on the other hand, help to close nutrient loop and mitigate nutrient leaching to natural water bodies. From an economic point of view, the rise in energy and fertilizer prices as well as tightening environmental targets opens new business opportunities in the field of circular economy.

Organic waste can be used directly in land application, animal feed or combustion; it can be treated by biological processes, such as composting, vermicomposting, black soldier fly treatment, anaerobic digestion, or fermentation; with physico-chemical treatment, in other words, transesterification or densification, or with thermo-chemical treatment, such as pyrolysis, liquefaction or gasification. (Lohri et al., 2017) This research will focus to biological treatment and more specifically to anaerobic digestion. Valorising organic matter by anaerobic digestion it is possible to produce two kinds of valuable products. At first, renewable energy in the form of biogas which can be directly used in cooking fuel or heat and electricity production, or it can be upgraded into biomethane (CH_4) to replace natural gas in vehicle and industrial use. Another valuable product of the process is nutrient-rich digestate, which can be used for soil improvement purposes and to replace mineral fertilizers in agriculture. Both main products help to reduce the use of fossil energy and the extraction of mineral nutrients.

According to Finnish Natural Resource Center, LUKE, biogas production in Finland could be ten times higher than the current production, if agricultural residues were used more efficiently (LUKE, 2022). In terms of waste management, anaerobic digestion on the one hand reduces the incineration and landfill of organic waste, and on the other hand stabilizes it into digestate. This research focuses on the treatment of organic waste streams from the entire food value chain, from field to food waste. However, due to the advantages of scale, other biomass options for feeding an industrial-scale biogas plant and balancing the anaerobic digestion process are also briefly discussed.

Food loss during the food value chain is significant. Approximately 50 per cent of food waste is generated between food production and retail. However, most of the studies are focused to understand food waste generation from household perspective. (Van Bemmel and Parizeau, 2020) This research focuses on creating a comprehensive picture of the utilization of organic waste streams throughout the entire food value chain, from fields to food waste.

In the country level, Finland's target is to be carbon neutral in the year 2035, to be World's first fossil-free welfare society, and Finland will strengthen carbon sinks and stocks in the short and long term (TEM, 2019). Anaerobic digestion as a treatment of organic wastes and residues, and on the other hand, produce renewable energy and biofertilizers, could be the one potential path to decrease greenhouse gas emissions and reach these targets.

1.2 Objective of the research and contents

The aim of this study is to increase understanding on different organic waste and residue streams in the food value chain from a waste management perspective and find more effective solutions for organic waste treatment. In addition, the study evaluates the profitability of a biorefinery for valorising organic wastes and residues into biogas and biofertilizers using an anaerobic digestion process.

The purpose of this thesis is to find more sustainable and value adding solutions for treatment of organic wastes and residue streams throughout the entire food value chain. This research will, on the one hand, discuss energy recovery potential by using anaerobic digestion, and on the other hand, find solutions to close nutrient loops by recovering nutrients from the organic waste and residues in order to produce biobased fertilizers to replace synthetic fertilizers.

Information related to the availability and composition of different raw material options, the investment-, and operating costs of the biorefinery, and the quantities and values of end products such as biomethane and biofertilizers are collected from existing literature and public sources regarding previous similar investments. Due to these limitations, the results and assumptions may be quite rough in some places. Therefore, information of this study is not accurate enough for an investment decision, and more calculations are needed.

This study focuses on the treatment process and the value of its main products such as biogas and biofertilizers in the end market. Waste collection and raw material logistics have not been included in the calculations. However, the optimal transportation of the raw material must be taken into account when evaluating the environmental effects and the economic profitability of the waste management process. Economic assessment of biorefinery in the Uusimaa region in Southern Finland is presented in the case example chapter. That chapter also discuss availability of potential feedstock in the chosen area and market potential of end-products in the Finnish markets.

2 ORGANIC WASTE VALORISATION PROCESS

Converting biomass into different biological products and biofuel is a sustainable option for organic waste management from different sources for example agricultural and cattle waste, food waste, kitchen waste, green waste, seaweed, algal biomass, sewage sludge, agro-industries, forestry-industries, and other industries which generates degradable organic waste (Jain et al., 2022). In order to achieve environmental goals related to greenhouse gas emissions and dependence on fossil fuels, the development of bioenergy plays an essential role. In the discussion about raw materials for biofuels, biomass residues from agriculture and industry as well as the organic fraction of municipal solid waste are raised as promising alternatives. Compared to the cultivation of energy crops, the use of organic waste and residues as raw material minimizes the competition for land use between food and energy. (Tabatabaei and Ghanavati, 2018, 35) In addition, anaerobic digestion is a promising technology to synchronize human activities and natural cycles by degrading organic matter and convert it to renewable energy and organic fertilizers for agriculture (Ruggeri et al., 2015, 161).

In the anaerobic digestion process, microorganisms decompose biodegradable material into biogas and digestate, which can be used for nutrient recovery or removal (Alengebavy et al., 2022). Anaerobic digesters have two key roles in society. On the one hand, it produces clean energy, in other words, biogas, and on the other hand, it sanitizes organic waste and sludge. Biogas has typically been used in the production of heat and electricity by burning it in CHP generators. Biogas can also be refined into pure biomethane, which can be used to replace natural gas. Biomethane can be injected into the gas network, pressurized to a container, or liquefied. Sanitized nutrient rich digestate can be used as a biofertilizer and it can replace mineral fertilizers. In this way, biogas plants can be seen as a biorefinery that produces heat, electricity, biofuel and biofertilizers. (Pasini et al., 2019)

2.1 Potential feedstock options

This study focuses on biogas and biofertilizer potential for organic waste and residue streams throughout the food value chain. Waste streams from agriculture, food processing, food waste, including source separated biowaste are included in the study. Those waste streams can be treated on the one hand, in decentralized biogas plants located to farms or industrial plants, or on the other hand, in centralized industrial scale biorefineries. This thesis discusses about industrial scale solutions, therefore also other biomass options to complete organic waste and residue streams for anaerobic digestion process are discussed due to higher need of feedstock, and on the other hand, due to high logistics costs, industrial scale biogas plant for one specific feedstock is usually not economically profitable.

In the decision related to feedstock selection for biogas plant, requirements of legislation should be taken in account. Legislation sets restrictions on the one hand, for sanitization of substrate, and on the other hand, used feedstock might affect to useability of digestate as a fertilizer. In the sanitizing process, the material is heated as required by legislation. In most cases, it is sufficient to crush particle size into 12 mm and heat the material to 70 °C for an hour, if it is animal-derived material of 3rd class according to the by-product regulation, for example biowaste. Pressure sterilization (temperature 133 °C, pressure 3 bar, least 20 min, particle size less than 50 mm) is required for 2nd class animal by-products, for example slaughterhouse waste. (Tampio et al. 2018)

Deng et al. (2020, 109) defines five different feedstock types for biogas production, which are animal waste, crop straws, industrial wastes, municipal wastes, and aquatic plants. Lee et al. (2021) discussed that AD process can use wide variety organic waste as a substrate, including agricultural residue, animal manure, horticultural waste, and the organic fraction of municipal solid waste, which includes food waste. According to Koul et al. (2022) large variety of different biomass options including manure, industrial waste, household wastes, sewage sludge, energy crops and crop residues can be used as a raw material in biogas production. In addition to agricultural wastes, organic wastes and residues from the whole food supply chain are potential raw materials for anaerobic digestion (Garcia and You, 2017). In this research feedstock options from food value chain are divided three groups as presented in figure 1: agricultural waste and residues including both plant- and animal-based wastes and residues, food waste including source separated biowaste, in other words, organic fraction of municipal solid waste, and industrial biowaste which includes both solid organic wastes and residues as well as liquid organic sludges. In addition, other possible biomass options to complete and balance substrate are shortly discussed in the end of the chapter. Outside the food value chain, sewage sludge plays a key role as raw material for biogas plants and sewage sludge is presented separately from other biomass options in its own chapter.

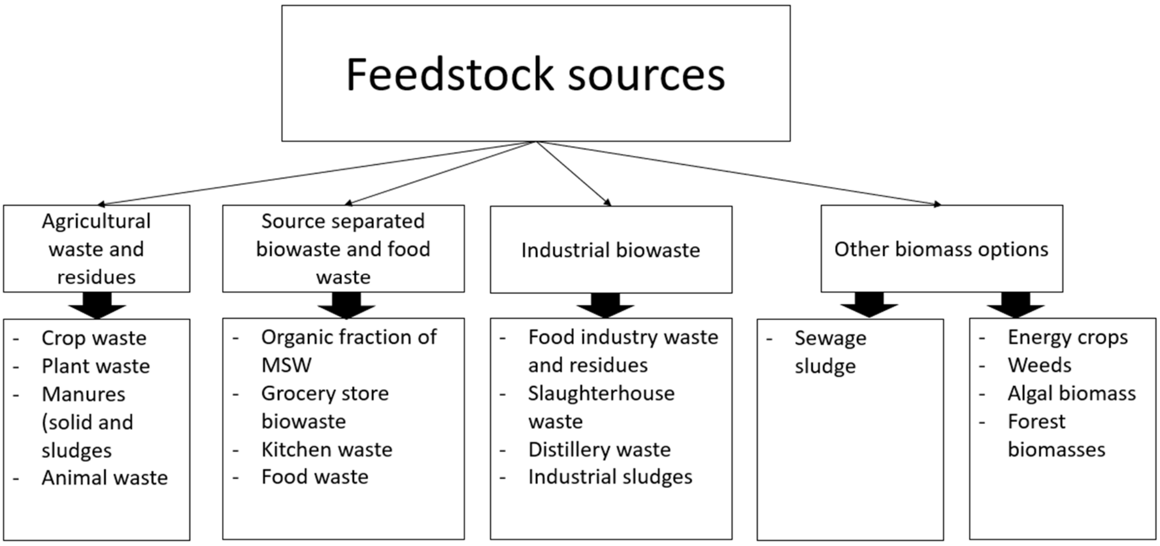

Fig. 1. Potential feedstock options (Modified from Jacob et al., 2020, 78)

2.1.1 Agricultural waste and residues

Agriculture is a significant producer of plant and animal organic waste and side streams, such as animal manure and sludge, surplus fodder, or plant residues, which all can be used in the production of biogas and biofertilizers (Al Seadi et al., 2008; Kymäläinen and Pakarinen 2015, 32–33; Koul et al., 2022). Annual biogas production in Finland is currently 1 TWh (Suomen Biokierto ja Biokaasu ry, 2022) According to the Finnish Natural Resources Agency, annual biogas production could be up to tenfold if agricultural waste and residual streams were used more efficiently in biogas production (LUKE, 2022). Despite the low economic value of agricultural residues, they play an important role in the circulation of carbon and mineral resources. Agricultural waste can be recycled directly on site, or it can be collected and transported to a biogas plant to produce biogas and biofertilizers. (Du et al., 2018) In this study, agricultural waste includes both animal and plant-based waste streams from agriculture. Agriculture also generates relatively high amount of other nonorganic waste streams, for instance plastics. However, this study only focuses on organic waste streams and other waste streams are excluded from the study.

Plant-based biomass can be cultivated energy plants on the one hand, or organic waste and side streams on the other. In Finland, grass has the greatest potential among cultivated energy crops. Compared to other energy crops, green fallow biomass, which not competing against other usage, can be sustainable option as a feedstock for biogas production. On the other hand, agriculture generates remarkable amount of plant-based side streams, for example straw, which can be used as a feedstock for anaerobic digestion. (Kymäläinen and Pakarinen, 2015, 37-38) The focus of this study is on the treatment of organic waste and residues, which is why the use of cultivated energy crops as the main substrate is not covered in this study. However, the study briefly examines the role of energy plants and other possible biomass options as supplements and stabilizers of the anaerobic digestion process. The usability of plant-derived biomasses in the anaerobic digestion process depends on their composition, and the most important characteristics are the ratio of total solids to volatile solids (TS/VS), fibre properties and nitrogen content. (Kymäläinen and Pakarinen, 2015, 38)

Two main components of the animal-based organic wastes in the agriculture are solid and liquid manure. Solid manure includes manure and beddings, while liquid manure includes manure, urinary waste, and wastewater. Without proper treatment, manure contaminates air and water systems. In terms of the water body, the most important disadvantages are the contamination of the water by pathogens and the leaching of nutrient-rich sludge into the water body. On the other hand, manure releases carbon dioxide and methane into the atmosphere, both of which are strong greenhouse gases. (Koul et al., 2022) From an environmental perspective, AD treatment of animal-based wastes such as manure could help reduce nutrient leaching into water, acidification of natural water systems, and water ecotoxicity (Burg et al., 2018). Anaerobic digestion for processing animal manure is on the one hand, a promising source of biomethane, and on the other hand, an effective way to reduce negative external effects, such as nutrient pollution (Cowley and Brorsen, 2018).

The methane yield of manure is not very high, because most of the easily degradable materials have already been used in animals' digestion (Kymäläinen and Pakarinen 2015, 34-37). However, stabile availability and good buffering capacity, makes it interesting substrate for co-digestion with other organic materials. Animal manure from pig, poultry and cattle farms can be significant carbon source in biogas production. Moisture content of the animal manure can be as high as 90 % and it is ideal substrate due its good buffering capacity. Nutrient content of the manure does not reduce significantly in the anaerobic digestion process and the digestate can be used as a fertilizer. Due to high nitrogen content of manure affects to C/N ratio and manure is most suitable feedstock for co-digestion with matters with high carbohydrate content. (Chozhavendhan et al., 2020, 116)

The profitability and biogas yield of biogas plants containing only manure is weak compared to biogas plants whose raw material consists of primary products, such as energy plants or biowaste. This is mainly since the organic matter of the manure has already been used once in animal digestion. Pig manure the potential is slightly better than that of cattle manure, which can be seen in plants utilizing pig manure slightly better profitability. Increasing the scale reduces the unit costs of production and improve profitability. The income of biogas plants whose earning logic is based on gate fees develops more stably and is easier to forecast than plants where the only income stream consists of the sale of biogas. (Luostarinen et al. 2019)

Also, on farm animal carcass might be completing feedstock for anaerobic digestion. However, animal carcass is animal-based by-product, and the legislation set up requirements for its pre-treatment and sanitation as well as the use of digestate as a fertilizer. (Kahiluoto et al., 2011)

In addition to agriculture, also aquaculture generates suitable organic waste streams for anaerobic digestion. Organic waste streams from fish farming, especially found in inland farms, includes sludge removed from fish tanks and dead spoiled fishes (Finnish Ministry of Environment, 2020).

2.1.2 Source separated biowaste and food waste

In this study definition of food waste consists of both categories, on the one hand food not intended for consumption, in other words inedible, such as bones and vegetable peels, and on the other hand, food originally intended for consumption, in other words edible, such as food not used as human food, feed or other value-added products (Riipi et al., 2021). Due to high variety of composition of food waste, it is quite hard to identify exact shares of different components due to heterogenous composition of biowaste (Paritosh et al., 2017). High variety of composition of feedstock affects to process stability and on the other hand, increases the variety in the production of end-products, biogas and biofertilizers.

Annual generation of food waste in Finland is approximately 360 000 t, and in addition, if harvest left in the field is included, the total amount of food waste is nearly 700 000 t (Riipi et al., 2021. For a comparison, globally annual generation of food waste is approximately 1.3 billion tonnes of edible food waste (FAO, 2013). Approximately 17 % of global food production is wasted and largest part of it 11% is lost in households, 5% in food services and 2% in retail. In addition, 14% of food production is lost between harvest and retail (UN, 2022). These numbers show clearly how huge problem food waste is in global as well as in national level.

According to Statistics Finland total amount of source separated biowaste in year 2020 was 494 279 tonnes and more than 80 % of it was treated by aerobic or anaerobic digestion. In addition, municipal solid waste consists of approximately 40 % organic waste, which can be treated by using anaerobic or aerobic digestion (OSF, 2021). However, it is important to notice that if the organic fraction of mixed waste is directed to the anaerobic digestion process, it will negatively affect the use of the digestate as biofertilizer.

2.1.3 Industrial biowaste

In addition to food waste and agricultural residues, industrial biomasses provide huge potential as a raw material for renewable energy and biofertilizers. Especially food, drink, fodder, beverage, and slaughterhouse industries, as well as other industries which uses biomass as a raw material, generates organic waste and residue streams which are potential feedstock for biogas production. This also justifies the essential role of biogas production in future's biorefineries. (Kymäläinen and Pakarinen, 2015, 43) Anaerobic digestion is suitable and widely used technology to treat organic fraction of industrial wastes and residues. Anaerobic digestion treatment can improve economic and process efficiency, produce renewable energy, stabilize organic materials, and close the nutrient cycles. (Ortner et al., 2013, 111)

Also, in industrial processing of agricultural products, a considerable amount of agricultural industry waste is generated, which is a valuable raw material for biorefineries. In addition to these, the food industry produces large amounts of liquid, gaseous and solid waste throughout the entire manufacturing process. Improper treatment of these side streams causes greenhouse gas emissions and global warming, as well as wasting valuable bio-resources. Instead, these material flows could be used as raw material for value-added products, such as biofuels, biofertilizers and other bio-based products. Most of the organic waste streams from the food industry are relatively homogeneous and are rich in carbohydrates, proteins, lipids, and minerals, making them a valuable raw material for anaerobic digestion to produce biogas and biofertilizers. The recovery of these material flows as material and renewable energy would have both economic and environmental benefits. (Jacob et al., 2020, 77)

Industrial wastes and residues have wide variety of organic matter which is useable in biogas production. Due to high variety of different materials, methane yield and pre-treatment requirements varies a lot. However, compared to solid fraction of municipal solid waste, substrate from industrial residue and waste streams are more homogenous which leads to more stable AD process. (Kymäläinen and Pakarinen, 2015, 44) Industrial greases and sludges usually contain relatively low solids concentrations, but on the other hand, the proportion of organic matter in them is usually relatively high (Kymäläinen and Pakarinen, 2015, 55).

2.1.4 Sewage sludge

Sewage sludge can be treated by using different methods such as landfill, incineration, land reclamation, composting, pyrolysis, gasification, or anaerobic digestion. Sewage sludge contains of both, organic matter and nutrients and it can be used as a fertilizer. In addition to increasing fertilizer value of sewage sludge, anaerobic digestion has also other benefits. Compared to raw sewage sludge, digestate is more stable, pathogen free and treatment increases to nutrient availability for plants. (Pigoli et al. 2021) Sewage sludge from wastewater treatment plants are potential feedstocks for biogas production. Typically, these sludges are treated biogas reactors which are located besides of wastewater treatment plants. Wastewater sludge can also be treated in co-digestion with other organic materials, for example municipal biowaste. However, co-digestion in separate biogas plants requires transportation of sludge. (Kymäläinen and Pakarinen, 2015, 41)

From the biogas production point of view, sewage sludge is useable raw material for anaerobic digestion. It also has relatively high methane yield, which varies between 160 and 400 $l/kg_{VS.}$ Sewage sludge also includes significant amount of nitrogen and phosphorous. Nitrogen content varies between 35 and 60 kg/t_{TS}, and phosphorous content varies between 20 and 35 $kg/t_{TS.}$ However, the use of digestate is more challenging, due to unwanted contents. (Kymäläinen and Pakarinen, 2015, 43) If substrate consists of least 10 % of sewage sludge following limitation as a fertilizer use should be taken account: the harmful substance and heavy metal content limits of the fertilizer must not be exceeded, the pH of the farmland must be at least 5.8, may only be used on farmland where, for example, grain, sugar beet, oil plants or other such plants are grown that are not used for food fresh, by eating the underground part or as animal feed, for grass only if it is established with cover crop, and in addition, 5 years after the end of use, during which only the above-mentioned products can be cultivated. (Pyykkönen et al. 2018)

2.1.5 Other biomass options

In addition to waste and residue streams discussed in earlier, also large variety of other biomass options can be used in AD process. Other types of biomasses such as algal biomass, forest biomass and for example common reed, can be used as a raw material for biogas and biofertilizers. If material flows are expanded to other biomass options than traditional waste and residue streams, it might affect to land-use and balance between energy and food production. However, on the one hand, the growing demand for renewable energy and biofertilizers and on the other hand due to the need for balance in the process, biomasses other than waste can also be used as supplementary and balancing raw materials in the anaerobic digestion process. Some other biomass options for completing waste and residue streams, are shortly introduced in this chapter.

Potential of energy crops as a feedstock for anaerobic digestion correlates with field area which can be used for cultivation of energy crops. Biogas potential of energy crops is approximately 20 to 40 MWh per hectare. Grass has a highest potential of energy crops in Finland (Kymäläinen and Pakarinen, 2015, 16, 37) In addition to cultivated energy crops, different weeds are potential raw materials for biogas production.

Potential of algal biomass as a feedstock of renewable fuels is discussed long time and it have many advantages compared to energy crops. Algal biomass is carbon-neutral source of energy, and it have huge carbon capture ability. Compared to cultivated energy crops, algal biomass does not affect to land-use and food production. On the other hand, algal biomass has higher productivity and better sustainability than energy crops do. Algal biomass consists of two main types, micro- and macro algae, which both have their own features. Biogas is most often produced from wild macro algae (seaweed) which is harvested from coastal areas. Microalgae, which have high lipid content is commonly used as a raw material of oil-based biofuels, for example biodiesel and there is relatively small amount of existing literature related to biogas production from microalgae. In contrast to microalgae, macroalgae has relatively low lipid content and relatively high content of fermentable sugar and is more suitable to biogas production than microalgae do. However, large-scale biogas production from algal biomass is not yet reality and most existing studies based on pilot scale research. (Benzie and Hynes, 2013, 82-96)

In addition to algal biomass, aquatic biomass includes also other plant-based biomass for example common reed as well as animal-based biomass such as coarse fish. Both plant- and animal-based biomasses might be potential feedstock for anaerobic digestion. (Kahiluoto et al., 2011)

Woody biomasses are most important source of renewable energy around the world. Forest biomasses consists of variety composition of cellulose, hemicellulose, and lignin. Forest residues are also very heterogenous combination branches, foliage, treetops, and bark. Due to high lignin content, forest biomasses are more suitable for thermo-chemical conversion than for anaerobic digestion. Due to high content of cellulose, hemicellulose and lignin, harsh pre-treatment is needed, and anaerobic digestion of forest biomass is more complicated compared to anaerobic digestion of agricultural biomass. (Braghiroli and Passarini, 2020) Co-digestion with more easily decomposing substrates, for example manures, could be one option to convert forest biomasses into biogas via anaerobic digestion (Eftaxias et al. 2022).

2.1.6 Feedstock properties

Nutrient composition is the major characteristic related to feedstocks suitability for biogas production. The nutrient composition influences on biogas yield, methane content of the biogas, biodegradability of the organic matter and kinetics of the biomass involved. Main compound types of the feedstock related to biogas production are carbohydrates, proteins, and fats. (Nwokolo et al., 2020) In table 1. theoretical methane yields of different nutrients are presented. Methane content varies between different nutrients, but on the other hand, nutrient content affects to process stability.

Table 1. Theoretical methane yield of different nutrients (Modified from Nwokolo et al., 2020)

Nutrient	Methane yield (m^3/kg_{VS})	CH_4 (%)	CO_2 (%)
Carbohydrate	0.42	50	50
Protein	0.50	50	50
Lipid	1.01	70	30

Organic wastes from kitchen, food, fruits, and vegetables have highest methane yield due to high lipid content, which is related to presence of animal fat and oil in the waste stream. Several studies have shown that, substrates with high lipid content have higher methane yield compared to substrates with high content of carbohydrates and proteins. However, high lipid content usually leads to higher formation of long fatty acids, which might cause system failure. In addition, higher moisture content of vegetable waste might increase the degradability of these matters and lead to higher methane yield. On the other hand, high lignin content in substrate might decrease the methane yield. In addition to nutritional composition, also other factors such as temperature, pH, C/N ratio, organic loading rate (OLR) and hydraulic retention time (HRT) influence their methane yield. (Nwokolo et al., 2020)

All different microorganisms have their own specific needs for different nutrients for growth and decomposition of organic matter in biogas production. In order to optimally satisfy these needs, raw materials with different nutrient concentrations can be co-digested together to improve the quality of the substrate. For instance, animal manure which have low carbon to nitrogen ratio, can be co-digestated with feedstock which carbon rich feedstocks. In addition to C/N ratio, protein, fat, and carbohydrate content affects to share of methane in biogas. To stabilize AD process and increasing biogas production, feedstocks that are rich in these compositions can be mixed with other feedstocks with lower protein, fat, and carbohydrate content. (Nwokolo et al., 2020)

Methane potential and nutrient composition of different feedstock options, agricultural waste and residue streams, food waste and organic fraction of municipal solid waste (OFMSW), waste streams from food processing industry, and other biomass options, are presented in table 2. Methane yield of different feedstocks in this table are based on assumption of 60 % methane content of the raw biogas. Methane yield for fresh matter (T_{FM}) is calculated by using average methane yield of T_{VS} based on literature.

Table 2. Properties of different feedstocks (Modified from Kahiluoto et al. 2011; Riihimäki et al. 2014)

Source of feedstock	Feedstock type	TS %	VS/TS %	Methane yield m^3/tvs (Biogas CH_4content 60%)	Methane yield m^3/tfm (based on average methane yield)	Nutrients % from TS			
						C	N	P	K
Agriculture	Uncultivated grass	20	86	330-530	74	47	3,4	0,6	3
	Green fallow biomass	20	86	330-530	74	47	3,4	0,6	3
	Silage	26	86	330-530	74	47	3,4	0,6	3
	Green plant material	11	85	340-450	37	40	2,2	0,2	2
	Straw	85	91	120-330	174	46	0,5	0,1	1
	Garden waste	50	78	300	192	48	0,5	0,1	1
	Potato	22	90	180-540	71	45	1,5	0,2	4,8
	Solid cattle manure	19	72	150-360	35	46	2,4	0,8	2,2
	Liquid cattle manure	6	80	60-480	13	45	5,5	0,9	5,3
	Solid pig manure	24	80	160-270	51	43	2,5	0,8	1,4
	Liquid pig manure	3	78	130-480	7	30	10,9	7,2	5,1
	Solid horse manure	37	84	200	51	34	1,5	0,1	5,3
	Solid poultry manure	38	77	150-480	92	38	3,1	1,5	2,1
	Onfarm animal carcass	30	80	180-680	103	56	8	1	1
	Fish farm sludge	12	69	110-450	23	35	4	2,5	1
	Spoiled fishes	28	55	650	100	40	10	0,2	1
Food waste & OFMSW	Biowaste	32	75	90-530	74	48	2	0,4	1
	MSW fat waste	100	89	6-720	323	73	0,1	0,1	1
Food processing industry	Slaughterhouse waste	42	80	180-680	144	56	8	1	1
	Fishwaste	21	80	650	109	40	10	0,2	1
	Milk waste	13	65	700	59	45	5	1	1
	Mill waste	88	95	300-420	301	45	2,5	1,1	1
	Bakery waste	57	98	350	196	45	2,3	0,2	1
	Distillery waste	10	88	180-420	26	45	4	0,9	1
	Potato pulp	16	90	180-540	52	45	1	0,1	1
	Potato cell sap	5	90	180-540	16	45	6	0,6	1
	Mash	22	90	180-420	59	45	8,5	2,8	1
	Vegetable waste	10	70	90-420	18	45	1,6	0,2	2
	Grease trap sludge	2	89	360-960	12	70	0,1	0,1	1
Other biomass options	Sewage sludge	12	69	110-450	23	35	4	2,5	1
	Common reed	42	82	500	172	48	0,3	0,1	3
	Micro algae	20	90	290-590	79				
	Macro algae	15	75	110-310	24				
	Coarse fish	28	55	650	100	40	10	0,2	1

As a conclusion, organic waste and residue streams throughout the food value chain offers large variety of potential feedstocks for anaerobic digestion. By combining different feedstock, it is possible to optimize anaerobic digestion process as well as methane production.

2.2 Biogas Production

Biogas is sustainable and low-cost energy that can help to minimize GHG emissions, and it has several advantages compared to other renewable energy options, such as wind and solar power. Firstly, biogas production is not dependent on weather conditions and due to relatively easy and cost-effective storage and transportation, biogas supply can be adapted to changes in demand side (Ogunlude et al., 2022). Biogas have also contribution to some urgent issues related to energy system transitions, such as renewable fuel for mobility, energy storage and grid stability (Weithmann et al., 2021). Main product of the AD process, biogas, can be used on the one hand traffic fuel, or on the other hand, cooking fuel, or in heat- or electricity production (Lohri et al., 2017). Traditionally biogas is used in CHP plants to produce heat and electricity. However, upgrading to biomethane has become more common within last decade. Upgraded biomethane can replace fossil methane, natural gas, and decrease GHG emissions significantly. Several research have shown that waste-based biomethane is best biofuel, on the one hand, from energy balance perspective, and on the other hand, from GHG emission perspective. (Kymäläinen and Pakarinen, 2015, 17)

2.2.1 Anaerobic digestion process

Anaerobic digestion is a natural process and is responsible for the recycling of carbon in different environments, such as wetlands, animal intestines, water sediments and manure. In this biological process, various microorganisms work synergistically in the absence of oxygen and convert organic carbon into its most oxidized form, carbon dioxide, and its most reduced form, methane. (Kougias and Angelidaki, 2018) The anaerobic digestion process consists of four different steps, which are hydrolysis, acidogenesis, acetogenesis and methanization. (Obileke et al. 2021) Different steps of the anaerobic digestion process are introduced in fig. 2.

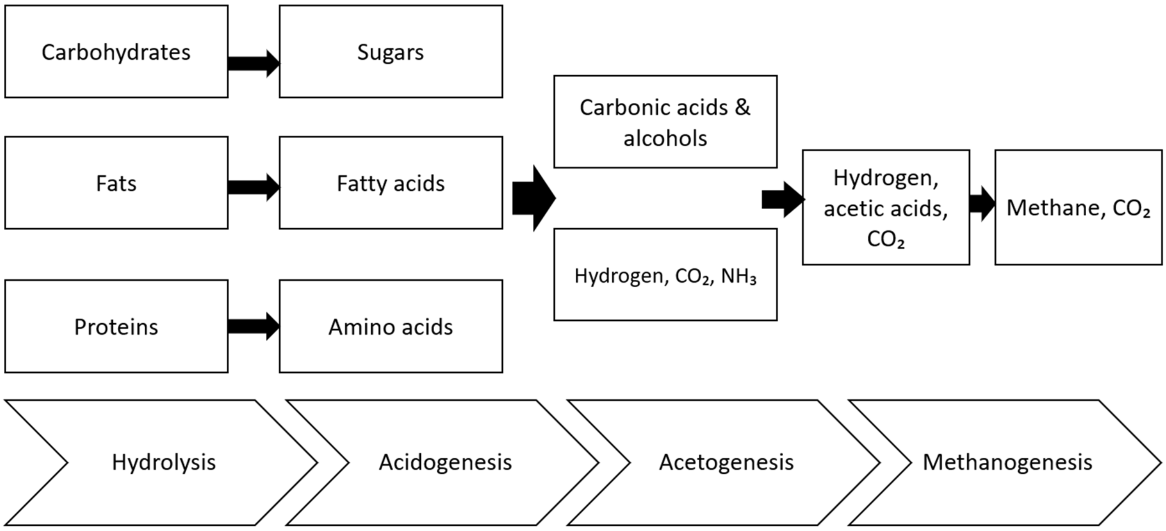

Fig. 2. Anaerobic digestion process (Modified from Obileke et al., 2021)

In the first stage, hydrolysis, carbohydrates, proteins, and fats will decompose into simpler organic compounds such as amino acids, sugars, and fatty acids by the hydrolytic bacteria. In the second stage, acidogenesis, is also known as the fermentation process, where micro-organisms convert organic material to alcohols or short chain fatty acids. Third stage of the anaerobic digestion, acetogenesis, hydrogen has an essential role. In this stage fatty acids and alcohol convert to form of hydrogen, acetate, and CO_2. In the last stage, methanogenesis, reaction between hydrogen and acetic acid forms methane and carbon dioxide. (Obileke et al., 2021)

From the biological perspective, anaerobic digestion complex and multistage process which include actions of several microbes, gases and liquids, and the process should be monitored carefully (Ruggeri et al., 2015, 162). The process needs quite tight limits related to most essential parameters. If circumstances are not optimal or changes during the process, micro-organisms do not decompose organic material as desired. Various parameter also affects the rates of different stages in AD process (Nazari et al., 2021, 80). Most essential parameters in order to optimize anaerobic digestion process are temperature, pH-value, ratio between carbon and nitrogen (C/N-ratio), hydraulic retention time (HRT), particle size, organic loading rate (OLR), mixing, ammonia- and water content. (Obileke et al. 2021)

The pH value refers to the acidity and alkalinity of the raw material used, and the pH value and its stability play an essential role in the anaerobic digestion process. The stability of the pH is particularly important in the early stages of the process, where hydrolysis and acidogenesis can lower the pH and to stabilize it, neutralizing substances such as calcium carbonate or lime may have to be used, which may cause additional process costs. To optimize the biogas yield in the anaerobic digestion process, the optimal pH is 6.5-7.5 depending on the technique used and the type of raw material, if the pH is lower than 6.1 or higher than 8.3, this can reduce biogas production. However, the optimum pH varies between the different stages of the AD process, and the optimum pH for the methanogenesis and acetogenesis stages is between 6.6 and 8.0, while for the hydrolysis and acidogenesis stages it varies between 5.5 and 6.5. The growth and reproduction of methanogenic bacteria are inhibited in acidic conditions, which negatively affects biogas production in methanogenesis stage. Thus, medium and substrate pH play an essential role in stabilizing the AD process. The pH value of the digester depends on the concentration of bicarbonate and volatile fatty acids, the alkalinity and the CO_2 level of the biogas. By adjusting the correct ratio between bicarbonates and volatile fatty acids, a stable and desired pH is achieved. Retention time and organic loading rate are determining factors in the stability of biogas production and the pH of the process. (Jacob et al., 2020, 89-90; Obileke et al., 2021; Nazari et al., 2021, 80)

The carbon to nitrogen ratio of the organic biomass added to the anaerobic digestion process plays an essential role in regulating the growth rate of microorganisms and the biogas yield, and it also enables efficient metabolic activity. During the process, different groups of bacteria selectively use different components of the substrate. Too high a C/N ratio reduces the efficiency of the process and leads to the accumulation of volatile fatty acids. On the other hand, too low a C/N ratio increases ammonia production, which is harmful to the bacterial population. Co-digestion of substrates with a high and low C/N ratio has an improving effect on methane production. In other words, by combining high C/N ratio and low C/N ratio feedstocks in the AD process can be used to achieve the ideal nutrient balance. Typically, the optimal ratio of carbon to nitrogen in an anaerobic digestion process varies between 20 and 30. (Obileke et al., 2021; Jacob et al., 2020, 79-80)

Hydraulic retention time (HRT) refers the time what substrate stays in the digester during the AD process (Obileke et al., 2021). By increasing the organic load, hydraulic retention time can be shortened. The hydraulic retention time must be long enough to ensure that the proliferation of microorganisms is greater than the number of microorganisms removed with the digestate. In general, the growth rate of anaerobic bacteria is at least 10 days, which should be considered when planning the process. A short HRT has a positive effect on the substrate flow, but correspondingly, the methane yield with a short HRT is lower. That is why it is important to adjust the hydraulic retention time according to the typical degradation rate of the substrates used. When the targeted HRT, daily feed of raw material and the retention time of the substrates are known, it is possible to calculate the required volume of the digester. (Al Seadi et al. 2008, 28)

Particle size has a very important role in AD process, and it affects to speed and stability of the process (Obileke et al., 2021). Smaller particle size increases the surface area of the particles and enables more effective decomposition of organic matter by microorganisms.

Organic loading rate (OLR) refers the amount of organic matter that are fed into the biogas digester each day per unit size of the biogas digester capacity. In other words, OLR is measure the quantity of organic matter which in digester in specific time. Typically measured in terms of kg COD/m^3/d (chemical oxygen demand) or VS/m^3/d. Variety in substrate loading and material flow during the process could lead to imbalance in acid formation and methanogenesis. High OLR with easily hydrolysable substrates might lead rapid acidogenesis and it may increase volatile fatty acid and hydrogen concentration in the process which decreases the pH. Lower pH can inhibit methanogenesis while higher pH inhibits acid conversion. Optimal level of organic loading rate for efficient digestion varies between 0.5 and 3.0 kg VS/m^3/d. (Obileke et al., 2021; Kymäläinen and Pakarinen, 2015, 72; Jacob et al., 2020, 90).

Ammonia is an important nitrogen nutrient for microbes and the most typical sources of ammonia are substrates with a high protein content and urea. The relative amount of ammonia depends on the pH of the medium and the process temperature. Increasing the pH and temperature increases the relative proportion of ammonia, which can increase the risk of ammonia inhibition. A substrate with a high nitrogen content, for example if poultry or pig manure and slaughterhouse waste are used as raw material, increases the risk of ammonia inhibition. (Kymäläinen and Pakarinen, 2015, 67)

Most suitable operational conditions for anaerobic digestion do not include dissolved oxygen or inhibitory substances such as heavy metals or sulphides, includes sufficient nitrogen and phosphorous, and have suitable ratio on the one hand, between carbon and nitrogen, which is 25-30:1, and on the other hand, suitable volatile fatty acid concentration between 2000 and 3000 mg/l. (Nazari et al. 2021, 80)

Despite the long history of anaerobic digestion, current knowledge related to anaerobic digestion process is not sufficient and there are still some bottlenecks such as characteristics of substrate, type of inoculum, pH, temperature reactor configuration, and concentration of inhibitory substances which limits the use of full potential of anaerobic digestion process. In order to expand anaerobic digestion as a process for recovering energy and nutrients from the organic matter, and on the other hand, decrease the volume of organic waste more effectively, improvement of process efficiency through modifications in the existing design of anaerobic digester for recycling of organic matter and the development of new mitigation technologies to overcome inhibitions caused by intermediate compounds are needed. (Jacob et al., 2020, 75)

2.2.2 Pre-treatment

Need of pre-treatment depends on feedstock and chosen treatment process. At easiest, pre-treatment is only mechanical crushing and transfer to the AD process, but it can also consist of difficult combination of several tanks and processes (Kymäläinen and Pakarinen, 2015, 48). The purpose of biological, chemical, or physical pre-treatment, is to prepare materials with difficult structures, for example lignocelluloses, for biological degradation (Wainaina et al., 2020).

The purpose of pre-treatment is to prepare organic matter to more easily decomposing form. Typically, first step of the AD process, hydrolysis, is quite slow, because complex organic structures such as cellulose, hemicellulose, lignin, proteins, polysaccharides, and lipids, should be solubilized and hydrolysed into simpler structures such as long-chain fatty acids, sugars, and alcohols. The hydrolysis step can be shortened by various pre-treatment methods. Suitable pre-treatment methods vary between different feedstocks and to wanted composition of substrate. Pre-treatment speeds the process, helps microorganisms to degrade organic matter and increase the quality of digestate. Pre-treatment technologies can be divided to mechanical-, thermal-, chemical- and biological methods, which all are presented later in this chapter. All these methods improve the material accessibility for microorganism by increasing surface are, porosity, recrystallization and solubilization. Also, methane yield can be increased by pre-treatment of the organic matter for anaerobic digestion. (Kasinath et al., 2021)

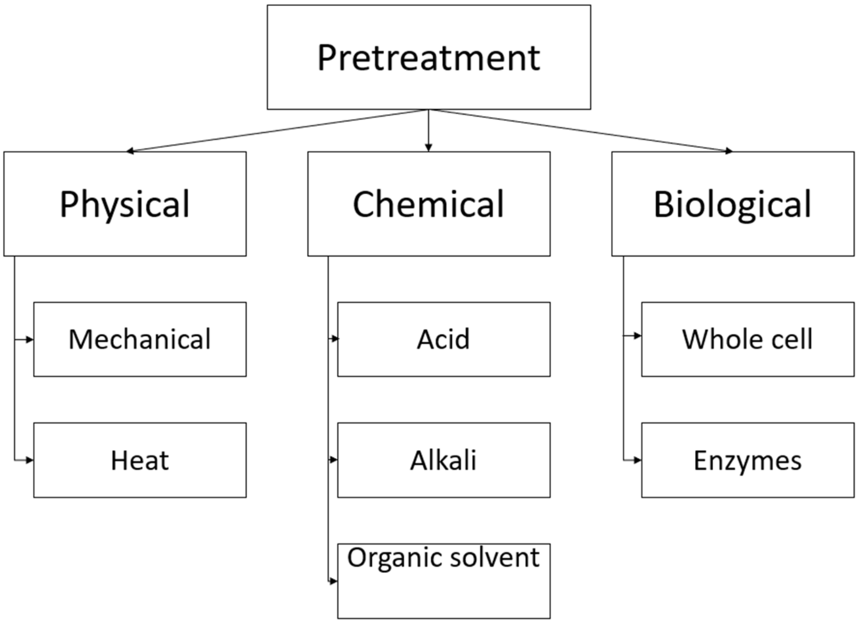

Fig. 3. Pre-treatment processes (Modified from Jacob et al., 2020, 88)

Physical pre-treatment prepares organic material for anaerobic digestion by using mechanical or thermal energy. On the one hand, mechanical pre-treatment cell structure of the organic material is broken by using pressure, translational or rotary energy. The process decreases particle size and increase the surface area which helps microbes to degrade material. This process is helpful, but on the other hand, disadvantage is high energy consumption. (Nazari et al., 2021, 79-80) On the other hand, the purpose of thermal pre-treatment is to destroy cell walls by using heat in order to make organic compounds available for biological degradation. This process is mostly used in heat range between 60 and 180 °C. If temperature rises higher than 200 °C, it might affect refractory and toxic compounds and it might decrease biodegradability. In addition, lower temperatures require less energy, and it will be more cost effective. However, higher pre-treatment temperature increases the biogas yield, biodegradability rate and need for the heating of digester, which increases the total energy production in the AD process. (Nazari et al., 2021, 78)

In the chemical pre-treatment process cell walls and membranes from the organic matter are hydrolysed in order to increase solubility of the organic matters within the cells. Mostly used chemical methods are acid pre-treatment, alkaline pre-treatment, ozonation and advanced oxidation methods. Alkaline pre-treatment is most cost-effective process due to its compatibility with latter AD process. The most essential reaction in the alkaline treatment process is solvation and saponification which swells the cells and makes organic matter more susceptible for biodegradation. On the other hand, acid pre-treatment breaks the lignin and cellulose and is more useable method for lignocellulosic feedstocks. The main process in acid treatment is breaking cellulose, hemicellulose and lignin to monomer and oligomers which decrease the digestion time. On the other hand, acid treatment has also disadvantaged such as formation of inhibitory by-products due to strong acid conditions, loss of fermentable sugars and high costs of used acids and neutralization of acid substrate before anaerobic digestion. Third mostly used method, ozonation, is oxidative process in order to enhance hydrolysis of biomass. Disadvantage of ozonation is its high energy consumption. (Nazari et al., 2021, 78-79)

Thermal and chemical pre-treatment methods can also be possible to use together. Advantage of this option is that helps to avoid need of high temperatures it might lead to better solubilization compared to use of only one of those processes. This combination is effective technology to breaking down cells that are difficult to hydrolyse for AD process. (Nazari et al., 2021, 79)

Best suited process for pre-treatment of organic matter for anaerobic digestion is biological pre-treatment. In this process microbial agents breaks down the structure of the cells and depolymerizes lignin. Lignin can also be removed by ligninolytic enzymes such as manganese peroxidase, lignin peroxidase or laccase. Advantages of this process are mild operating conditions, target specificity, eco-friendly, cost-effective, re-usability of microbes and it do not cause damage to equipment. (Jacob et al., 2020, 87)

Need for pre-treatment differs quite much between different feedstocks. For instance, manure sludge is ready-to-use for anaerobic digestion and pre-treatment is not needed. Only homogenization by mixing is needed, due to separation of sludge. Features of dry manure varies more due to type of used bedding. In order to pre-treat dry manure for biogas production shredding is typically needed. Mechanical pre-treatment also enables more effective digestion in the AD process. Manure and other easily degradable fractions should be transferred to biogas process as soon as possible, in order to avoid degradation of organic matter before the AD process. (Kymäläinen and Pakarinen, 2015, 49)

2.2.3 Biogas production technologies

This study will focus to industrial scale biogas plant, where needed components are more complex compared to rural household digesters. Industrial digesters are typically built above the ground, or they are half-buried, and construction needs more capital investments. Biogas plant consists of a main body, monitoring, control, and maintenance facilities, etc. Professionals of process, structure, equipment, electrical and control are required to do the design according to the feedstock and site conditions. (Deng et al., 2020, 109)

Digester types can be categorized to different group and most commonly use categories are one-stage, two-stage, dry digester, wet digester, batch digester, continuous digester, and high-rate digester (Nizami et al., 2013, 142). Anaerobic digestion processes can be divided by using different categories. In this research characteristics of digester are divided different groups by operating temperature, operational phase, mode of operation, mixing and solid content as presented in fig. 4.

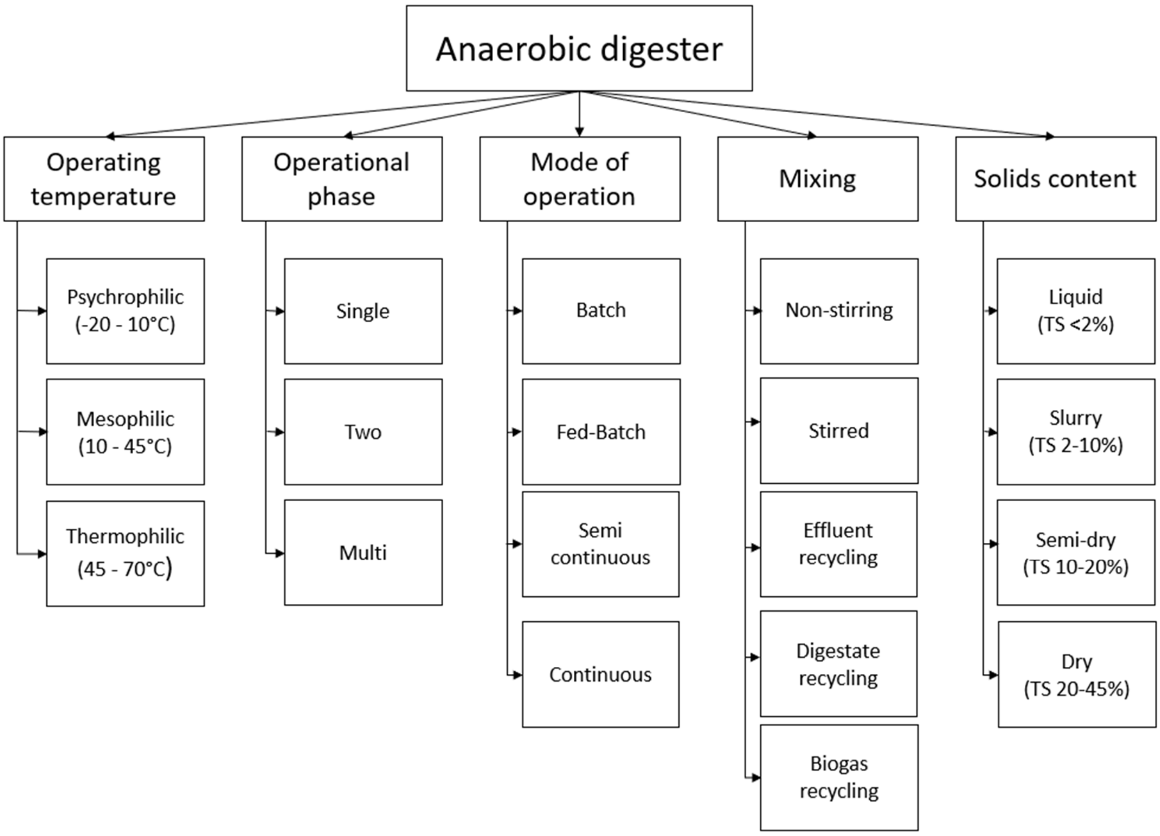

Fig. 4. Classification of anaerobic digesters (Modified from Khuntia et al., 2022)

Optimal temperature depends on chosen process. In biogas production, typical operating temperature varies in mesophilic condition between 30 and 38 °C and in thermophilic conditions between 55 and 60 °C (Tchobanoglous et al., 1993, 702). In addition, psychrophilic conditions temperature between -20 and 10 °C might also be potential operating temperature in cold climate countries due to smaller energy need for heating biomass. (Tiwari et al., 2021) Stabile temperature is essential for the functioning of microbial consortia and the decision related to chosen operating temperature should be done depending upon the local climate consideration. In the cold environment thermophilic reactor needs lot of energy and it might be better to operate in mesophilic temperature. (Jacob et al., 2020, 88-89)

Temperature plays an essential role in regulating the growth rate and fatty acid content of microorganisms during anaerobic digestion. On the one hand, the increase in temperature increases the growth rate of microorganisms and the solubility of organic compounds, improves biological and chemical reactions and the mortality of pathogens, but on the other hand, it also increases the concentration of fatty acids, which has been found to have a negative effect on methane yield. The high ammonium content of the substrate has a greater effect on the methane yield in the thermophilic process than in the mesophilic process and lowering the operating temperature to the mesophilic phase under these conditions has a positive effect on the methane yield. In a thermophilic process, where the temperature varies greatly, the fractionation of free ammonia can increase and cause disturbances in the process. (Nazari et al., 2021, 80; Jacob et al., 2020, 88-89) Depending on the chosen process, the optimal temperature can vary over a wide range, and temperature stability is therefore more important than absolute temperature. The optimal temperature variation is +/- 0.5 °C and the range should be less than +/- 2 °C. (Kymäläinen and Pakarinen, 2015, 64) In terms of the functioning of microbial consortia, a stable temperature is essential and the decision on the selected operating temperature should be made according to the local climate aspect. In a cold environment, a thermophilic reactor needs a lot of energy and could be better used in a mesophilic temperature. In addition, thermophilic microbes tolerate about twice as much fatty acids as mesophilic microbes. (Jacob et al., 2020, 88-89)

Anaerobic digestion process can consist of single or multiple operational phases. In the single-stage process, biogas plant has only one digester, where digestion happens. In the two-stage process, hydrolysis and methanogenesis stages are divided to different digesters, in order to optimize circumstances for different processes. (Kymäläinen and Pakarinen, 2015, 89)

Typically, wet digestion process is always continuous process and dry digestion process can be either batch-based or continuous process. Continuous process means regular substrate feeding which leads to stabile biogas production. In batch process, on the other hand, one batch is fed to digester and digester will be emptied before it is possible to feed another batch. (Kymäläinen and Pakarinen 2015, 83)

Mixing improves anaerobic digestion process significantly. Missing or improper mixing could lead to hydraulic dead zones which affects to methane yield and process stability. In existing literature have found that mixing of the substrate have affected to efficiency of the conversion process and most essential factors that affected to efficiency are duration, intensity, mixing strategy and location of impeller in the digester. However, performance in the AD process is inconsistent with the duration and intensity of mixing. Homogenous material in the digester can be achieved by proper mixing, whereas improper mixing causes separation of different phases and formatting solid floating layer. (Jacob et al., 2020, 91)

Typically, reactor type in anaerobic digestion is classified by using dry matter content of used substrate. On the one hand, dry fermentation or in other words, high solids anaerobic digestion is the degradation process where content of solid matter varies between 15 % and 35 %. On the other hand, in the wet fermentation or in other words, low solids anaerobic digestion, solid content of the substrate is up to 10 % and liquid content is higher compared to high solids process. The most important decision in design process of the biogas plant is to choose one of these operating modes, dry or wet anaerobic digestion. Chosen process and chemical composition of used feedstock affects to methane yield. (Kougias and Angelidaki, 2018)

2.2.4 Biogas purification and upgrading

Raw biogas consists of 50 to 75 % of methane, 30 to 50 % of carbon dioxide small amounts of nitrogen, hydrogen carbon monoxides other impurities. Need for purification and upgrading depends on used energy converting type. In order to upgrade biogas to biomethane, which can be used in similar purposes than natural gas, carbon dioxide, water vapour and other impurities should be removed. First step of the process is gas cleaning where impurities, which can damage mechanical appliances, are removed by using adsorption with silica gel and activated carbon or molecular sieves. Purified biogas can be burned in CHP plant to produce heat and electricity. In order to increase caloric value of the gas, CO_2 should be removed from methane. Methods for removing CO_2 are water scrubbing, pressure swing adsorption, cryogenic technology, membrane separation and organic scrubbing using amines such as diethanolamine, diglycolamine and monoethanolamine. (Wainaina et al., 2020; Mulvaney, 2020, 136) Biogas purification and upgrading needs for different energy conversion types are presented in figure 5.

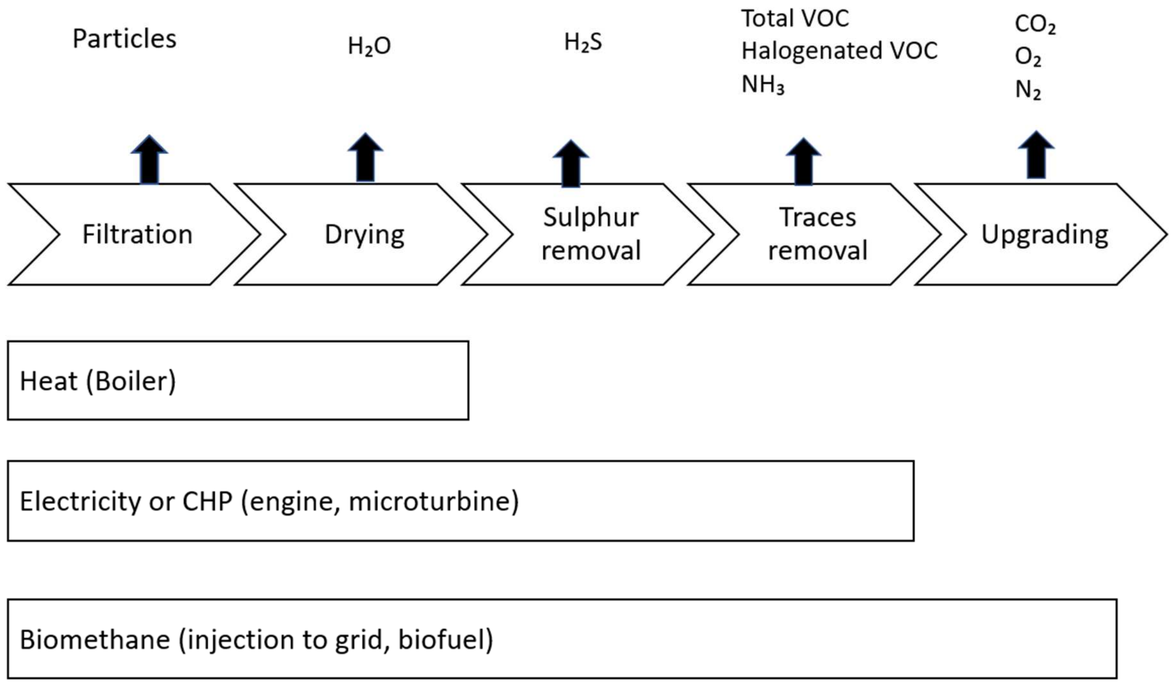

Fig. 5. Process treatment needs according to energy conversion type (Modified from Nzihou, 2020, 1087)

The conversion process of biogas into biomethane consists of two major steps. In the first step, gas is cleaned, and impurities are removed, and in the second step, gas is upgraded, and the caloric value has adjusted. In general, the purpose of upgrading process is to process gas to meet the standards of vehicle use or standards for grid injected gas. In the upgrading process, different methods can be used. Used methods differs in function, needed quality conditions of incoming gas, the efficiency, and their bottlenecks. Condensation methods such as demisters, cyclone separators and moisture traps and drying methods such as adsorption and absorption are used in order to remove water in combination with foam and dust. Also, different techniques such as air dosing of biogas, and addition of iron chloride to digester tank are developed to H_2S from biogas. Adsorption on iron oxide pellets and adsorption in liquids will remove H_2S after digestion. If trace components for instance siloxanes, hydrocarbons, ammonia, oxygen, carbon monoxides or nitrogen are not removed in other treatment steps, removing them in subsequently might need extra removal steps. After removing impurities from the gas, methane and carbon dioxide should be separated by using pressure swing adsorption, membrane filtering, physical or chemical CO_2-absorption. (Ryckebosch et al., 2021)

As simplest biogas utilization can be direct burning in boilers or burners to produce heat and electricity. Direct burning for heat production does not need any upgrading of biogas, but gas should go through particulate removal, condensation, compression, cooling and drying. (Al Seadi et al., 2008, 42)

The physical drying method by refrigeration is the simplest way for removing condensate water from biogas. However, this method can decrease the dewpoint only 0.5 °C due the freezing on the surface of the heat exchanger. If lower dewpoints are needed, gas should be compressed before the cooling and later expanded to desired pressure. The lower the dew point, the higher pressure is needed to be applied. In this process, condensed water droplets can be removed. By physical drying methods, water contact and corrosion with downstream equipment such as compressors, pipes, activated carbon beds and other parts of the process are prevented. Physical separation techniques of condensed water consist of demisters, cyclone separators, moisture traps and water tap in the pipeline. Pipeline quality standards allows 10 mg/m^3 water content and dew point of compressed natural gas for vehicle use is least 10 °C below the 99 % winter design temperature for the local air condition at atmospheric pressure. Usually raw and untreated biogas is saturated with water and the absolute water content depends on temperature. The water content beyond the permitted limits should be purified into the allowed limits. Water can be removed by using physical separation of condensing water or by using chemical drying. These methods will also remove other impurities such as foam and dust from the biogas. (Ryckebosch et al., 2021) Different impurities, their affects to equipment, emission disadvantages and different methods for purification of these impurities are presented in table 3.

Table 3. Biogas impurities, the problems they cause and their cleaning methods (Modified from Kymäläinen and Pakarinen, 2015, 131)

Impurity	**Equipment malfunctions**	**Emission disadvantages**	**Purification method**
Water Vapour	Corrosion, stagnation		Adsorption (silica gel), absorption (glycol), cooling, compression
Sulphur compounds	Corrosion	Acidification, poisonous, odours	Biological absorption (water), adsorption (iron, activated carbon), chemical
Halogenated Hydrocarbons	Corrosion	Acidification, poisonous	Adsorption, absorption, cooling
Ammonia		Poisonous, eutrophication	Absorption (water), adsorption
Siloxanes	Sooting		Physical adsorption (activated carbon, silica-gel), chemical adsorption, cooling, absorption (water, organic liquids)
Particulate matter	Sooting		Adsorption, filtering, cyclone
Oxygen	Explosion		Adsorption, chemical

The decrease in incentives for heat and electricity production and, on the other hand, the growing interest in biomethane as part of the natural gas market, forces biogas plants to refine raw biogas into methane instead of producing electricity from it (Pasini et al., 2019). In order to upgrade raw biogas into biomethane, carbon dioxide and other impurities should be removed. In addition, methane content should be increased from typical 50-75% level to more than 95 %. The needed result is possible to achieve by using different technologies, which advantages and disadvantages are presented in table 4.

Table 4. Comparison of different upgrading technologies (Modified from Kymäläinen and Pakarinen, 2015, 137)

	Water wash	**Chemical wash**	**Aluminium wash**	**Adsorption**	**Cryogenic**	**Membrane filtering**
Methane loss - %	< 8%	< 4%	< 0,1%	< 23%	< 0,5%	< 25%
Methane leakage	< 1%	< 1%	< 0,1%	< 1%	< 0,1%	< 0,5%
Electricity consumption kWh/Nm3	0,21-0,30	0,10-0,28	0,10-0,15	0,20-0,30	0,25	0,20-0,30
Heat consumption kWh/Nm3			0,13			
Temperature requirement	10-20	55-80	120-160		< -80	
CH4 content without N2	> 97%	> 96%	> 99%	> 96%	> 99%	> 96%
CH4 content if 20% N2	78%	78%	80%	< 94%	99%	< 94%
The need for pre-cleaning	No	Yes	Yes	Yes	Yes	Yes
N2 separation	No	No	Yes	Yes	Yes	Yes
Capacity Nm3/h	>5	>100	>100	>5	>100	>5

In the CO_2 removing process, also small amount of CH_4 is removed. Methane loss, in other words methane slip, refers to the amount of methane gas that pass through upgrading process and will be recycled back to the process. Methane leakage on the other hand, refers the amount of methane which has passed through the refining process and is measured in the exhaust gas. (Pyykkönen et al. 2018; Kymäläinen and Pakarinen, 2015, 136-137)

From environmental point of view, low methane loss is the most important characteristic for upgrading technology. If methane loss is more than 10 %, greenhouse gas emissions of biogas are higher than greenhouse gas emissions of gasoline or diesel when entire lifecycle is taken in account. Values related to methane leakage of different upgrading technologies in table 4. is based the methane loss of early technologies. Methane loss in current technologies is much lower, but the risk of high leakage levels is taken in account in this table. (Kymäläinen and Pakarinen, 2015, 136-137)

Purified biomethane is an easily storable and renewable energy source that can be used to produce heat and energy on the one hand and as fuel for vehicles on the other hand. Biomethane is usually refined from biogas using various refining techniques. There are several different upgrading technologies in commercial scale such as pressure swing adsorption, water scrubbing, chemical scrubbing, membrane separation and cryogenic separation (Prussi et al., 2019). By removing of carbon dioxide, is possible to reach needed Wobbe index of gas (Al Seadi et al., 2008, 47). The most common method for processing biomethane is water scrubbing due to its reliability and simplicity. (Ghaib, 2017) Also, other upgrading methods such as adsorption, absorption, membrane filtering or cryogenic methods are possible for upgrading biomethane to grid injection quality (Ogunlude et al., 2022). The total cost of cleaning and upgrading biogas includes investment costs and maintenance costs during the operation. Most essential factor related to investment cost is the size of the plant. On the one hand, size of the plant increases total investment costs, but on the other hand, decreases cost per unit compared to smaller plants. The most expensive part of the operational cost is the removal of carbon dioxide. (Al Seadi et al., 2008, 47-48)

Membranes which can be used in biogas upgrading have two major types which are polymer and inorganic membranes. Polymer membranes can be divided to porous and non-porous membranes and their use in industrial processes depends on the properties of the membrane and intended application. However, despite the studies related to polymer membranes, their constraints of low chemical and thermal stability will limit their use in industrial purposes. Inorganic membranes, on the other hand, have been gaining interest because they are chemically and thermally more stable than polymer membranes do. (Ogunlude et al., 2022)

2.2.5 Biogas distribution and use

The need for purification and upgrading raw biogas depends on the energy conversion method as mentioned in earlier chapter. The purpose of this chapter is to introduce different distribution methods, on the one hand biogas which is purified for heat and energy production, and on the other hand upgraded biomethane which can be used in vehicle or industrial use to replace natural gas. Different distribution and utilization options for purified and upgraded biogas are presented in fig. 6.

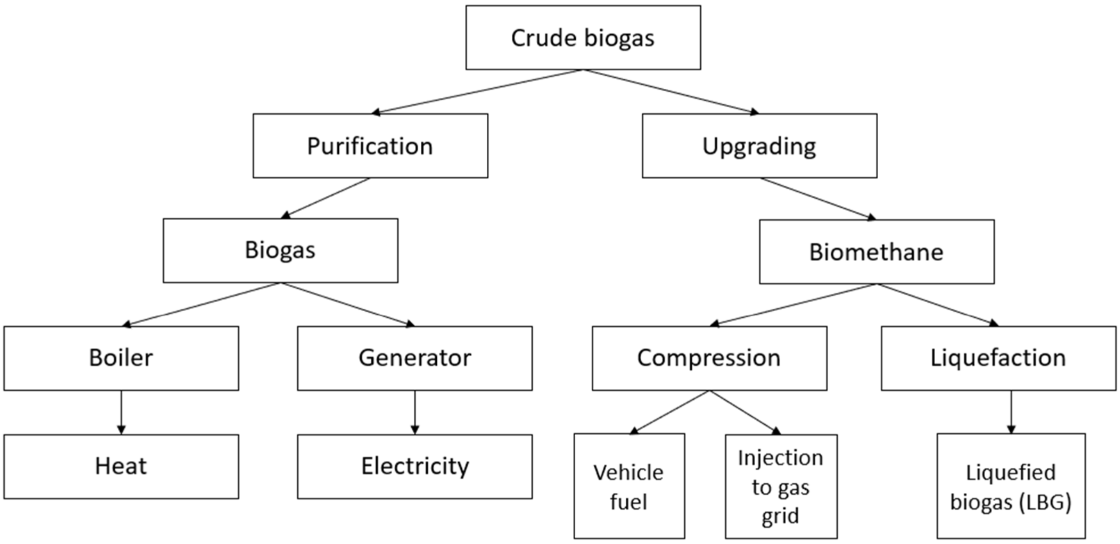

Fig. 6. Biogas utilization (Modified from Al Seadi et al., 2008)

Traditionally biogas has utilized as a heat and electricity by burning it in CHP plant (Pasini et al. 2019). In order to convert biogas to heat and electricity, only purification of raw biogas is needed. Purified biogas can be directly applied for generating electricity and heat while upgraded biomethane can be injected to natural gas grid or used as a vehicle fuel (Wainaina et al., 2020).

Upgraded biomethane is possible to distribute via existing natural gas pipelines and use similarly with natural gas, or it can be delivered as a compressed form and use as a renewable vehicle fuel (Al Seadi et al., 2008, 47-48). If access to gas grid connection is available and connection costs are low, injection to gas grid is most profitable distribution channel (Pasini et al., 2019). Biomethane can be injected to same grid with natural gas, and they can also be used as a mixture. Replacing natural gas partly by biomethane, negative environmental impacts of fossil gas can be decreased. However, volumes of current gas pipelines are much higher than biomethane potential in Finland and they cannot be used for biomethane distribution only.

In addition to pipeline distribution, compressed biomethane can be distributed by using tanks or containers, and it can be transported by using trucks or railways. Typically, standardized containers can carry up to 120 MWh biomethane and it is comparable transportation method in cases, where pipeline connection is not available. (Kymäläinen and Pakarinen 2015, 167) The desired transport pressure of the containers affects the energy consumption and thus the price of gas distribution (Bauer et al. 2013).

Biomethane and natural gas can be liquefied to maximize energy intensity. The energy content of liquefied biomethane corresponds to biomethane compressed to 600 bars. It can be transported by ships, trucks, or trains. In road traffic, a full truck can transport up to 80 m³ or 28 tons of LBG, which has an energy content of 530 MWh. (Kymäläinen and Pakarinen, 2015, 168) Transportation of liquefied biomethane in a 25 tons trailer is economically viable compared to compressed biomethane in steel containers if transportation distance is more than 200 km and annual amount is more than 100 GWh. In shorter distances and smaller volumes costs of liquefaction are too high (Gustafsson et al., 2020)

2.3 Biofertilizer production

In addition to energy supply, anaerobic digestion has also other advantages. Anaerobic digestion decreases the volume of organic waste, and the by-product of the biogas production, however, without comprehensive management strategies, digestate can contribute to nutrient pollution and spread harmful pathogens (Lamolinara et al., 2022). Compared to direct use of agricultural waste as a soil improvement in farms, digestate from anaerobic digestion have several advantages. Firstly, it helps to avoid odours in the case of direct use of manure as a fertilizer, secondly, it helps to remove pathogens from animal-based feedstock, and thirdly, helps to concentrate micro- and macro nutrients in the present feedstock biomass. (Jurgutis et al., 2021) Another advantage of using digestate instead of untreated manure and slurries as a fertilizer is increasing veterinary safety. In fertilizer use sanitation of the digestate should be done by using controlled process. The need for sanitation depends on used substrate, and in some cases, it can be provided by using AD process itself, through a minimum guaranteed retention time in the digester or by using thermophilic process. Sanitation can also be done by separated process with pasteurisation or by pressure sterilisation. The purpose of sanitation is to inactive pathogens, weed seeds and other biological hazards in order to prevent disease transmission trough biofertilizers. (Al Seadi et al., 2008, 14)

Digestate is also valuable products as a biofertilizer, and it can offer additional income to biogas plants (Du et al., 2018; Jurgutis et al., 2021). Nutrient content of the digestate is not reduced compared to nutrient content of the used feedstock and anaerobic digestion rather increase the characteristics of it (Havukainen and Dace, 2023, 105). Digestate consists of non-degradable material and microbial biomass, but also nutrients from the feedstock such as nitrogen, phosphorous, and potassium are concentrated to digestate. During the AD process, nutrients convert to soluble form, which helps plants to use those nutrients. Digestate can be used as a biofertilizer and soil improvement purposes. In order to produce more valuable products from the digestate, solid and liquid fractions can be separated. Advantages of the digestate use as a fertilizer are on the one hand, closing the nutrient loops and avoid nutrient pollution to water systems, and on the other hand, achieve energy savings compared to mineral fertilizer production. (Kymäläinen and Pakarinen, 2015, 18)

Replacing mineral fertilizers by biofertilizers produced from digestate have many advantages it saves energy and natural resources. The nitrogen fertilizers production by using Harber-Bosch process is very energy intensive and it covers approximately 1-2 percent of total global energy demand. Phosphorous, on the other hand, is a finite natural resource which is almost exclusively mined from mineral deposit. (Orner et al., 2021)

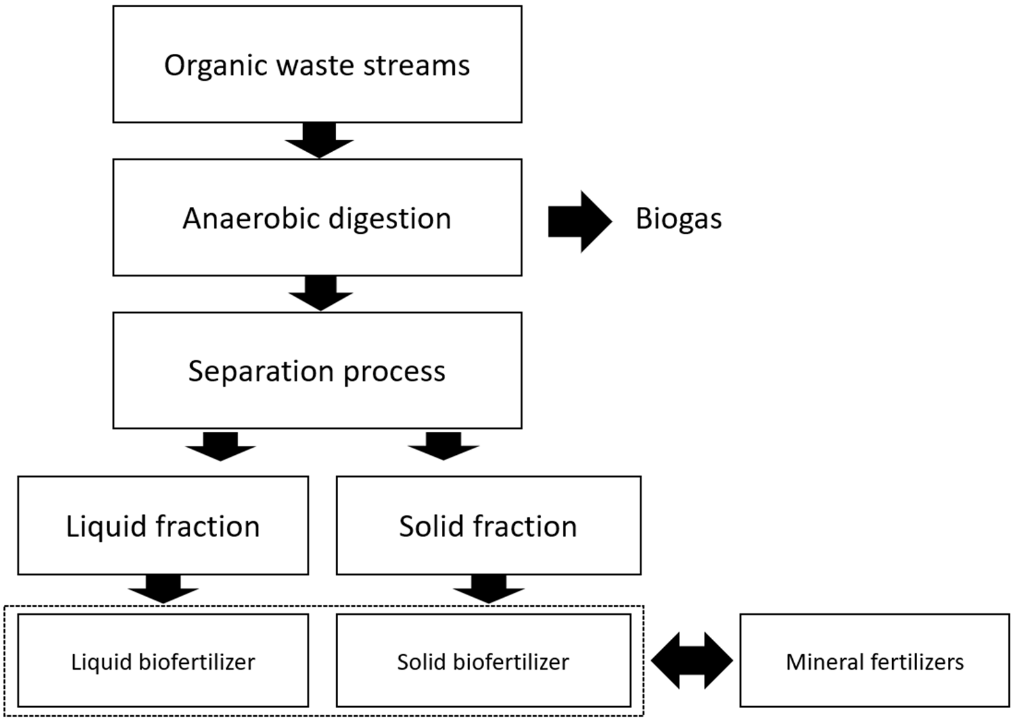

Fig. 7. Schematic figure for biofertilizer production (Modified from Orner et al., 2021)

One option for nutrient recovery is direct land application of liquid digestate, but it has some disadvantages compared to mineral fertilizers such as lower fertilizer value, higher potential for ammonia loss, higher transportation costs, odours, additional undesirable constituents like heavy metals and organic pollutants. (Orner et al., 2021) Raw digestate without further treatment can be used as a soil improvement purposes, or solid and liquid fractions can be separated in order to increase the value of the end-product into more concentrate biofertilizers (Tampio et al. 2022).

2.3.1 Digestate separation

First step in order to increase the value of the digestate as a biofertilizer is the separation of solid and liquid fractions from the digestate (Tampio et al. 2022). Separation can be done by using methods based on density differences of different fractions, for example by using centrifuges, different fraction can also be separated by using sieves or membranes, in order to separate different particle sizes from each other, or by using thermal methods such as evaporation or drying. (Kymäläinen and Pakarinen 2015, 99) Most common practices for separating liquid and solid fractions is centrifuges and screw press (Tampio et al. 2018).

2.3.2 Liquid fraction

Most of the nitrogen is concentrated to liquid fraction. Also, liquid part can be further treated by using different methods, for instance by striping of nitrogen into form of ammonia (NH_3). After the stripping process, nutrients can be recovered, or product can be washed with sulphuric acid in order to form ammonium sulphate which is high-quality organic nitrogen fertilizer. (Alengebawy et al., 2022)

Liquid fraction can be used as-it as a liquid fertilizer, or it can be further treated into more valuable products by using different methods such as ammonia stripping, struvite precipitation, membrane treatment, or evaporation, depends on wanted end-product (Tampio et al., 2022). The liquid fraction of digestate has a high moisture content, which increases transport costs. By concentrating the liquid fraction, the nutrient content of the product can be increased and thereby increase the value of the end products as well as reduce transport costs.

The liquid fraction separated from digestate can be further processed to concentrate nutrients. Further processing techniques can be roughly divided into separating and chemical techniques. Membrane techniques and evaporation/concentration are discriminating methods. Chemical techniques include, for example, stripping and struvite crystallization. (Tampio et al. 2018)

2.3.3 Solid fraction

Solid fraction has high phosphorous concentration, and it can be used directly in soil improving purposes, it can be composted, in order to produce nutrient rich compost, or it can be further treated by drying and pelletizing or granulating dried material before the use as a material. Dried material can also be further treated by pyrolysis in order to produce biochar. (Alengebawy et al., 2022; Tampio et al. 2022)

Composting is one of the preferred post-treatment processes for the digestate, in order to convert it into mature, stable, safe, humus- and nutrient rich compost (Kovacic et al., 2022). Composting is the biological process where microbes stabilize and decompose organic matter in aerobic condition. The end-product of aerobic digestion process is compost, which is nutrient rich humus which can be used as a biofertilizer. Anaerobic and aerobic digestion processes can be combined and digestate from anaerobic digestion process can be further treated by aerobic digestion. (Chojnacka et al., 2019)

In thermal techniques, such as combustion, pyrolysis and drying, the pulp is heated. In this case, the volume is reduced, and transportability is improved. The increase in temperature weakens the usability of phosphorus for plants and slows down the rate of decomposition of the carbon added to the soil. As the temperature rises, the nitrogen evaporates, so attention must be paid to its recovery. (Tampio et al. 2018)

2.3.4 Upgrading to value-added biofertilizers

Direct use of digestate might be harmful for several reasons, it might affect heavy metal accumulation, GHG emissions, and pathogen contamination. Due to those concerns, digestate can be upgraded to more valuable biofertilizers instead of direct use. The goal of digestate treatment is two-fold. On the one hand, concentrate digestate more intense form in order to optimize logistical costs of biofertilizer, and on the other hand, produce high-quality biofertilizers. These reasons are most essential motivators for digestate treatment. (Alengebawy et al., 2022) Increased amount of biogas plants in some areas might lead to oversupply of digestate and local farms cannot use all of that as a fertilizer. That increases transportation distance of digestate which causes economic, environmental, and social drawbacks. (O'Shea et al., 2020)

Volume of the solid fraction of the digestate, which includes most part of the phosphorous, can be decreased by using thermal methods such as combustion or pyrolysis. In the thermal processes phosphorous remains in the final product, but nitrogen is lost during the process. (Horn et al., 2020, 13-14) Thermal drying is one option to reduce volume of the digestate and decrease transportation costs of the end-product. However, thermal drying needs lot of energy and for that reason it is rarely used. It can still be potential process in cases where thermal energy from the process is not possible use in other purposes.

Pyrolysis is the thermo-chemical process which degrades organic matter in absence of oxygen condition and in high temperature, typically between 250 and 700 °C. End-products of the pyrolysis are pyrolysis liquid and -gases, which can be used in energy production, and organic char which have high phosphorous content. Char can be used as an organic fertilizer in crop cultivation. Share and quality of different end-products depends on features of used substrate and operating conditions. (Horn et al., 2020, 13-14) By pyrolysis digestate can be converted to biofuels such as syngas and bio-oil, or other profitable materials for instance biochar. Pyrolysis process usually needs the drying of the digestate, and this process is quite energy intensive. High energy consumption of the process can be covered by using surplus heat from the biogas use in combined heat and power production. By combining anaerobic digestion and pyrolysis in electricity production is possible to achieve 42 % higher electricity yield compared to sole AD process. Syngas and bio-oil from the process can be used as a source of renewable energy and biochar, which is very nutrient rich, can be used as a biofertilizer in soil improvement purposes. (Peng et al., 2020)

Energy consumption of different upgrading methods has a large variety. In the digestate upgrading process, holistic view of the value of the upgraded end-products and on the other hand costs and energy consumption of the upgrading process, should always be evaluated case by case.

3 PRODUCTION- AND MARKET POTENTIAL IN FINLAND

The focus of this research is, on the one hand, to assess the recovery potential of energy and nutrients from organic waste and residual streams of the food value chain in Finland. This chapter discusses on the one hand the supply side of biogas and biofertilizers, in other words the raw material and production potential, and on the other hand the demand side and market potential of both products, as well as the economic viability of valorisation of waste and residues with anaerobic digestion in Finland. On the other hand, this research will assess the economic profitability of biorefinery in the Finnish business environment.

3.1 Material Flows

This chapter will introduce material flows related to organic waste valorisation process in the Finnish food value chain. Potential organic waste and residue streams are converted into renewable energy, in other words, heat, electricity and biomethane and the nutrient rich digestate into biofertilizers via anaerobic digestion.

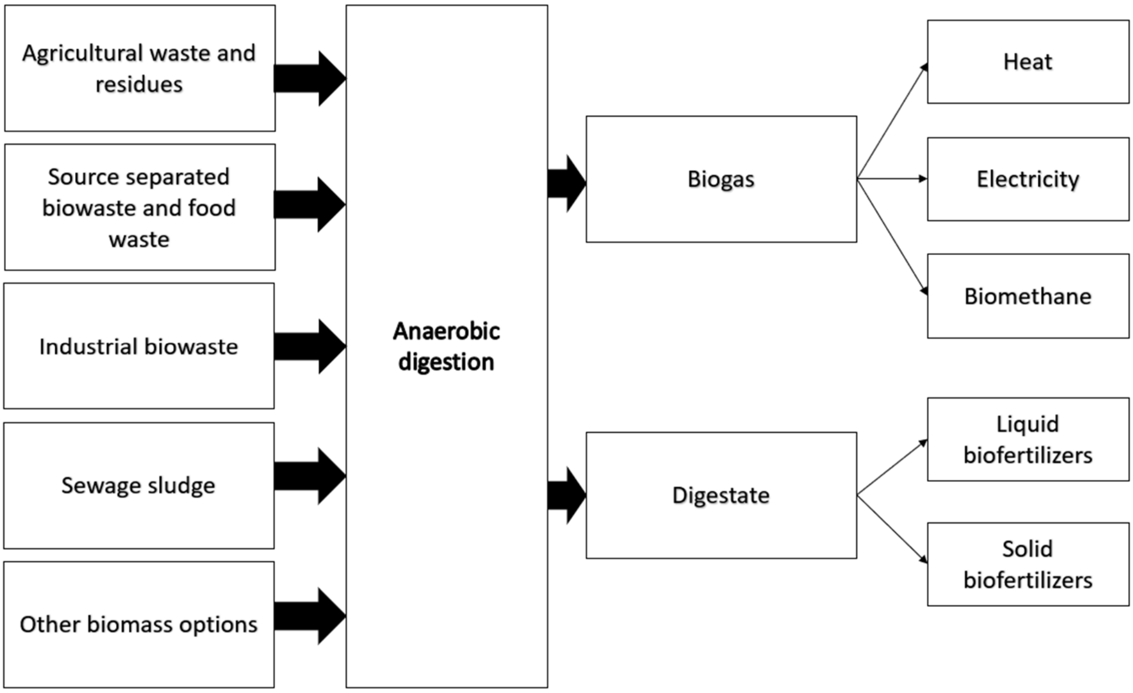

Fig. 8. Material flow diagram of organic waste valorisation

Material flows of the valorisation process of the organic waste and residue streams are presented in fig. 8. Biomass from entire food value chain is converted into renewable energy and nutrient rich digestate via anaerobic digestion. First main product of the process, biogas, is converted into heat and electricity by burning it in CHP plant or it can be upgraded into pure biomethane for replacing natural gas in vehicle fuel or in industrial use. Another main product from the anaerobic digestion process is nutrient rich digestate, which can be used as it in soil improvement purposes, or liquid and solid fractions can be separated into more valuable form of biofertilizers. Both fractions can also be further treated into more concentrate forms, which increases their nutrient intensity and the value of the end-products. However, digestate upgrading consumes energy and the decision of upgrading should always be based on the comparison of the value of end-products and the amount of used energy in upgrading process.

3.2 Biomass potential for anaerobic digestion in Finland

Large variety of different biomasses can be used as a raw material for anaerobic digestion. Data related the available biomass for anaerobic digestion, on the country and regional level is presented in table 5. based on Biomassa-Atlas database. Based on this database potential feedstock in the country level is approximately 34 million tons annually and in the Uusimaa region around two million tons annually. On the other hand, Tampio et al. (2018) mentioned that totally 21 million tons of nutrient rich biomass is annually generated in Finland (Tampio et al. 2018). However, all this biomass is not technically available for anaerobic treatment, and that 21 million tons could be more realistic feedstock potential than 34 million tons per annum.

Based on the table 5. more than half of the potential biomass in the Uusimaa region and almost 90% in the country level is generated in the agricultural sector. Approximately 10 % in the country level and almost half in regional level of the total organic biomass is generated in municipal waste management. As a comparison to total volumes, the share of organic wastes from food industry is relatively low. However, these waste streams are more homogenous and easier for treatment.

Table 5. Annual biomass potential (Modified from Biomassa-Atlas, 2023)

Biomass	Annual potential (t)	
	Finland	Uusimaa
Municipal		
Municipal biowaste	486 945	149 172
Municipal, other biodegrable waste	1 750 809	536 348
Municipal solid waste	116 094	11 900
Sewage sludge	1 210 635	175 541
Municipal total	**3 564 483**	**872 961**
Agriculture		
Animal-based	99 162	1 658
Plant-based	4 949	60
Animal-based, unsuitable for production	29 645	1 427
Straw	2 338 630	189 358
Green fallow biomass	311 509	34 050
Other plant-based side streams	296 364	13 242
Grass	162 046	11 095
Cattle, liquid manure	11 507 354	298 842
Cattle, solid manure	7 654 537	185 790
Cattle, urea	1 703 588	44 213
Pig, liquid manure	4 186 232	92 739
Pig, solid manure	82 252	1 362
Pig, urea	105 080	1 632
Poultry, liquid manure	31 556	76
Poultry, solid manure	498 314	485
Horse, solid manure	1 316 839	232 813
Agriculture, total	**30 328 057**	**1 108 842**
Food industry		
Industrial sludges, meat industry	2 454	0
Industrial sludges, plant-based industry	78 077	1 117
Kitchen waste	36 948	1 431
Fat waste	1 433	97
Garden waste	13 117	845
Food industry, total	**132 029**	**3 490**
Biomasses,total	**34 024 569**	**1 985 293**

3.3 Biogas potential and markets in Finland

The challenge of biogas business in Finland is small market size and long distances. Biogas is potential income source to agriculture, and it can combine food and energy production, and in addition, cut GHG emission. Biogas is still marginal business in Finland, but at least former and current governments in Finland have supported biogas production as well as biomethane as a traffic fuel. Despite the small share of biogas production, measured both in absolute production amount and per capita, biomethane use as a traffic fuel have increased rapidly. (Winquist et al., 2021)

3.3.1 Biogas production potential in Finland

The biogas production potential of biomasses which are suitable for biogas production is approximately 10.2 TWh/a. Most of the potential is in agricultural biomass (grass and straw 72%, manure 14%) and the rest in forest industry sludge (6%), in side streams of the food industry (3%), biowaste (3%) and municipal sewage sludge (2%). Regarding the production potential of biogas, the current production is only approx. 7% of the total potential. (Winquist et al. 2018) On the other hand, in Finnish biogas association estimation biomethane potential in Finland is 10 to 25 TWh, which is also much enough to be a main product in grid-markets. (SBB, 2022)

Theoretically, 3.93 TWh of energy can be produced per year from all the manure in Finland. However, the evaluation should take into account that manure storage causes emissions and reduces methane production due to the decomposition of organic matter during storage. Due to the short storage time, the more realistic biogas potential, which is the technically and economically available manure biogas potential, is about 1.8 TWh. (Luostarinen et al. 2019)

According to Suomen Biokierto ja Biokaasu ry (2022) target for the biogas production in 2030 is 4 TWh. Current production is about 1 TWh. In order to reach that target production in 2030 should be four time as high than today. Almost half (45 %) of it can be achieved from wastes and residues of agriculture and food industry, and 5 % from more effective source separation of biowaste and 25 % from new technologies and feedstocks.

Estimation about the biogas potential has a wide variety in existing literature. In general, it is possible to see that potential production is much higher than current production and there is still space for new biogas plants in the Finnish markets. In the scope of this study, regional potential of substrate supply is more interesting than total production potential.

3.3.2 Market potential and economic value of biogas in Finland

Market potential and economic value of the Finnish biogas markets are estimated by comparing it to use of natural gas in Finland. This chapter will focus to measure potential markets for biomethane in Finland. Estimation of potential market size is based on the one hand, annual use of natural gas in Finnish market, and on the other hand, potential biomethane production from Finnish biowaste and other potential organic side streams.

Annual consumption of natural gas in Finland was in year 2021 approximately 20.776 TWh (OSF, 2023). According to Finnish integrated energy and climate plan (TEM, 2019) The minimum target is to have 250,000 electric and 50,000 gas-powered vehicles on the roads in year 2035. However, Gasum (2022) estimates that potential biogas production in Finland is approximately 10 TWh per annum which fulfils the need of one million gas powered cars.

The size of the Finnish gas grid market has been approximately 25 TWh in last two years and the share of biomethane was only 0.15 TWh/a. In addition, the share of off-grid gas market is approximately 3 TWh and biomethane's share of it is about 0.7 TWh. The first target of biogas industry is to increase biomethane production into four TWh in year 2030. Main market will be in transport sector which can consume 2.5 TWh/a, and other off-grid use. (SBB, 2022)

As a conclusion, if assumed total biomethane production potential in Finland to be approximately 10 TWh annually, renewable biomethane can replace approximately half of the annual use natural gas in Finland. By replacing 10 TWh of the use of fossil fuels energy by using renewable energy, it could have huge impact, on the one hand to Finland's greenhouse gas emissions, and on the other hand, energy independence.

3.4 Biofertilizer potential and markets in Finland

In addition to energy security, Finland is also highly dependent on imported mineral fertilizers. By-product of the anaerobic digestion process, nutrient rich digestate, could be used as a fertilizer to replace mineral fertilizers. By replacing mineral fertilizers with recycled nutrients, it is possible to save energy and natural resources as well as mitigate emissions and energy consumption in the fertilizer production. Increasing prices of different fertilizer raw materials, on the other hand, drives fertilizer users to replace mineral fertilizers by recycled biofertilizers, which opens new business opportunities to biogas plants. Limited resources and increasing prices of most essential nutrients, phosphorous (P), nitrogen (N) and potassium (K), will open new business opportunities to biogas plants and, in addition, increase the interest digestate upgrading to biofertilizers.

Compared the data of Biomassa-Atlas and earlier calculations related to nutrient composition of different waste streams, theoretical recovery potential of nitrogen in case where all potential biomass is treated by using anaerobic digestion could be in country level 136 030 tons annually and in Uusimaa region 9 696 tons annually and phosphorous potential in country level 40650 tons annually and in Uusimaa region 2 402 tons per annum. Due to small amount of data related to potassium recovery potential, annual recovery potential for potassium is not considered.

Potential of recyclable phosphorous in Finland is approximately 26 000 tons per annum. Total amount consists of 360 tons of side streams from food industry, 230 tons from forest industry sludges, 2880 tons from municipal sewage sludge, 730 tons from biowaste, 2540 tons from surplus grass, and most remarkable source, animal manure approximately 19300 tons per annum. (Tampio et al. 2018)

Annual consumption of inorganic phosphorous fertilizers in Finland in year 2021 was 12 761 tons, and consumption of inorganic nitrogen fertilizer was 145 807 tons (Eurostat, 2023). Compared the use of mineral fertilizers and recycling potential of nutrients, it is possible to say that in case of phosphorous all used mineral fertilizer can be replaced by recycled phosphorous. Also, in case of nitrogen, 93 % of used inorganic fertilizers can theoretically be replaced by recycled nitrogen.

3.5 Economic assessment of the biorefinery

From the economic perspective, feasibility of biorefinery depends on the one hand, investment, operating and maintenance costs, and on the other hand, incoming revenue from gate fees and selling of end-products. Revenue streams of the biorefinery consists of selling of biogas and biofertilizers, and on the other hand, gate fee of incoming material. This research will assess the economic viability of industrial scale biorefinery and analyse the role of used feedstock in the profitability of biorefinery.

3.5.1 Investment costs

The amount of industrial-scale biogas plant investments varies between 10 and 35 million euros and the typical payback time for industrial scale biogas plant is approximately 8 to 10 years. In addition to the relatively high investment costs, the cash flow profile of the investments is front oriented. In other words, most of the invested capital is spent at the beginning of the process and the income is generated from the sale of end products such as biogas and biofertilizers and gate fees for incoming material. (Lummaa et al., 2021)

The investment costs of the biogas plant are estimated in this study by comparing public data related similar industrial scale biogas plant investments. Data related nine different investments are presented in table 6. In the calculations of this study, rate is assumed to be 8% and investment time is assumed to be ten years.

Table 6. Investment costs of biogas plant.

Investor	**Treatment capacity (1000 t/a)**	**Gas production capacity (GWh/a)**	**Feedstock**	**Investment cost (Meur)**	**Public incentives (Meur)**
Etelä-Karjalan Jätehuolto Oy Reference: EKJH, 2020	19,90	12,3	Biowaste, Sewage sludge	11,7	2,2
Nordic Biogas Oy (Tornion Energia Oy) Reference: Tornion Energia, 2022	19,7	13,7	Biowaste, Sewage sludge	8-10	NA
Mäntsälän Biovoima Oy Reference: TEM, 2022	20	15,8	Biowaste, Sewage sludge	13,5	3,65
Honkajoki Oy Reference: TEM, 2022	60	35	Biowaste, Industrial biowaste	9	NA
Gasum Oy, Lohja plant Reference: TEM, 2022; Gasum, 2023	60	50	Biowaste, industrial sludges, OFMSW	27,4	7,83
Gasum Oy, Oulu plant Reference: TEM, 2022; Gasum, 2023	60	35	Biowaste, industrial sludges, OFMSW	7+27,4	2,16 + 7,94
Labio Oy Reference: TEM, 2022	60	50	Biowaste, Sewage sludge	14,25	4,275
Suomen Lantakaasu Oy Reference: Valio, 2022	460	125	Manure	NA	19,15
Biomylly (Pirkanmaan Jätehuolto Oy) Reference: Pjhoy, 2022	34	25	Biowaste, Sewage sludge	23	4,55

3.5.2 Potential investment aids and financing options

Due the green transition, it is possible to get different incentives for biorefinery investment at both national level and EU level. Industrial biogas plant investments are typically worth 10-35 million euros. Typically, investments are made in the form of a limited company, and its financing structure typically consists of 30-50 percent equity financing and 50-70 percent financed with loans. The amount of equity financing includes public investment aids, which have averaged 27% of investment costs in industrial-scale investments. Therefore, the need for other equity financing is 10-30 percent of the total investment costs. (Lummaa et al., 2021)

3.5.3 Operating costs

In the values of operating costs of the biogas plant have a large variety in existing literature. Due to variation in values, some values are estimations based on the averages of found data. Values used in this study are presented in table 7.

Table 7. Operating costs (Modified from Tampio et al. 2016; Hupponen et al. 2012)

OPERATING COSTS		
Substrate heating		
Energy consumption	4,18	kJ/kg/°C
Energy efficiency	95 %	
Heating 12 to 75 °C	63	°C
Operating personnel		
Salary	2500	€/month
Salary including personnel expence	3750	€/month
Annual salary including personnel expence	45000	€/year
Maintanance costs	27400	€/a
Electricity, biogas plant	Depends on digester capacity.	
Electricity, CH_4 Production	0,75	kWh/m^3CH_4
Electricity, digestate separation	3,50	kWh/t
Electricity, digestate treatment, liquid fraction	3,50	kWh/t
Electricity, digestate treatment, solid fraction	7,50	kWh/t

Operating temperature in thermophilic process is in this study 55 °C, however, heating of substrate is calculated into 75°C due to need of feedstock sanitation. Energy consumption of the liquid solid separation by using centrifuge is approximately 3.5 kWh/t (Tampio et al. 2016).

Energy consumption of treatment of liquid fraction depends on chosen treatment method. In this study, energy consumption of liquid fraction treatment is assumed to be average of those methods, in other words 3.5 kWh per ton of liquid digestate. (Tampio et al. 2016)

Energy consumption of the solid fraction treatment depends on chosen treatment process. Solid fraction can be used directly as a fertilizer, or it can be upgraded to more valuable forms. In the calculation of this study, solid fraction is assumed to be treated by thermal drying. Energy consumption of thermal drying is 4-5 kWh/m³ (Hupponen et al., 2012). Density of solid fraction is assumed to be 600 kg/m³, so energy consumption for solid fraction treatment is assumed to be 7.5 kWh/t.

Energy consumption of purification and upgrading depends on chosen process. According to table 4. energy consumption of biogas upgrading into biomethane is between 0.10 kWh/Nm³ and 0,30 kWh/Nm³ depends on chosen process. In this study energy need of upgrading is included in the energy consumption of methane production.

4 DIFFERENT BIOREFINERY SCENARIOS

As discussed in earlier chapters, wide range of different feedstocks are possible raw materials for biogas and biofertilizer production by using anaerobic digestion. The purpose of this study is to evaluate economic profitability of biorefinery in the Uusimaa region in Finland. In order to evaluate role of the different feedstocks in the economic feasibility of biorefinery, three different case examples with different composition of feedstocks are presented in this chapter.

4.1 Assessment of different scenarios of biorefinery investment in Uusimaa region

In order to reach comparability of different scenarios, similar biorefinery investment is used in all scenarios. Chosen annual capacity is 60 000 tons, which is quite common capacity for large biogas plant. Investment cost of the biogas plant are presented in earlier chapter, and for case example investment cost is assumed to be same than in Gasum's Lohja plant, which treatment capacity and location are comparable, and on the other hand, that plant is built within few years. By using same assumption related to investment- and operational costs as well as annual treatment capacity, it is easier to compare the role of different feedstock in the profitability of biorefinery. The chosen process in all scenarios is thermophilic anaerobic digestion in process temperature of 55 °C. However, substrate is heated into 75 °C for sanitizing substrate. As a reference gate fees for this analysis, public gate fees of HSY and Salpakierto are used. Probably these public gate fees are higher than gate fees for contract suppliers, and realistic gate fee is somewhere between break-even point and public price. All biomethane and produced biofertilizers are assumed to be sold in the scenario calculations and all used energy for process is bought from the energy markets. The value of the biofertilizers is assumed to be 70 % of the price of mineral fertilizers.

Table 8. Values in scenario calculations.

Annual treatment capacity		
Digester capacity	60000	t/a
Purchased energy		
Electricity	0,08019	€/kWh
Electricity transmission	0,05	€/kWh
Heat energy	40	€/MWh
Operating personnel		
Number of employees	3	Persons
Salary	2500	€/month
Salary including personnel expence	3750	€/month
Annual salary including personnel expence	45000	€/year
Substrate heating		
Energy consumption	4,18	kJ/kg/°C
Energy efficiency	95 %	
Heating 12 to 75 °C	63	°C
Required energy	277,2	kJ/kg
	77,0616	kWh/t
Selling price of end-products		
P fertilizer	322,50	$/t
N fertilizer	357,50	$/t
K fertilizer	562,50	$/t
Biomethane	1,05	€/kg
Currency conversion rate	0,948332	€/$
Gate fees		
Biowaste	79,04	€/t
Sewage sludge	109,00	€/t
Horse manure	10,00	€/t

4.1.1 Scenario 1: Biowaste only

Investment and operating costs are same in all scenarios. In the first scenario all annual 60 000 tons treatment capacity is filled by biowaste only. Gate fee is assumed to be 79.04 €/t, which is HSY's public gate fee for biowaste. Output of this scenario are presented in table 9. and profitability of this scenario is presented in table 10.

Table 9. Output of the scenario 1.

CH_4 production	4 464 000	m^3/a
CH_4 production	44 640	GWh/a
CH_4 production	3 720 000	kg/a
N production	384	t/a
P production	77	t/a
K production	192	t/a
Gate fee revenue	4 742 400	€/a

In this scenario methane production approximately 44 600 GWh/a is in line compared to similar size biogas plants presented in table 6. In this scenario sales of recycled nutrients do not play an essential role in total production.

Table 10. Profitability of scenario 1.

ANNUAL REVENUE	
Methane sales	3 906 000 €
N Fertilizer sales	91 131 €
P Fertilizer sales	16 442 €
K Fertilizer sales	71 694 €
Gate fees	4 742 400 €
Total incoms	**8 827 667 €**
ANNUAL COSTS	
Annuity	**2 858 386 €**
Operating costs	
Personnel	135 000 €
Heat	194 682 €
Electricity	1 465 808 €
Maintanance	27 400 €
Operating costs, total	**1 822 890 €**
Total costs	**4 681 276 €**
PROFIT	**4 146 391 €**

As presented in table 10. gate fees 54 % of total incomes and methane sales 44 % of total incomes are most essential characteristics of the total incomes. Sales of recovered nutrients covers only 2 % of total incomes in this scenario.

4.1.2 Scenario 2: Biowaste and Sewage sludge

Investment and operating costs are same in all scenarios. In second scenario 70 % of annual capacity is fed by biowaste and 30 % of the annual capacity is fed by sewage sludge. Usually, sewage sludge will be treated in separate reactor, which might affect the investment costs. In this study is assumed that all investments include two different reactors and the need for extra reactor is not included these calculations. However, this should be taken in account in investment plan related to biogas plant. Combination of biowaste and sewage sludge is quite common combination as a substrate of biogas plant. Gate fee is assumed to be 79.04 €/t, which is HSY's public gate fee for biowaste and 109,00 €/t for sewage sludge, which is Salpakierto's public price for sewage sludge. Output of this scenario are presented in table 11. and profitability of this scenario is presented in table 12.

Table 11. Output of the scenario 2.

CH_4 production	3 542 112	m^3/a
CH_4 production	35 421	GWh/a
CH_4 production	2 951 760	kg/a
N production	355	t/a
P production	108	t/a
K production	156	t/a
Gate fee revenue	5 281 680	€/a

In this scenario methane production approximately 35 400 GWh/a is a bit lower compared to similar size biogas plants presented in table 6. Also, in this scenario sales of recycled nutrients do not play an essential role in total production.

Table 12. Profitability scenario 2.

ANNUAL REVENUE	
Methane sales	3 099 348 €
N Fertilizer sales	84 296 €
P Fertilizer sales	23 070 €
K Fertilizer sales	58 251 €
Gate fees	5 281 680 €
Total incoms	**8 546 645 €**
ANNUAL COSTS	
Annuity	**2 858 386 €**
Operating costs	
Personnel	135 000 €
Heat	194 682 €
Electricity	1 375 793 €
Maintanance	27 400 €
Operating costs, total	**1 732 875 €**
Total costs	**4 591 260 €**
PROFIT	**3 955 385 €**

As presented in table 12. gate fees 62 % of total incomes and methane sales 37 % of total incomes are most essential characteristics of the total incomes. Sales of recovered nutrients covers less than 2 % of total incomes in this scenario.

4.1.3 Scenario 3: Biowaste, Sewage sludge and Horse manure

Investment and operating costs are same in all scenarios. In third scenario 50 % of annual capacity is fed by biowaste, 30 % by solid horse manure and 20 % of the annual capacity is fed by sewage sludge. Combination of biowaste and sewage sludge is quite common combination as a substrate of biogas plant. Gate fee is assumed to be 79.04 €/t, which is HSY's public gate fee for biowaste, 10 €/t for horse manure, which is lowest price for manure in HSY price list (HSY, 2023) and 109,00 €/t for sewage sludge, which is Salpakierto's public price for sewage sludge (Salpakierto, 2023). 18 % of horse manure generated in Finland, is generated in Uusimaa region. On the other hand, other types of manure have quite small share of the total biomass option in Uusimaa region, and for that reason horse manure is chosen to this scenario. Output of this scenario are presented in table 13. and profitability of this scenario is presented in table 14.

Table 13. Output of scenario 3.

CH_4 production	3 428 208	m^3/a
CH_4 production	34 282	GWh/a
CH_4 production	2 856 840	kg/a
N production	350	t/a
P production	81	t/a
K production	463	t/a
Gate fee revenue	3 859 200	€/a

In this scenario methane production approximately 34 300 GWh/a is a bit lower compared to similar size biogas plants presented in table 6 as well as compared to other two case examples. Also, in this scenario sales of recycled nutrients do not play an essential role in total production.

Table 14. Profitability of scenario 3.

ANNUAL REVENUE	
Methane sales	2 999 682 €
N Fertilizer sales	82 943 €
P Fertilizer sales	17 354 €
K Fertilizer sales	173 029 €
Gate fees	3 859 200 €
Total incoms	**7 132 208 €**
ANNUAL COSTS	
Annuity	**2 858 386 €**
Operating costs	
Personnel	135 000 €
Heat	194 682 €
Electricity	1 364 671 €
Maintanance	27 400 €
Operating costs, total	**1 721 753 €**
Total costs	**4 580 138 €**
PROFIT	**2 552 070 €**

As presented in table 14. gate fees 42% of total incomes and methane sales 54 % of total incomes are most essential characteristics of the total incomes. Sales of recovered nutrients covers only 4 % of total incomes in this scenario.

4.2 Comparison of different scenarios

In order to assess the role of used feedstock in the economic performance of biogas plant, three different scenarios with same investment costs and different substrate composition are compared.

Table 15. Comparison of different scenarios.

	Scenario 1.	**Scenario 2.**	**Scenario 3.**	
ANNUAL PRODUCTION				
CH_4 production	4 464 000	3 542 112	3 428 208	m^3/a
CH_4 production	44 640	35 421	34 282	GWh/a
CH_4 production	3 720 000	2 951 760	2 856 840	kg/a
N production	384	355	350	t/a
P production	77	108	81	t/a
K production	192	156	463	t/a
Gate fee revenue	4 742 400	5 281 680	3 859 200	€/a
ANNUAL REVENUE				
Methane sales	3 906 000	3 099 348	2 999 682	€/a
N Fertilizer sales	91 131	84 296	82 943	€/a
P Fertilizer sales	16 442	23 070	17 354	€/a
K Fertilizer sales	71 694	58 251	173 029	€/a
Gate fees	4 742 400	5 281 680	3 859 200	€/a
Total incoms	**8 827 667**	**8 546 645**	**7 132 208**	**€/a**
ANNUAL COSTS				
Annuity	2 858 386	2 858 386	2 858 386	€/a
Operating costs				€/a
Personnel	135 000	135 000	135 000	€/a
Heat	194 682	194 682	194 682	€/a
Electricity	1 465 808	1 375 793	1 364 671	€/a
Maintanance	27 400	27 400	27 400	€/a
Operating costs, total	**1 822 890**	**1 732 875**	**1 721 753**	€/a
Total costs	**4 681 276**	**4 591 260**	**4 580 138**	**€/a**
PROFIT	**4 146 391**	**3 955 385**	**2 552 070**	**€/a**

As a comparison of all three different scenarios, it is possible to say that most essential characteristics related to profitability of biogas plant are methane sales and gate fees. It seems that the profitability of biorefinery is highly depended on gate fees. If feedstock with high gate fee should be replaced by other feedstock without gate fee, the change in profitability is significant. In all scenarios operating without the proper gate fee will lead to negative profitability of biogas plant. Another important factor to total profitability is methane yield. In all cases methane sales has essential role in the profitability of the biogas plant.

Estimated break-even points for different feedstocks, when used separately as a substrate, helps to figure out how much of different feedstocks with low gate fee is possible to use as a substrate. For example, break-even point for biowaste is 10 €/t, for sewage sludge 51 €/t, and for solid horse manure 23 €/t.

In the results of these scenarios, seems that economic value of recovered nutrients in digestate does not play an essential role in the profitability of biorefinery. Even if recycled fertilizers were valued at the same price as mineral fertilizers, it would not seem to play a significant role in the profitability of the biorefinery.

However, recycling of nutrients could decrease the need for mineral fertilizers, increase the nutrient independency and mitigate emissions of the agriculture. In any case, as case examples showed, nutrient recovery by using current technology, is not profitable itself, but it might bring additional incomes for biogas plants.

4.3 Limitations

Existing data relating to investment and operating costs of the biorefinery varies a lot between different literature sources. That will affect the useability of the findings in the investment planning process, and further calculations are needed. All data about the investment costs or operating costs is based on existing literature and public sources and the content of data between different sources might differ significantly.

5 CONCLUSIONS

Food value chain consists of large variety of organic waste and residue streams which can be converted into renewable energy and recycled fertilizers. This study showed that anaerobic digestion has several roles in the green transition. On the one hand, it can help to reduce of fossil fuels and mineral fertilizers by converting organic waste streams into biomethane to replace natural gas and the by-product of the biogas production, digestate can be upgraded into biofertilizers in order to decrease the use of mineral fertilizers. On the other hand, anaerobic digestion has an essential role in the waste management. Anaerobic digestion is effective method for decreasing the volume of organic waste, and in addition, stabilize waste.

In the Finnish perspective, converting potential biomass into biomethane, it is possible to produce energy which replace approximately half of historic annual use of the natural gas. If the current geopolitical situation and the resulting economic sanctions continue and, on the other hand, the transition to renewable energy instead of fossil fuels continues as predicted, the potential share of biogas in the future may be even greater if the use of natural gas remains at a permanently lower level. This will increase the energy independency and help Finland to achieve it environmental targets such as carbon neutrality. On the other hand, if all potential biomasses will be treated by using anaerobic digestion, biofertilizers upgraded form digestate, could replace in case on phosphorous all need of mineral fertilizers, and in case in of nitrogen more than 93 % of the number of mineral fertilizers.

In addition to biogas and three most important nutrients, phosphorous, nitrogen and potassium, anaerobic digestion produces also other valuable products, which can be upgraded into valuable products. For example, CO_2 the side stream of the biogas upgrading, has use in industrial purposes and economic value as a product. On the other hand, digestate consists of significant amount of organic carbon, which is also valuable product.

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