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Sustainable Bioenergy
Solutions for Tomorrow

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**Saija Rasi, Erika Winquist, Vilja Varho, Minna Kahala, Eila Järvenpää, Yrjö Virtanen, Vesa Joutsjoki, Lucia Blasco**

# Non-wood biomass as raw material in biorefinery processes

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# Summary

A shift from the present fossil economy to a truly biobased economy increases the need of all renewable biomass. Agricultural and food waste biomaterials are essential raw materials for production of value added products, energy and nutrients. Transformation of byproducts into commercial products must be market driven or create a product that has a realistic possibility of being sold with an economic margin within a reasonable time period. At the same time, because of the scarce amount of raw materials, the processes has to be resource efficient.

The policy environment brings boundaries, what raw materials are accepted and in which way the environmental effect of the process is calculated. Nevertheless, the demand for environmental effect minimization through greenhouse gas emissions is increasing in EU. This brings both possibilities and challenges as in biorefineries the biomass is used more effectively to various end products while increasing processing methods may increase energy use and the cost of the products.

This paper brings a brief overview of the different possibilities to utilize agricultural and food waste based biomasses instead of energy use (alone). Two potential processes for non-wood based biomass valorization were evaluated. The selected cases were from food industry and municipal food waste but same processes are valid for various biomasses. The biomass availability and policy environment are also discussed.

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Helsinki, December 2016

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# 1 Introduction

There is a growing need to replace fossil resources with renewable resources due to both the exhaustion of fossil resources and the climate change. A shift from the present fossil economy to a truly biobased economy increases the need of all renewable biomass. Along with the increasing demand, the use of biomass has to be prioritized for food, feed, biomaterials, biochemicals and biofuels although the recent technological developments allow the efficient utilization of various biomasses and wastes as energy products (electricity, heat, cool, traffic fuel) as well as other value added products. The choice of a particular biomass raw material for food or feed applications, power, fuel, and biomaterials depends on a variety of factors, such as availability, public policy, cost of biomass, capital cost of process equipment and facilities, and markets for alternative energy and materials. The operational cost and the value of the target products are the two main factors that determine the feasibility of a biomass conversion process. An important factor in future is also the biomass availability, which might be among the barriers for a transition to biobased compounds. Biomass availability is also often seasonal, as many crops and plants are harvested at a specific time of the year, and this causes challenges for the storage, logistics and processing. Transformation of byproducts into commercial products must be market driven or create a product that has a realistic possibility of being sold with an economic margin within a reasonable time period.

Food waste from homes, restaurants and catering facilities, food markets and food processing activities represents a large proportion of the municipal waste stream. The Food and Agriculture Organization (FAO) estimates that the producers' direct costs of food going to waste are $750 billion every year. It is estimated that the total global economic mitigation potential for reducing waste sector emissions by 2030 is more than 1000 Mt $CO_2$-eq (or 70% of estimated emissions) at costs less than 100 US$ $t^{-1}$ $CO_2$ -eq per year (Bogner et al 2008). The circular economy can offer tools to enhance and optimize the sustainability of food waste management and give European companies tools for increasing competitiveness and export.

The aim of this work was to gather information about valuable compounds in various biomasses and evaluate two potential processes for non-wood based biomass valorization. The biomass availability and policy environment are also discussed. The selected cases are from food industry and municipal food waste but same processes are valid for various biomasses.

**References:**
Bogner et al. 2008. Mitigation of global greenhouse gas emissions from waste: conclusions and strategies from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. Working Group 3 (Mitigation). Waste Management & Research.26:11-32.

# 2 Availability of agricultural and food waste based biomasses

In Finland, the greatest biomass resources lie in forests, and the majority of new bioenergy is expected to be found in the forests up to 2030 and beyond. However, in the EU and global level most bioenergy increases are expected to result from agricultural biomasses (Kallio et al. 2015). Related research efforts and increased experience in this area may lead to fast technological development and cost reductions. In addition, the need for climate-neutral energy is so significant that it seems inevitable that also agricultural biomasses are required for bio-based processes in Finland to some extent.

Although it is possible to produce crops for energy production, in this chapter the focus is on agricultural side streams as manure and straw. In addition, grass, which is mainly used for feed, is discussed here from the perspective of energy use. In current Finnish conditions, the gathering and use of agricultural biomass for energy alone is rarely profitable. Instead, the adopted solutions combine energy production with waste management or other needs.

In this part of the study, policies that affect the availability and feasibility of using agricultural biomasses are reviewed. In addition, perspectives related to farming practices and conditions in Finland are discussed for straw, manure and grass. The analysis is based on document analyses and consultation of researchers as well as representatives of Finnish authorities, in e.g. Finnish Food Safety Authority Evira, Ministry of Transport and Communications, and the Ministry of Agriculture and Forestry.

## 2.1 Policy environment

There is a strong political mandate for using agricultural biomasses for energy production. For example, concepts like bioeconomy and circular economy have become very important political terms. Climate policies promoting renewable energy are even more widespread. In addition, there do not seem to be any policies directly forbidding or hindering the use of straw, manure and grass to energy production.

Barriers in the energy networks, practices and legislation have been found to be significant in hindering distributed energy production. The Finnish Ministry of Economic Affairs and Employment set a working group in September 2016 to study the use of intelligent networks in serving customers and enabling small-scale renewable energy production.

The Finnish Bioeconomy Strategy (2014) set the goals of increasing the bioeconomy output from the 60 billion EUR in 2014 to 100 billion EUR by 2025, and creating 100,000 new jobs. An important initiative within the strategy, expected to improve the prerequisites of biomass use is “Biomassa-atlas”. It will bring detailed information about different biomasses and their locations to open use and will be published in 2017 (Lehtonen et al. 2014).

In the European Union there are several policies, both existing ones and those under current renewing processes, which support and influence the use of biomasses in energy production. Many of these are related to other policy sectors than energy. Nutrient recycling is particular importance when discussing agricultural biomasses. For example, the vital nutrient phosphorus (or more correctly its source phosphate rock) has been classified as a critical resource in the EU, relying heavily on imports from outside the EU (European Commission 2014). It must be assumed that policies that improve the recycling of phosphorus will continue to be developed and enforced in the EU.

The European Union fertilizer legislation and waste legislation are ongoing modifications. As part of the European Union Circular Economy Package, a new proposal for regulating fertilizers from biowaste or other secondary materials was recently presented (European Parliament 2016). It is meant to enable the growth of production and markets of organic fertilizers. Recycling nutrients is often compatible with the energy use of agricultural biomasses, and getting income from, for example, both biogas and organic fertilizers would increase the feasibility of both. Both the Ministry of Agriculture and Forestry and the Ministry of the Environment have funds for projects that aim for increased recycling of nutrients. In Finland, the tools seem to be more “carrots” than “sticks”, meaning e.g. investment subsidies and agricultural extension.

The waste hierarchy that promotes the reuse or recycling of materials over the retrieval of energy content still stands, meaning that waste materials should not be burned if other uses are available. This often favors the recycling of nutrients, as many nutrients are lost during burning.

Finnish policies reflecting the nutrient issues include the current Finnish Government Programme (Prime Minister’s Office, 2015) which has set a target of getting half of all manure to improved processing by the year 2025. The goal is based on the need to recycle nutrients and reduce eutrophication, but it may also have energy implications.

Similarly, in waste management a new policy is to increase the recycling of organic waste. The Government regulation (VNa 331/2013) mandates that from the beginning of 2016, waste with higher than 10 % organic content may not be placed in ordinary landfills. This means that there will be various types of biomass that need to be processed, such as garden and park residues, waste streams from industry, and sludge from waste water treatment facilities. Whether these will be in competition with agricultural biomasses or whether their use will complement and make possible the use of agricultural biomasses is not yet clear.

The EU Energy Package is also currently being renewed. The EU climate targets include cutting at least 40% of greenhouse gas emissions compared to

1990 levels, at least 27% share of renewable energy consumption, and at least 27% energy savings compared to the business-as-usual scenario (the new Commission proposal is 30% energy efficiency by 2030 (European Commission 2016). In Finland, the current Government Programme (Prime Minister's Office, 2015) sets the targets of reaching over 50% share of emission-free renewable energy during the 2020s.

The Finnish energy and climate strategy is also under review. The Government accepted a new energy and climate strategy on Nov. 24th 2016 and it will be discussed in the Parliament soon after.

The Finnish renewable energy subsidies have so far mainly consisted of investment subsidies and feed-in-tariffs. The new trend is towards auctioning, in which payments to renewable energy installations are determined by a competitive system. Only those projects that that have won a tender will receive payments for the power they supply. This type of support is in line with European Commission's goal of having market-based renewable energy policy structures. The aim is to have a technology neutral system, but as the legislation is not yet finalized, It is not yet clear whether the Finnish system will be tailored for different energy forms or project sizes (as in Germany).

Promotion of renewable fuels has been important in cutting $CO_2$ emissions from transport. For example, the current Finnish Government Programme (Prime Minister's Office, 2015) states that 40% of transport fuels should come from sustainable biological resources by the year 2030, and the use of imported oil for domestic needs should be halved during the 2020s. The focus is particularly on liquid biofuels and biogas. In the new energy and climate strategy (Valtioneuvosto 2016) this goal has been specified to include also electricity from renewable sources and to count double the energy content of biofuels from wastes or inedible cellulose or lignocellulose.

The new Finnish energy and climate strategy states that the better utilization of the biogas potential of agricultural biomasses will be promoted. National regulation regarding biogas production and use will be clarified, economic support to biogas plants will be continued on at least current level, and there will be actions directed at the uptake of vehicles and machinery that use biogas.

Agricultural biomasses could be used for producing biogas that can be treated to produce biomethane for transport. Farm level biogas plant investments are currently eligible for a 40% subsidy, but this applies only to the use within the farm, not to gas sold out of the farm.

Transport biomethane has so far been exempt from energy taxes, but this situation may change. There were only about 2 200 vehicles using gas in Finland in the beginning of 2016, or only 0.05% of passenger car fleet. At the same time, there were 24 pressurized gas fueling stations (Ministry of Transport and Communications 2016). There has been a vicious circle so far: there have not been many vehicles that use biogas, partly because there has not been enough supply of transport biomethane, and on the other hand, there have not been enough incentives to build a methane supply network, because there is not sufficient demand. However, the use of biomethane is expected to increase in Finland, partly as a result of Directive on the deployment of alternative fuels infrastructure (Directive (EU) 94/2014). By the end of the year 2020, the Directive requires there to be enough fueling points offering pressurized gas (CNG) to ensure availability of gas in cities, suburbs and other densely populated areas. By the end of 2025, there needs to be enough CNG refueling stations along the TEN-T Core Network to be possible for CNG vehicles to circulate everywhere in the Union. There are also requirements for the supply of liquefied natural gas (LNG) for heavy transport and in particular for water transport. Although these requirements may be fulfilled with natural gas alone, biomethane can also be used.

The Finnish company Gasum is the largest provider of transport biomethane in Finland with 18 stations situated in Southern Finland. Gasum offers both natural gas and biomethane at all its public fueling stations. It aims to construct 35 new fueling stations in the next ten years (http://www.gasum.com/Transport/Filling-stations/ 29.9.2016). About 40 % of transport methane used in Finland was from biogas in 2015 (Valtioneuvosto 2016), even though it is more expensive than natural gas on Gasum stations.

A potential longer-term risk for the use of biomethane is that electric vehicles become the norm, and that combustion engines will be banned, as has been suggested in e.g., Germany. Currently the prices of cars using methane are, however, very reasonable compared to many electric vehicles, and as using methane is cheaper than using gasoline or diesel, a biomethane car is one of the cheapest methods for reducing greenhouse gas emissions from transport available for an individual.

If materials for bioenergy or biofuels come from fields that have previously been used for food or feed production, it may lead to the production of food and feed in additional lands. If the new fields have existing carbon storages, the change in their use may lead to a release of carbon into the atmosphere (not taking additional lands to use, on the other hand, could lead to diminishing global food security.) To counter these indirect land use changes, the so-called ILUC directive (Directive (EU) 2015/1513) limits the share of biofuels from crops grown on agricultural land that can be counted towards the 2020 renewable energy targets to 7% (the new renewable energy directive proposal giving the limit as 3.8% in 2030). The Member States are also encouraged to discontinue public subsidies to the use of such biofuels.

Agricultural side streams such as straw and manure are not affected directly by these changes, but it can be assumed that their competitiveness increases in the market as a result. In addition, fuels from straw and manure are specifically mentioned to be counted double, meaning that they contribute double their actual energy content to the energy target.

Post-2030 it is likely that the so-called 1st generation biofuels will be phased out entirely, and the cascade use, waste hierarchy and advanced biofuel technologies will significantly limit the use of many currently used biomasses for energy production.

According to existing EU sustainability criteria, biofuels must achieve significant greenhouse gas savings compared to fossil fuels. This savings requirement of has been at least 35%, rising to 50% in 2017. In 2018, the requirement will rise again to 60% but only for new production plants. All life cycle emissions are taken into account, including emissions from cultivation, processing, and transport. This means that materials with rather low energy content, such as manure, cannot be transported long distances for fuel production.

In the new renewable energy directive proposal, the EU sustainability criteria are extended to cover solid biomass and biogas used in heat and power plants of over 20 MW. This would mean that electricity and heat from biomass have to produce at least 80% lower GHG emission compared to fossil fuels by 2021. This would be significant for e.g., biogas use, but the sustainability criteria are not finalized yet.

In Finland, a large majority of biofuels already come from non-food sources, such as food waste and forestry side streams. There is much production of bioethanol and renewable diesel, and very little production or use of traditional biodiesel (FAME). Finland has a high level of biofuel use: in absolute terms some 13% share, and over 20% share when the double counting is used (Ministry of Transport and Communications 2016). This has been achieved through e.g. legislation that sets the minimum share of biofuels to all transport fuel distributers, namely the Act on the Promotion of the Use of Biofuels for Transport (446/2007). The new energy and climate strategy sets the new target as 30% (absolute share, i.e. 53% using the double counting).

## 2.2 Straw

The straw crop is quite substantial, essentially of a similar size as the cereal crop, meaning some 4,000 million tons yearly in Finland (Satafood Kehittämisyhdistys ry & Raisio Oyj 2014, Luonnonvarakeskus 2016a). There is therefore quite large biomass potential, but straw is not used significantly for energy in Finland. It can be burned as such, normally with other fuels such as peat or wood, or it can be turned to biogas or bioethanol.

Currently some straw is gathered for animal bedding, but the most common way to utilize straw is to shred and leave it to the fields. This is the cheapest method and it may have significance for farming conditions. Plowing vegetable residues such as straw into the soil upkeeps the amount of organic matter in soil. The amount of organic matter is one of the most important factors determining the growing conditions in a field, and it has been declining in Finnish fields for decades.

Carbon storages in soil are also an important question from the perspective of climate change mitigation. The Paris climate agreement includes commitments to increase soil carbon storages. In various studies removal of straw has had an impact on carbon in soil, but the impact has been fairly small and has rarely been statistically significant (e.g. Blanco-Canqui & Lal 2009, Powlson et al. 2011, Regina 2015). It is not likely that agricultural soils would become carbon sinks in Finland.

There is no definite answer to how often residues can be removed from the field without weakening the productivity of fields. The answer depends on soil quality, climate, topography, sensitivity to erosion, crop rotation, application of organic fertilizers, etc. Although the impact to soil quality is not very clear, it is probably not wise to remove all straw on a yearly basis from the fields. In addition, there needs to be some compensation for the farmer for giving up straw. Sustainable removal has been estimated to be 1-2 times out of three years, but this should be determined based on the local conditions (Blanco-Canqui & Lal 2009, Powlson et al. 2011, Pahkala & Lötjönen 2015). In terms of energy, money and labor used in the harvest, it is more sensible to harvest more straw every other year than to harvest shorter stalks every year.

Harvesting heavy loads can increase the compression of soil, which is detrimental for farming. Benefits of straw include the fact that it is dry at the time of harvesting, reducing weight. Straw also has a high dry matter content. Adding 5 percent (weight) of straw to cow manure in a biogas process could increase the yield nearly twofold compared to manure alone (Tähti & Rintala 2010).

A survey was conducted in South-Western Finland (Varsinais-Suomi and Satakunta) in March 2013. The questionnaire was sent to 1936 farmers, of whom 403 (=21%) answered. Of those who answered, 54% were interested in selling straw yearly, and 26% of the respondents would sell straw every other year. Views about the suitable price varied greatly.

For farmers the most pressing difficulty to gather straw may be the lack of manpower. During the harvest there is little time to gather straw. In general, the surveyed farmers thought that straw should be gathered by an outside contractor (Satafood Kehittämisyhdistys ry & Raisio Oyj 2014).

The window of harvesting is short in Finland and a wet fall could cause significant variations in yearly supply. Straw is only available during the fall. There are detailed studies on harvesting, storage and possible uses of straw available in Finnish (Satafood Kehittämisyhdistys ry & Raisio Oyj 2014; Äijäläinen 2016).

TTS (Työtehoseura) and Neste Oil studied in 2013-2014 the possibility of gathering straw from Finnish farms to be used as raw material in the production of renewable diesel. Although the results regarding straw harvesting were rather positive (Työtehoseura 2014), Neste decided not to invest in its use at the present.

The company Suomen Bioetanoli (SBE) is planning to establish an ethanol plant at Myllykoski. The original idea was to use only straw, but because sufficient number of contracts with suppliers could not be made, the company has searched for alternative sources, such as hulls from cereals. Similarly, Scanchips is planning on a bioethanol plant in Sievi, with straw being one of the raw materials.

It has been suggested (e.g. Paakkarinen 2014) that a company or co-operative that specializes in the collection and logistics of straw would be needed in Finland. Such a company could ensure the availability of sufficient amounts of straw every year, adequate logistics and storage facilities and year-round supply of straw to processing companies.

## 2.3 Manure

Compared to some other agricultural biomasses, manure has the advantage of being available at fairly steady amounts around the year. The amount of manure is some 17.3 million tons yearly in Finland, excluding fur animals. Cows produce the overwhelming majority, some 12.3 million tons. Pigs produce some 3.5 million tons, horses 0.77 and poultry 0.4 million tons a year. Most of the manure is spread to fields without any treatment (Luonnonvarakeskus 2016b).

The manures are not distributed evenly across Finland. Instead, there are “cattle regions” and “cereal regions”. In some areas, farmers have difficulties to find fields where to spread manure. This is partly a result of increasing farm and cattle size, which is expected to continue as farmers aim to improve the profitability of their farms through specialization and economies of scale (Lehtonen et al. 2011). Paying a gate fee to a biogas plant, for example, may be an option for manure management.

Finnish biogas operators do not take in manure, if there are other materials that pay a gate fee, such as industrial side streams. Manure delivery is often based on a gate fee or at least the delivery costs are covered by the farmer. Manure deliveries may be connected to biogas plants shares so that shareholders deliver manure and receive digestate to their fields according to their share. There is often no price on the digestate, but some operators produce and sell organic fertilizers made from the digestate. Currently the profits of biogas operation result mainly from gate fees. The significance of energy or fertilizer production in the business may change if the costs of energy or fertilizers increase, or legislation and subsidies are altered (Juvonen 2012, www.bio10.fi).

As manure is already normally spread to fields (or the digestate is), there is no direct positive impact to soil carbon storages from treating manure differently. However, it is likely that the carbon that turns into biogas is of the type that would have decomposed quickly in the soil as well. This means that replacing fossil fuels with biogas can lower the overall $CO_2$ emissions without compromising soil carbon storages. This matter has not been thoroughly investigated, however, and there is an ongoing research project in Natural Resources Institute Finland (Luke) regarding the decomposition of different materials in soil (Maanparannusaineiden hiilitasevaikutuksen mallinnus).

In addition, treating manure so that it can be economically transported longer distances and spread to existing fields could reduce the need to clear additional lands for the spreading of manure. These new fields are often peat soils in Finland, and they emit large quantities of carbon when cleared and tilled (Regina 2015).

### 2.3.1 Horse manure

Approximately one million $m^3$ of horse manure was produced in Finland in 2014 (Luostarinen et al. 2016). Its management depends on its location, availability of fields for spreading manure and the bedding material used in the stables. Manure is often first stored and then spread to fields, particularly in the countryside. In more densely built areas composting is used, mainly in larger facilities that treat also other biological wastes. Nitrogen is often lost in the process. For energy use, three treatments are possible. Energy use is secondary to recycling according to the waste hierarchy.

***Burning***: The burning of horse manure is strictly regulated, and has to meet the norms of waste burning, incl. continuous measurement of emissions. Finland has tried to effect a change within the European Union to have horse manure classified differently. Allowing the use of horse manure in energy production is also listed in the current Government Programme (Prime Minister's Office, 2015) as a means for increasing the share of renewable energy production. However, this change in EU regulations is not likely to take place, according to the current Finnish Minister on Agriculture and Forestry Kimmo Tiilikainen.

The energy company Fortum recently gained a permit to burn horse manure in an ordinary heat plant in Järvenpää, after a pilot phase and monitoring of the impact of adding manure to fuel mixture. Whether horse manure burning becomes more widely acceptable or not, researchers estimate that its use will not be very widespread in Finland. The most potential areas are those where there are a lot of stables and not enough fields or other waste management opportunities, but instead high energy demand. These are most likely to be near cities, and in fact, the largest density of horses is found near cities (Helsinki Metropolitan Area, Turku, Tampere, Lahti, Jyväskylä, Kuopio, Vaasa, Oulu). The idea behind Fortum's business model Horse Power is to provide stables with a service: providing the bedding material to stables and taking the manure to the power plant. The stables pay a fee for the service.

Although stables might like to burn their own manure to reduce the need for other energy for heating, managing small-scale burning in terms of e.g. emissions may be difficult (Luostarinen et al. 2016). Burning horse manure may produce high nitrogen oxide emissions and also other nutrients are often lost.

***Biogas*:** Currently horse manure does not commonly end up in biogas facilities. Stables could aim to treat manure in biogas reactors, but some of the bedding materials used, namely wood chips or sawdust and peat, are not the most suitable for biogas production in wet processes. It is possible to use it in dry processes, but wood chips require some pre-treatment in order do not produce methane. This type of manure does not compost well, and it is not suitable for spreading to fields, which makes it the most difficult manure to dispose. Straw as a bedding material would be better for biogas production.

The biogas production process has additional advantages in the disposal of manure. First, it turns part of the nitrogen in the manure into a dissolved form, which the plants can quickly use. This can reduce the amount of nitrogen that flows into waterbodies. Second, the process has been found to turn seeds of the weed wild oat (*Avena fatua*) infertile, so the digestate can safely be used as a fertilizer (Tampio et al. 2014).

***Gasification/pyrolysis*:** Gasification and pyrolysis means turning solid fuel into gaseous and/or liquid form with heat. This would enable the capture of nitrogen from gas stream, and allow a more effective recycling of also other nutrients. The process will require further development, but it might be possible in plants of a few megawatts (Luostarinen et al. 2016).

### 2.3.2 Pig and cow manure

Pig and cow manure is wet (not suitable for burning) and is most commonly spread to the fields as such. Difficulties arise to the farmer if the fields already have a high phosphorus content, and suitable fields are not found for spreading.

Nitrogen fertilizing is affected by the so-called nitrates directive (European Council 1991). It sets, for example, the maximum annual limit to nitrogen from manure that is spread to fields (170 kg of nitrogen per hectare per year) for Nitrate Vulnerable Zones. This is often not a problem with manure in Finland. Over-fertilizing with very high nitrogen levels is not sensible anyway, as it can e.g., increase the height of cereal plants causing a risk of them being flattened to ground.

As phosphorus stays in the soil for longer, it is common to use phosphorus fertilizers (such as manure) only once every few years. Adding over 15 kg of phosphorus per hectare per year on fields that already have good phosphorus content disqualifies the farmer from the EU environmental compensation system. In this system, farmers receive payments that provide compensation for additional costs and income losses that result from environmentally friendly farming practices. Using more phosphorus fertilizers is therefore legal but often not advisable from the economic perspective. Over 90% of farms get this compensation in Finland. From the environmental perspective, over-fertilization causes eutrophication of waters, which is a common problem in Finland.

It is difficult to replace inorganic fertilizers with manure, because the nutrient content of manure is not as exact, especially if the manure is not mixed well. Organic materials need to be processed to improve their consistency and usability before they can be competitive in the market. Digestate can be separated to liquid and solid phase. The liquid phase of digestate from a biogas plant has higher nitrogen content than raw manure, whereas the solid phase has less soluble nitrogen but plenty of phosphorus.

Organic fertilizers may have use also in forests in the future. Spreading of manure is not possible in forests in Finland at the moment. The application of more advanced organic fertilizers is currently hindered by lack of spreading equipment and uncertainties regarding their long-term impacts to forest microbes, fungi and flora. There are also increasing amounts of ash for which new uses need to be found, but currently there is a lack of suitable equipment for spreading ash in the forests.

### 2.3.3 Poultry and fur animal manure

The EU regulations (Commission Regulation (EU) No 592/2014) allow the burning of poultry manure for energy without waste burning requirements. The power plant can only use the manure of the single farm it is located on, has to produce less than 5 MW, and has strict regulations concerning the heat level and the emissions, but the emissions do not have to be measured continuously. However, the Finnish poultry farms have not taken advantage of this possibility and no plant permission requests have been filed by October 2016.

Poultry manure is being largely used for organic fertilizers in Finland. There have also been very small imports of poultry manure for fertilize use. However, many farms are currently struggling with new fertilizer limits and a third of poultry farms were left outside the environmental compensation. Farmers wish to get more use out of the manure and a new research project in the Natural Resources Institute Finland (Luke) called “Enhancement of poultry manure use - Teholanta” is studying the use of poultry manure for both fertilizers and energy. Digestate from biogas would be available for fertilizer use but also burning is being studied.

Fur animals such as minks and foxes are raised mainly in Pohjanmaa (western Finland). The manure is commonly composted and then spread to fields. There is some difficulty in finding suitable fields, as the fur farms are concentrated in a relatively small area, commonly do not have fields of their own, and the manure contains high levels of phosphorus. A recently started project by Natural Resources Institute Finland (Luke) and the City of Kalajoki called “Arvobiolanta” is aiming to combine manure from fur animals with biochar to produce growing substrates. The aims are to reduce the environmental impact of fur production and to increase nutrient cycling from Baltic fishes to farming and food production.

## 2.4 Grass

Grass is grown not only on fields and pastures but also on various environmentally motivated fields or strips. Most of these types of grass areas, such as buffer strips or green fallow may be harvested. Ecological focus areas, however, are not to be harvested. The fields need to be mowed in order to keep e.g. tree saplings at bay, but the grass is not always gathered. Cutting grass is relatively quick and cheap, but gathering, transporting and storing the grass requires more effort. Often the grass is simply crushed and plowed into the ground. There are estimated to be over 680,000 hectares of grass in the production of feed in Finland in 2016 and over 260,000 hectares of grass-covered fields outside feed production (Luonnonvarakeskus 2016c). Many fields or strips are very small, however, making harvesting difficult or uneconomical.

Because the grass crop varies yearly, animal farms often aim to produce some surplus grass. In this way they are not dependent on the market for their needs if the grass crop is smaller than usual. This means that usually a few percent of grass that is harvested and stored over the winter remains unused. Getting rid of the surplus means some extra work for the farmer. Often the surplus is composted or crushed and placed in soil. Small-scale marketing of the surplus also takes place, but on a good year most farmers already have surplus and are not buying. This surplus as well as the grass from the various types of fallow fields could be used for energy production, particularly biogas.

In the USA, some farmers specifically grow grass for biogas production. In Germany, maize is grown for biogas production. In Finland, the lower biomass production rate combined with less intensive land-use (fields dispersed) and low energy prices make this type of production less lucrative. If non-animal farmers knew that there was a market for grass, they might grow grass for energy production also in Finland. Considering the need to avoid indirect land use changes (ILUC), the use of existing grass fields that are not in agricultural production as well as the surplus feed might be seen to be best. However, grass grown specifically for biogas production would compete not only with agricultural production but also with fallows, and therefore only very large scale biogas production based on grass would have significant impact on cereal production in Finland (Seppälä et al. 2014). As grass fields do not need to be tilled yearly, they help to upkeep the carbon in soil. This is particularly important in peat soils, which can emit a lot of carbon when the peat decomposes.

The problem is often in getting enough grass in a small enough area for economically feasible biogas production. At the moment, biomethane for transport seems to be most profitable.

Farmers' willingness to produce grass to energy use was estimated in the Bionurmi –project. Economic calculations were carried out for crop producing farms in the Southern Finland. The estimates were conducted assuming that the farmer receives no direct compensation from the biogas producer. The biogas producer is granted access to the fields, and allowed to harvest grass from them. The producer is also expected to fertilize the fields and to ensure that the farmer receives no sanctions for neglecting good local farming practices. The benefits to the farmer result mainly from the reduced time spent on farming and visits to the fields. Having grass in the crop rotation has many advantages for crop production, e.g. in the form of improved soil consistency, reduced pressure from crop diseases and reduced need for nitrogen fertilizers (Seppälä et al. 2014).

According to the analysis, small farms were estimated to benefit most from this model. With biogas grass the farm can enjoy the crop rotation benefits without worrying about marketing the harvested grass. On mid-sized and large farms this no-payment biogas business model is likely to be less lucrative. Their equipment is often not in full use and growing biogas grass or leaving fields fallow does not provide crucial cost savings. If the farmer has a need to maintain or increase farming income and has sufficient human resources for larger field area, he/she is not likely to leave the fields for biogas grass production without payment for grass (Seppälä et al. 2014).

The Bionurmi project concluded that a significant portion of farms in Southern Finland could consider grass for biogas as an interesting option to growing cereals and having fallows. Most interested are likely to be small farms that have need for crop rotation, but the grass to be gained from them would likely be in small lots from geographically dispersed farms. Large farms would probably be interested in grass production if they have need for crop rotation and have alternative uses for equipment or personnel (Seppälä et al. 2014).

There were also workshops for farmers in the Bionurmi project. Farmers were interested in the biogas opportunity. They noted that single farms are often too small for a biogas reactor, and grass from several dozens of farms would usually be needed. The farmers expressed a desire to keep the energy production in local hands, wishing to counter the perceived dominancy of large energy companies. For example, co-operatives could be formed on the community level. The farmers also expressed concern about increased traffic in the area caused by a plant. They wanted to have control of farming decisions on their farms, such as when the grass is gathered and where the digestate is spread. It seems that various types of contracts between farmers and a biogas producer are required to meet the individual needs and circumstances of the farmers (Seppälä et al. 2014).

## 2.5 Food waste

Food waste can also be seen as an agricultural product, even though unwanted. There are numerous initiatives ongoing in Finland and abroad that aim at reducing the waste of food. However, there will always be some waste, resulting in e.g. food processing, and it would be important to take these valuable materials to use.

A study published in the EU in 2010 revealed that almost 90 million tonnes of food waste are expelled every year and 35 Mt of this amount originates from the food industry (*Preparatory study on food waste across EU 27*, 2010). The highest volumes of food waste is usually found within the production chains of fresh fruit, vegetables and bakery products. Significant losses also occur within dairy and grain production chains (Bos-brouwers et al. 2012). Food waste can be used as raw material for energy production. For example, St1 is producing bioethanol for transport, using food waste from bakeries, industry, shops and consumers. Food waste is also a reservoir of nutrients; Carbohydrates, proteins and lipids can serve as raw materials for commercially important new compounds (Ravindran & Jaiswal, 2016). Food waste is often available around the year and has potential to complement the use of straw or other agricultural biomasses that are only available for shorter periods. Using the same equipment to treat multiple raw materials such as food waste and manure can increase the efficiency of a system. Questions may be raised, however, about the acceptable uses of products from manure and other waste.

There are numerous research efforts regarding the bioconversion of food industry waste for commercially important products like biofuels, enzymes, organic acids, biopolymers and nutraceuticals. Chapters 3 and 4 present examples of producing such valuable compounds, but only from plant-based materials. Animal-based by-products have been experimentally tested and piloted earlier in Luke (Aalto, 2010; Pihlanto et al, 2012; Tikka, 2010). In chapter 5 an example is given regarding the treatment of separately collected food waste.

Integrated valorization of main and by-product biomass flows within or near agricultural production systems gains advantages. It is important to ensure the optimal use of the biomass, i.e. the use of cascade systems and system integration in the whole value chain. Recent studies suggest that the production of bulk chemicals from biomass waste is 3.5 times more profitable than converting it into biofuel (Ravindran & Jaiswal, 2016). The development of advanced conversion technologies suitable for different types of biomass and the implementation of flexible and fast-to-install small-scale production technologies would have potential to make bio-based products competitive with petroleum-based products. Coproduction of a range of platform chemicals or materials and biofuels in integrated biorefineries could play a key role in the return on investment. Potential of the multi-biomass approach has been shown by using two biomass sources instead of one, resulting in a 15–20% cost reduction (Bos-brouwers et al., 2012; Rentizelas, Tolis, & Tatsiopoulos, 2009). In a Danish survey the most important market sectors in a transition towards a BioEconomy were suggested to be chemical industry and the biofuels sector (Jörgensen, 2015).

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# 3 Extraction and fractionation as preprocessing tools for the recovery of value-added compounds

Food industry by-products are suitable raw materials for production of many commercial compounds, and this could be in many cases more feasible added-value use than the use as food or feed. Compounds include vitamins, colorants, other bioactive compounds, fats and oils, proteins and dietary fibers and other functional biopolymers (see Table 1). Now these originate from virgin agro-food materials and they are produced via established extraction and fractionation processes. If the quality and stability of the recycled raw materials is high enough, they could be processed same way. Proposed methodologies typically involve organic solvent extractions (e.g. Mirabella et al, 2014) but also “greener” solvent systems have been proposed (e.g. Herrero et al, 2015). A COST Action review is one of the most recent and thorough presentation of the technologies (Arshadi et al 2016). Typical European examples are lycopene (carotenoid) from tomato waste resveratrol (polyphenolic compound) from wine production waste. A Finnish company Aromtech Oy (www.aromtech.com) extracts berry seed oils from juice press-cake, and sells them as nutraceutical ingredients. Especially small-molecular weight compounds are also produced by chemical and biotechnological industries, often based on non-renewable (fossil-based) raw materials. Extraction and separation/fractionation processes are involved also there, and the end products include oil- or ethanol-based essences or fragrances, as well as flavours, pigments, nutraceuticals and APIs. It should be notified here, that by microbial and enzymatic bioprocessing, overall quality of the biomass itself, and the content and nature of its added-value compounds can be modified (see chapter 5).

An example of processing options of a vegetable-based biomass is illustrated in Figure 1. In this case a carrot by-product is extracted using vegetable oil. Oil dissolves oil-soluble compounds, in this case carotenoid pigments and oil-soluble flavor and aroma compounds. Fractionation by centrifugation (as in the illustration) or pressing removes water and/or oil with dissolved valuable compounds and solids remain. Carotene-rich oil is easily obtained by additional separation process of oil and water phases. One further advantage of the pressing/centrifugation of carrot and other plant-based biomass is found, when the material needs to be transported long distances – a portion of excess water is removed, thus the transportable biomass weight is reduced, and leaking of nutrient-rich water is prevented.

This simple separation provides raw extracts, which can be sometimes used as such e.g. for non-food applications or as a nutritional additive in feeds. More specific separation processes are needed for the purification of natural or by fermentation produced biomolecules for pharma or special food or feed ingredient use.

**Table 1.** Resource potentials from different food waste (*based on mass balance).

| Food waste fractions and sub-fractions | Biocomponents | Energy value reduction %* | Other comments |
|---|---|---|---|
| **Vegetables:**<br>Proteinous<br>Starch-plants<br>Oils (see below)<br>Others<br>whole/intact rejected vegetables | Aromas, flavours, pigments, antioxidants, other bioactives (S- and N-compounds)<br>Dietary fibers, prebiotics<br>Proteins, peptides | <1 %<br>5-20 %, depending on the source<br>5-20 %, depending on the source | DM low → logistics to processing and storage<br>→shelf life |
| **Grains/ milling and bakery waste**<br>Protein rich fractions<br>Fiber rich fractions<br>Some fractions contain high amounts of fat and/or sugars | Proteins: functionality and nutritional value<br>Fiber fractions | < 20 %, depending on the source<br>5-20 %, depending on the source | |
| **Berries and fruits:**<br>Skin/peeling waste, seeds<br>”berry/fruit marc” whole/intact rejected products | Aromas, flavours, pigments, antioxidants, other bioactives (S- and N-compounds)<br>Seed oils<br>Dietary fibers, prebiotics | <1 %<br>5-50 %, depending on the source | Typically, high content of sugars, fruit acids and volatile esters. This waste prone to native fermentation → energy value drops? |
| **Meat, poultry, fish waste:**<br>trimmings (connective tissues, membranes, skin, bones)<br>fatty fractions (see below)<br>protein (tissue) fractions | Feed use<br>Food use: proteins peptides, fat<br>Functional components e.g. to edible films,nutraceuticals | 5-60 %, depending on the source and how fully the useful ingredients can be recovered | |
| **Plant oils and fats**<br>**Fish oils**<br>**Other animal fats** | Energy source in feeds<br>Refined oils of plants and fish for nutraceutical products (food, feed) | Up to 60 % | |

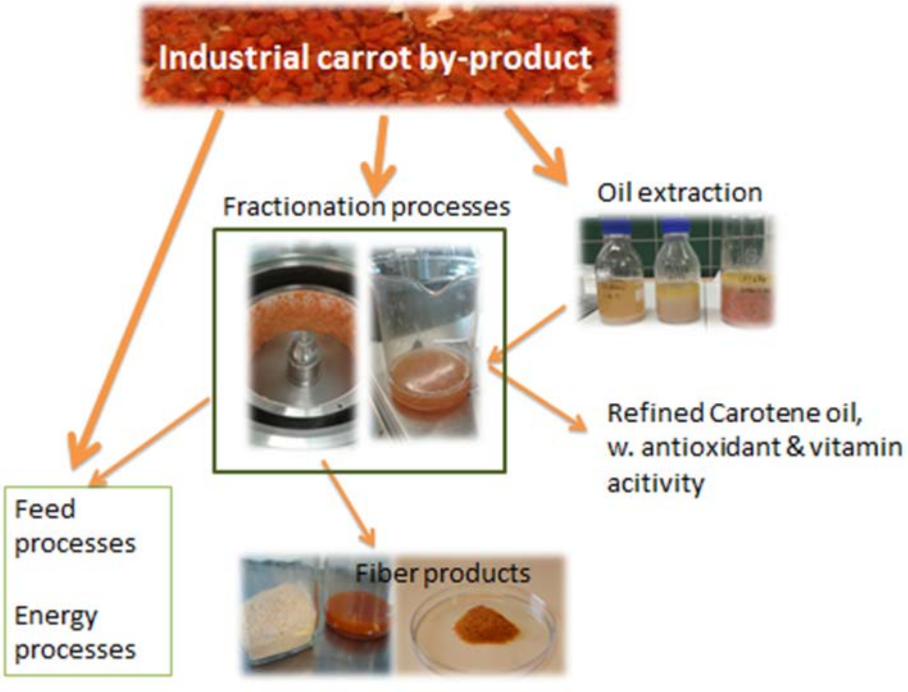

**Figure 1.** Processing options of a vegetable-based biomass (Photos: Marja Kallioinen & Eila Järvenpää; Luke).

Removal of valuable compounds improves the overall feasibility of the process, but does not usually remarkably reduce organic content of bulk. For example, carotene content of carrots is ca. 0.01-0.04% (wet basis). Soluble carbohydrates are removed with water, and this remarkably reduces the dry matter content of the residual solid biomass, as the sugars constitute ca. 50-60% of the dry matter of carrots. However, both liquid and solid process residues can be used for bioenergy production after the more valuable carotenoids are extracted.

Carrots are the main vegetable grown in fields in Finland. Year 2015 the amount of crop was 64 Mkg (Tike, 2016). Foodspill2-project has been calculated that 26% (ca 17 Mkg) of the ready to harvest carrots is not sold for food use in Finland, and the percentage is quite similar in the Nordic countries - and affected by weather condition during harvest (Franke et al 2016). Most of it is used as feed for livestock and game (ca 7 Mkg), nutrients (through composting, ca. 5 Mkg) and almost 3 Mkg remains unharvested. The better utilisation of these crops as raw materials for value-added products would benefit the farmers and the overall economy of agro-food chain.

The companies, which process fresh carrots to fresh or prepared foods, and households, use ca. 50 Mkg domestic carrots annually. The import takes the markets for few months during early spring-early summer. Ca. 10-20% of weight of the carrots is peeling residues, which form either heated or fresh biomass – the exact amount has not been analysed precisely. Averaged estimation values given by FAO (2011) are only giving an idea, e.g. that by processing and packaging 15% loss is found, which is similar to the consumption losses of 17%. Despite of the estimation, from those companies processing carrots to frozen foods as well as large fresh produce packaging companies may produce quantities daily, which would be of interest for industrial biomass processing. The production is often seasonal, thus the technology should be adaptable to various raw materials, or the biomass has to be conserved and stored for later use. For livestock feed it is estimated that ca. 500 kg daily by-product production would be interesting and feasible, considering that the transport distance should not be longer than ca 70-90 km (SivuHyöty project, unpublished results).

MarketsandMarkets (www.marketsandmarkets.com), a large market research firm, recently estimated that the global carotenoids market could be growing at a CAGR of 3.78% from 2016 to 2021 (newsletter, 19.11.2016). The company estimates that the carotenoid market volume is over 1 billion USD, year 2016. Carotenoids are also manufactured synthetically, but their biological functions relate to natural isomers found in plant and animal tissues, synthetic ones are mixtures, thus less active. This is one reason why lycopene nutraceutical business has been interested in tomato processing by-products. All carotenoid pigments are antioxidants in biological and food systems, especially in the systems involving fats and oils and biological membranes. Also other bioactivities have been shown, which support carotenoids use in drug formulations, nutraceuticals and as food/feed additive. Carotenoids found in carrots owe relatively high vitamin A activity, thus they are especially important in human and animal nutrition. Animals cannot synthetize carotenoids, thus they have to be part of their diet.

Considering the by-product as a raw material for bioactive compounds, it has to be notified, that particularly fruit and vegetable by-products are highly perishable. For better utilization for extraction and fractionation of value-added compounds, conservation of these materials is needed, especially in the cases of centralized processing of the by-products. Most common conservation methods are fermentation and drying, which could be conducted on-site of vegetable/fruit processing. Fermentation processes which are also suitable for conservation, are discussed further in chapter 4.

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# 4 Valorisation of food industry side-products by fermentation processes

## 4.1 Conservation

Fruit and vegetable wastes are usually highly perishable and fermentable, mainly because of high moisture (80−90%), total soluble sugars (6−64%) and crude protein (10−24%) contents (Wadhwa, Bakshi, & Makkar, 2013). Side streams of e.g. flour, beer and ethanol production contain relatively high amounts of protein, fibre and fat. Some by-products are continuously used as animal feed. Logistical (high water content of plant based material) and animal feed regulations (risk of toxic components) may limit the utilization of the by-product as a feed material (Bos-brouwers et al., 2012). Food safety is a prerequisite for all food production chains and limits upgrading side streams to food or feed applications. Conservation of these materials is needed for utilization as food, feed or further processing, e.g. preceding the fractionation of value compounds. Ensiling (fermentation) or drying of by-products are the most common methods of conservation for long periods (Chedly & Lee, 2000; Wadhwa et al., 2013).

## 4.2 Waste and side-products as starting materials for biobased products

Replacing of nonrenewable fossil resources by renewable biomass as primary raw materials for the production of valuable chemicals is an important goal of sustainability. Developments on chemical building blocks from biomass, either from natural precursors or from sugars by fermentation processes have potential for substitution of oil-based chemicals/building blocks with biobased alternatives. Competition of biobased products with conventional products on cost is often difficult and feedstock costs are critical in the processing. The proposed second generation bio-based economy is founded on the full utilization of agricultural biomass for the production of food, feed, fuels and chemicals. Biomass-based routes are constantly developing and further improvements are likely to take place in the future. Improvements in the material and energy efficiency, land use and process economics, innovations in the field of fractionation, fermentation, catalytic processes and restructuring processes, preferably in combination with a lower environmental impact, could result in competitive prices of new biobased products and components (Bos-brouwers et al., 2012). Bio-energy could still be a valuable by-product after more valuable materials are extracted (Sheldon & Sanders, 2015).

## 4.3 Building blocks from renewable materials

Starting materials of commercial compounds are often derived from edible biomass and compete with feed and foodstocks, therefore, the development of bio-based processes that utilize renewable feedstocks is desirable. A variety of agricultural waste streams including e.g. sugar cane bagasse, corn stover, rice husks, dried distillers grain and solubles (DDGS), vegetable and fruit peels as a starting material have been studied on a laboratory and pilot scale. Biobased building blocks, such as lactic acid, succinic acid, glycerol , sorbitol, 3-hydroxypropionic acid, and isosorbide are currently used (http://biobasedproducts.com/info/, Sari, 2015). The products are versatile and applications range from cosmetics to food, feed and chemical industry.

Production of biopolymers such as polylactic acid, polyesters and polyamides by bio-based routes rather than from fossil sources is five to 20 times more efficient than production of transportation fuels or electricity (Bos-brouwers et al., 2012). For many biomass-derived chemical applications, bioenergy can be produced as a by-product instead of being the main product.

By-product streams as starting materials for organic acids and some other compound production are further discussed.

## 4.4 Succinic acid

Typically succinic acid is a potential alternative to petroleum-based chemicals. It is seen as a compound of a strategic importance in a future chemical industry based upon renewable raw materials and can be found in a “Top 10” list of biomass-derived compounds (Werpy & Petersen, 2004). It can serve as raw materials to yield a variety of organic molecules, polymers, many industrial and commercial products, such as food ingredients, cosmetics, pharmaceuticals, surfactants, detergents, plastics, coatings, paints, nylons, adhesives, clothing fibers and biodegradable solvents ( (Root, 2011), https://www.bio-amber.com/bioamber/en/products). Commercial succinic acid is commonly produced from petroleum. The production of succinic by anaerobic fermentation is a relatively simple process with the added benefit of carbon fixation. Globally, worldwide market for succinic acid is estimated at approximately $7.5 billion annually in new and existing applications (Myriant Corp., 2013). The major potential markets for green succinic acid are a biobased replacement for maleic anhydride, polymers currently derived from butane and pyrrolidinones used to make green solvents and eco-friendly chemicals for water treatment (Ebert, 2007).

In a pilot scale plant, designed for converting 1 tonne/day of bakery waste in Hong Kong into succinic acid, the total capital investment, total production cost and profitability of the production process were estimated to be $0.55–1.10 per kg, which is competitive to that of petrochemical process. The total capital investment for the plant and the total production cost were US$ 1,118,243 and US$230,750/year respectively. Overall income was US$ 374,041/year. The return on investment, payback period and internal rate of return of the project were 12.8%, 7.2 years and 15.3% respectively. The experimental result showed that the overall yield of the production was 0.55 g SA per g bread. (Lam, Leung, Lei, & Lin, 2016; Lin, 2013)

In an EU project, cascading concept for the valorisation of subproducts from the fruit and vegetable processing industry using biotechnological solutions like fermentation and enzyme-conversion strategies were investigated. The aim was to obtain valuable bioproducts like plastics (PHB), nutraceuticals / platform chemical succinic acid and enzymes for detergent applications (www.transbio.eu). Production selectivity towards succinic acid was validated at small pilot scale. Anaerobic digestion of the remaining solid residuals was stated to be a promising technology to valorize vegetable waste after bio-product extraction. The energy (biogas) that is produced during anaerobic digestion can be used in the production processes improving the overall sustainability of the chain.

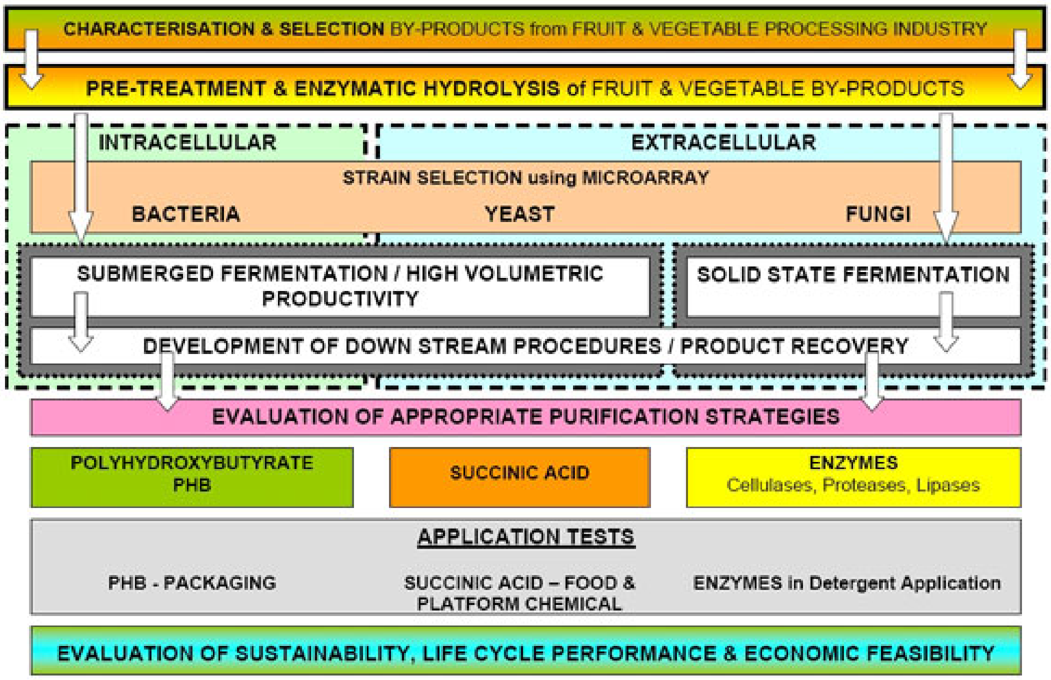

**Figure 2.** The transbio strategy (from http://www.transbio.eu/en/the_project.asp)

Commercial production and demonstration plants producing succinic acid from renewable feedstock using microbial fermentation of different glucose sources have been established by companies such as Myriant, Bioamber, Succinity and Reverdia. Bioamber's Sarnia plant, built at a cost of US $141,5 million, apply fermentation for producing bio-based succinic acid at a commercial scale, 30 kt/year, using corn, wheat, cassava, rice, sugarcane, sugar beets and forest waste as starting materials. Reverdia has commercialized Biosuccinium™, succinic acid produced from renewable, plant-based resources (corn), and produce it with a capacity of about 10 kilotons per year. Myriant's succinic acid biorefinery employs grain sorghum grits and other cellulosic materials as feedstocks. Companies have announced the longer-term goal to move to agricultural, forestry and industrial waste as alternatives for feedstocks. Succinic acid forms the basis for many high-value replacement products, including phthalic anhydride, adipic acid, and maleic anhydride *http://www.myriant.com/ Myriant, http://www.bio-amber.com/.*

Life Cycle Assessment (LCA) and carbon footprint of processes is becoming increasingly important to downstream customers. Recent study on sustainability of biobased succinic acid production in Myriant and Reverdia cases showed slighty higher energy efficiency and lower material efficiency compared with petrochemical route. The costs for biobased production were lower and it was seen to be competitive with chemical route (Pinazo, Domine, Parvulescu, & Petru, 2015).

Current markets for succinic acid include pharmaceuticals, food, flavor, coatings, pigments and metal plating and new applications are emerging, including the production of bio-based polyurethanes, polybutylene succinate (PBS), plasticizers, composite and coating resins, solvents, 1,4 butanediol and Tetrahydrofuran (THF) for usage in many end-user products like packaging, footwear, elastane clothing, shopping bags, mulch films, automotive interior. According to companies, as a result of price competiveness and its renewable nature, bio-based succinic acid is addressing a larger market than fossil feedstock based succinic acid.

## 4.5 Lactic acid

Lactic acid (LA) is a platform chemical and has a long history of commercial uses and applications. Growing interest has been focused on cheap and renewable materials as an alternative to the refined carbohydrates for the production of lactic acid for the food, cosmetic, textile, chemical and pharmaceutical industries.

Presently, approximately 90% of all LA worldwide is produced by bacterial fermentation from the renewable resources such as molasses, corn syrup or sugar (Juodeikiene et al., 2015). Estimated production of lactic acid was around 259 kt in 2012. Food-related applications account for approximately 85% of the demand for lactic acid (John, Anisha, Nampoothiri Madhavan, & Pandey, 2009)**.** Production of polylactic acid to replace the petrochemical packaging materials such as PET has a wide range of applications in food and pharmaceutical industry. Lactic acid has the potential to become a commodity chemical for biodegradable polymers, oxygenated chemicals, plant growth regulators, environmental friendly solvents, and special chemical intermediates (Abdel-Rahman, Tashiro, & Sonomoto, 2013).

Conversion of food waste into lactic acid by fermentation has been studied using several feedstocks such as wheat, corn, sugarcane juice, starch and cassava powder. Microbiological process enables the production of optically high pure lactic acid by selecting an appropriate strain, whereas in chemical synthesis a mixture of different LA isomers is formed. The produced isomer composition of LA is a very important criterion in bioplastics production.

Using corn sweet sorghum juice as starting material lactic acid has been produced at high yields, once process was supplemented with enzymes, including alpha-amylase and/or glucoamylase (Abdel-Rahman et al., 2013; Wang et al., 2016).

In an EU financed project, Transbio, lactic acid production was one important step in cascade utilization of plant biomass resources. www.transbio.eu

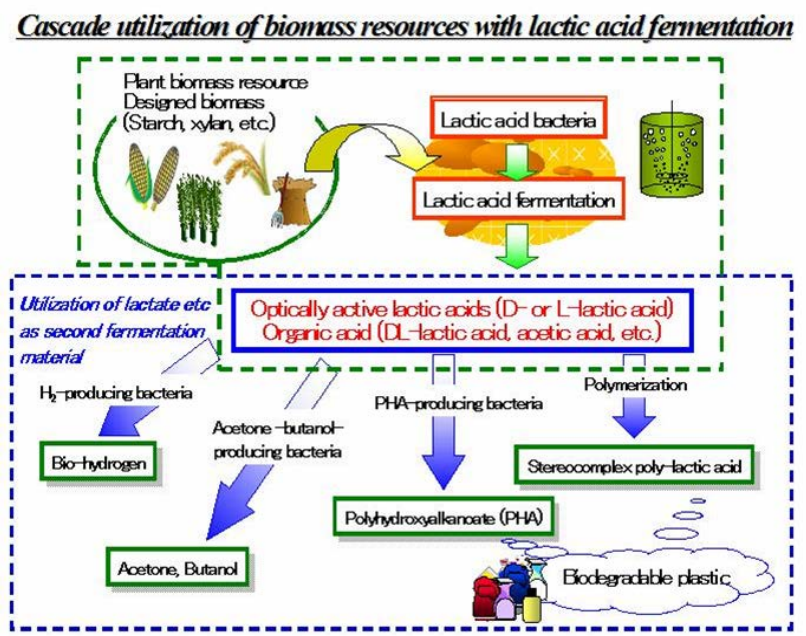

**Figure 3. Cascade utilization of biomass resources with lactic acid fermentation (www.transbio.eu)**

Milling by-products like corn, rice, and wheat bran have been utilized for LA production and they provide a good raw material substitute because of their low prices. Incorporation of enzymatic hydrolysis in a fermentation process of Brewer’s spent grains (BSG) was shown to enhance the production of LA. BSG agro-industrial waste has also been used for citric acid (CA) production (ElMekawy, Diels, De Wever, & Pant, 2013).

The costs of LA production were evaluated in a study using wheat biomass as feedstock. The total costs for the fermentative LA production from wheat biomass were 1020 US$/ton. In an economical evaluation operational costs contributed about 77% of the total costs: raw materials (26%), fermentation (34%), electrodialysis (27%) and hydrolysis (12%) (Juodeikiene et al., 2015).

Biobased conversion of wheat biomass to LA was shown to have higher economical effect; it has been calculated to increase the energy efficiency by 47 % and decreasing the total costs by 17 % compared to chemical synthesis (Juodeikiene et al., 2015). Mass efficiency was lower in biobased process. The total costs for LA in the petrochemical process were estimated to be 1.225 USD/kg, while the commercial prices of food grade lactic acid ranged between 1.38 USD/kg (for 50% purity) and 1.54–1.76 USD/kg (for 88% purity). Technical grade lactic acid with 88% purity has been priced for 1.58–1.87 USD/kg (www.ICIS.com). On an industrial scale, the production costs of LA will be targeted to less than 0.8 USD/kg (Juodeikiene et al., 2015). Developments are still needed to further reducing the costs of the processes, such as selection or development of microbes, choosing of cheaper raw materials (byproducts), development of the processing equipment or optimizing the process conditions.

Big LA manufacturing industries such as Musashino, Chemical Laboratory, Ltd. (Japan), Corbion Purac (The Netherlands), NatureWorks LLC (USA), Galactic (Belgium) have switched over to a fermentation based technology. The latest biofermentation technique and advanced refinement technique has been combined in industrial LA processes.

## 4.6 Other products

***Enzymes*****.** Microorganisms are important sources for the production of commercial enzymes. Certain microbes are capable of degrading complex polymers in plant biomass and utilize the sugars released for their sustenance. Organic food and agro-industrial waste have potential for enzyme production and there is various examples of the production of commercially important enzymes including cellulases, laccases, pectinases, amylases, xylanase, phytase, and lipases, particularly through solid state fermentation (Kiran, Trzcinski, Ng, & Liu, 2014; Ravindran & Jaiswal, 2016); multi-enzyme solution from waste bread (Melikoglu, Sze, Lin, & Webb, 2013), α-amylase from untreated brewer's spent grain, cellulose from wheat bran and untreated corn cob as few examples. Raw material represents almost 28% of the operational cost in commercial enzyme production The global market for feed enzymes is a major industry. The global market size was estimated to reach $727 million in 2015 (Ravindran & Jaiswal, 2016).

***Aroma compounds*****.** Current interest in the development of processes for producing biopolymers from renewable resources involves aromatic compounds, such as obtaining vanillin by bioconversion of ferulic acid which is derived from enzymatically hydrolyzed wheat bran (ElMekawy et al., 2013). Evolva is planning to begin producing natural fragrances and flavorings based on fermentation (Scott-Thomas, 2015).

***Fibre*****.** Nutraceutical Innovations produces ingredients by fermentation process in which protein and fibre are released from the rice bran (Watson, 2014). Betafib is a micro-cellulose fibre made from vegetable residual flows after microbial process (Cosun, 2014). CelluComp LTD (UK) produces Curran®, a nanocellulosic fiber product made of carrot waste. Company webpages present several applications (http://cellucomp.com/applications/, read 11.11.2016)

***Biodegradable Plastics*****.** Food waste and agricultural residue have been used as substrates for the production of PHAs and poly-3-hydroxybutyrate (PHB) that has potential for replacements for petroleum-derived plastics. Wheat bran, wheat and rice straw hydrolysate, bagasse, potato waste and was spent coffee waste are examples of substrates for microbial PHB production (Ravindran & Jaiswal, 2016).

***Green biorefinery, multiproducts.*** Green biorefinerys can use a wide variety of biomass - grass or other green/fresh biomass to a cascade of processing stages. The aim is a zero-waste and zero-emission extraction of valuable substrates. As an example of green biorefinery is a plant of OÖ Bioraffinerie Forschung und Entwicklung GmbH, in Austria, in which feedstock silage is utilized as raw material ending up to several products including amino acids, lactic acid, biomethane, electricity, heat, fertilizer and fibre. (de Jong, Langeveld, & van Ree, 2009).

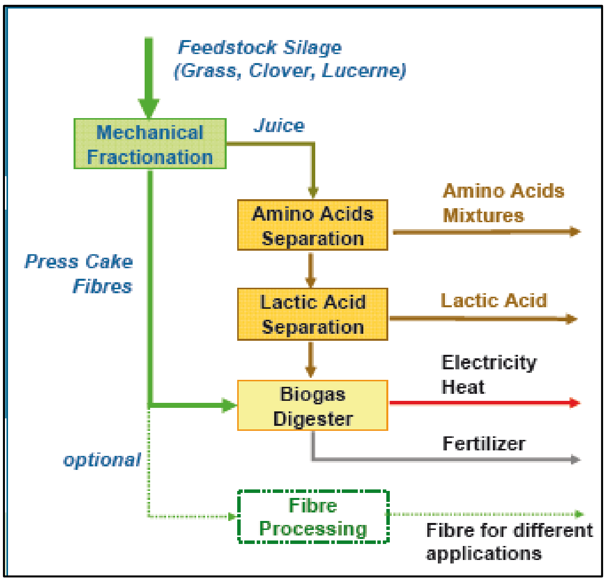

**Figure 4.** Green biorefinery using feedstock silage as raw material (de Jong, Langeveld, & van Ree, 2009).

***Biofuels.*** Plant biomass has been used for the production of fuel ethanol for almost a century. Residues of various crops are extensively used for the biofuel production. A range of technologies are investigated or developed for production of second –generation biofuels such as ethanol, gasoline and diesel equivalents, butanol and biogas made from non-food feedstocks. Furthermore, microbe strains are engineered to produce renewable fuels. Currently ethanol is mainly produced from crops, however, a number of waste based ethanol pilot and commercial plants are appearing today utilizing brewery, bakery, potato processing by-products as feedstocks (Hirschnitz-Garbers & Gosens, 2015). Efficiency of anaerobic acetone-butanol-ethanol (ABE) fermentation on glucose substrate from maize starch was evaluated, leading to the conclusion of significantly higher material and energy efficiencies, as well as lower production costs of the petrochemical process compared to the biobased process (Uyttebroek, Hecke, & Vanbroekhoven, 2015). This indicates the need further developments in technologies for biobased fuels.

## 4.7 Demonstration plants

The new biorefinery concepts are still mostly in the R&D, pilot or small-scale demonstration phase. Biobase NWE is a three year project set up by the EU to accelerate the growth of the biobased economy in North West Europe (NWE). A pilot facility with latest technology and operating scale from a laboratory level to a multi-ton, enable SMEs from North West Europe to test and develop innovative biobased products and processes.  It focuses on conversion of biomass (agricultural crops and by-products, industrial side streams) into biochemicals, biomaterials, biofuels and other bioproducts (www.biobasenwe.org/en/home/, 2016). In Finland there is a versatile small semi-pilot scale plants for developing new bio-based materials, however, bigger scale pilot equipments are limited (http://www.biotalous.fi/suomalaiset-bio-ja-kiertotalouden-prosessitekniikan-pilotointiymparistot/).

## 4.8 Case study: carrot by-product from food industry

Biomass is allocated to preferential value and valorization levels based on the value pyramid (WTC-BBE, 2011) and Moerman's Ladder. High-value applications are given priority, followed by a move to lower value applications (Bos-brouwers, Langelaan, & Sanders, 2012):

1. food for human consumption
2. feed for animals
3. functional materials and products (e.g. paper, biodegradable packaging, building materials and basic chemicals)
4. fuels and their applications.

Probiotic foods and feeds are growing sectors in the global market. Probiotics could serve as alternatives to antibiotic growth promoters in livestock production. Food industrial by-products as starting material and energy-efficient production system could be considered as an option to produce probiotic products. In addition, when lactic acid bacteria are used, the process yields organic acids, in this case lactic acid. Further processing is still needed to recover and purify the acid. The purification of lactic acid could be done by removing the solid materials by filtration, concentration by evaporation and then separation of lactate e.g. by ion-exchange or membrane technologies.

In this case study different valorization levels were surveyed to yield added value to a by-product from carrot processing.

**Processing of carrot by-product**

Carrot by-product waste was collected from an industrial plant after processing. For practical reasons carrot slices were frozen before further processing. 7.5 kg of the waste was processed using 30 l (in-house designed and built) bioreactor as described in fig. 5.

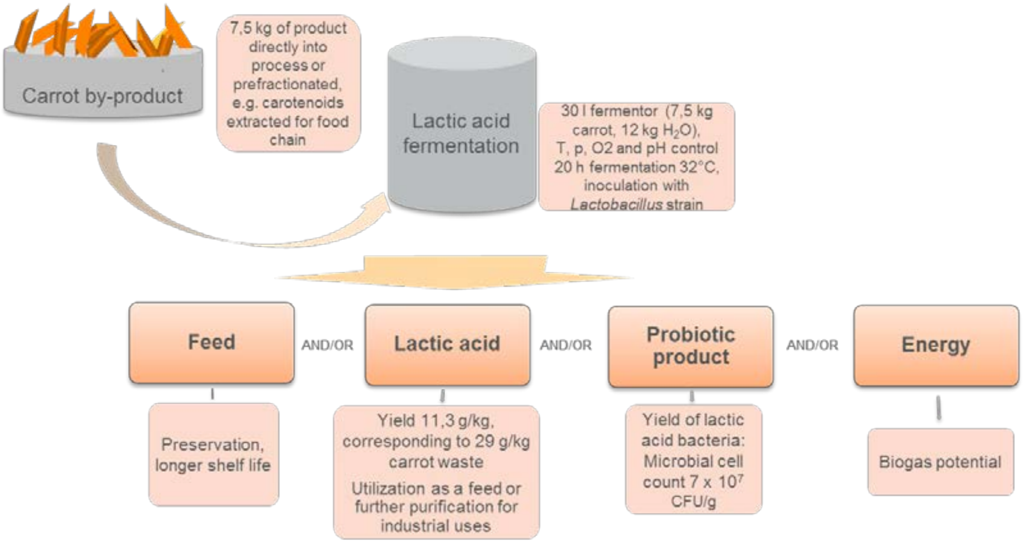

**Figure 5.** Processing of carrot by-product

### Fermentation process

Raw material utilized was steam peeled, sliced carrot, 7.5 kg, in which 12 kg of water was added. The fermentation was performed using lactic acid bacteria strain belonging to *Lactobacillus* genus. When starting fermentation, oxygen was removed from the reaction vessel to produce anaerobic conditions for fermentation.

The aim was to study the production and yield of probiotic product and lactic acid. The yield for the probiotic product was 7 x $10^7$ cfu/g (colony forming units/g) in a final volume of 19.5 kg (total amount was 1.37 x $10^{12}$ cfu in this batch). This equals for example 140 daily doses for piglets. The yield of lactic acid was 1.16 % corresponding to 0.226 kg in a fermentation volume studied**.** The dry matter of the product was 3.5 %. Normal fill of the bioreactor is 24 kg, calculations based on this amount are added in the tables 3-5.

**Table 2.** Specific energy costs for probiotic product (19.5 kg) and lactic acid (kg LA)

| **Oxygen removal and fermentation** | **Probiotic product kWh/kg** | **LA kWh /kg** | **Total (kWh)** |
|---|---|---|---|
| Electric energy | 0.20 | 17.01 | 3.85 |
| Heat energy | 0.12 | 10.21 | 2.31 |
| | | | |
| Total energy costs | €/kg | €/kg | |
| Heat = District heating | 0.027 | 2.34 | |
| Heat = Waste heat from return water of district heating | 0.019 | 1.64 | |
| Heat = Waste heat from own processes | 0.018 | 1.56 | |

Prices used in the calculations:
*Electric energy*
Energy 4.9 c/kWhFortum 22.3.2015, SME tariff
Transfer 4.0 c/kWh
Total 8.9 c/kWh
*Heat energy*
District heating 82.0 €/MWh Vapo, Forssa
Waste heat from return water of district heating 12.9 €/MWh Power charge, Vapo, Forssa
Waste heat from own processes 4.5 €/MWh Estimated transfer costs

**Table 3.** Specific energy costs for $10^{12}$ cfu (corresponds circa 140 daily probiotic portions of piglets) of the batch.

| **Oxygen removal and fermentation** | | **Reduced for the normal fill (24 kg)** |
|---|---|---|
| Total energy costs | €/$10^{12}$ cfu | €/$10^{12}$ cfu |
| Heat = District heating | 0,39 | 0,31 |
| Heat = Waste heat from return water of district heating | 0,27 | 0,22 |
| Heat = Waste heat from own processes | 0,26 | 0,21 |

**Table 4.** Energy required for dewatered probiotic product

| **Oxygen removal and fermentation, total energy** | | **Reduced for the normal fill (24 kg)** |
|---|---|---|
| Electric energy | 3.85 kWh | 3.85 kWh |
| Heat energy | 2.30kWh | 2.30 kWh |
| | | |
| Dewatered probiotic product | | |
| Dry matter content | 75 % | 75 % |
| Mass | 0.90 kg | 1.11 kg |
| Water to be removed | 18.60 kg | 22.89 kg |
| Probiotic cfu count | 1.37 x $10^{12}$ cfu | 1.69 x $10^{12}$ cfu |
| | | |
| Specific energy for dewatering | | |
| Electric energy | 1.75 kWh/kg of water | |
| Heat energy | 1.94 kWh/kg of water | |
| Total energy for dewatering | | |
| Electric energy | 32.5 kWh | 40.0 kWh |
| Heat energy | 36.1 kWh | 44.4 kWh |

**Table 5.** Energy costs for dewatered probiotic product
(dry matter 75 %, 1.37 x $10^{12}$ cfu in total amount of 0.9 kg, corresponds to 1.55 x $10^{9}$ cfu/g)

| | **Heat = District heating** | **Heat = Waste heat from return water of district heating** | **Heat = Waste heat from own processes** |
|---|---|---|---|
| Probiotic product | €/$10^{12}$ cfu | €/$10^{12}$ cfu | €/$10^{12}$ cfu |
| Oxygen removal and fermentation | 0.25 | 0.25 | 0.25 |
| Dewatering | | | |
| Electric energy | 2.10 | 2.10 | 2.10 |
| Heat energy | 0.02 | 0.003 | 0.001 |
| Total | **2.38** | **2.36** | **2.35** |
| | | | |
| | €/kg | €/kg | €/kg |
| Total energy costs | **3.63** | **3.60** | **3.59** |
| | | | |
| Reduced for the normal fill (24 kg) | €/$10^{12}$ cfu | €/$10^{12}$ cfu | €/$10^{12}$ cfu |
| Oxygen removal and fermentation | 0.20 | 0.20 | 0.20 |
| Dewatering | | | |
| Electric energy | 2.10 | 2.10 | 2.10 |
| Heat energy | 0.02 | 0.003 | 0.003 |
| Total | **2.33** | **2.31** | **2.31** |

During the fermentation pH was reduced to 3.5, the amount of enterobacteria and molds decreased to <100 CFU/g, and yeasts were detected in levels of $10^3$ CFU/g. This indicates longer shelf life of the product compared to the unprocessed product and better utilization for animal feeding purposes. Calculations of energy consumption and costs were made for probiotic or lactic acid production with alternative forms of thermal energy (tables 1 – 4). Costs of a probiotic product were calculated for a fermented product and estimated for a product dried to a moisture content of 25 % (table 2 and table 4). The prices of lactic acid, e.g. in Chinese markets: Lactic acid, food grade, US $1100-1300/tonne, ~1,30 $/kg. Rates of commercial probiotic product for animals ($10^7$ – $10^8$ cfu/g) vary between 23 and 70 €/kg.

Processing was made using an in-house designed bioreactor with the option of heat circulation and utilizing waste heat, which can reduce the costs considerably. By optimization the yield of lactic acid and the number of the bacterial cells attained could be further enhanced, e.g. by adjusting the process parameters and by selection of the bacterial strains.

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# 5 Volatile fatty acid production by anaerobic digestion from food waste

Anaerobic digestion (AD) is a flexible microbial process, which can be modified to produce different energy carriers, e.g. methane ($CH_4$), hydrogen ($H_2$) and volatile fatty acids (VFAs) from waste biomass, such as municipal sewage sludge, organic fraction of municipal solid waste (or separately collected biowaste), side streams from food processing industry, agricultural residues and animal manure. Volatile fatty acids (VFA) are short-chain fatty acids, i.e. fatty acids from C2 to C6 (acetic, propionic, butyric, etc.). The resource- and cost-effective production of VFAs from waste materials has become an interesting option for the production of e.g. biomaterials and biofuels. These renewable substrates could replace the extensive industrial use of non-renewable petrochemicals for plastics and fuels.

Currently AD-process is used mainly for production of methane containing biogas. However, compared to the price of methane, the price of hexanoic acid (also known as caproic acid) is more than double and the price of polyhydroxybutyrate (PHB) (produced from butyric acid) five times the price of methane in Europe (Table 6).

**Table 6.** Approximate price for different organic compounds (Kleerebezem et al. 2015).

| Compound | Chemical formula | Price, €/kg |
|---|---|---|
| Coal | C | 0.05 |
| Methane (US June 2013) | $CH_4$ | 0.20 |
| Methane (Europe June 2013) | $CH_4$ | 0.40 |
| Oil (June 2013) | $CH_2$ | 0.64 |
| Hydrogen | $H_2$ | 2.00 |
| Sugar (June 2013) | $C_6H_{12}O_6$ | 0.28 |
| Ethanol (2013) | $C_2H_6O$ | 0.52 |
| Hexanoic acid | $C_6H_{12}O_2$ | 1.00 |
| PHB | $CH_3O$ | 2.00 |

## 5.1 Anaerobic digestion and the production of biogas

Through AD production, renewable biomass streams can be used to replace fossil fuels in energy production and mineral fertilizers in agriculture. At the same time, it is possible to avoid the greenhouse gas emissions from the spontaneous degradation of liquid or solid wastes in open ponds or stockpiles. AD is a biological process where mixed culture of various anaerobic micro-organism cause successive reactions. The process chain can be divided into four main reaction types, i.e. hydrolysis, fermentation, acetogenesis and methanogenesis. During hydrolysis the complex polymers in biomass raw material are first degraded to simpler monomers, which are then converted by fermentation to VFA, further by acetogenesis to acetate, and finally by methanogenesis to biogas, which contains around 55 – 70 % of methane (and 30 – 45 % of carbon dioxide) depending on the process conditions and raw materials (Luostarinen et al. 2011).

Biogas is commonly produced in a single anaerobic reactor where all the four successive reaction types are carried out simultaneously. However, the optimal process conditions vary for each reaction type and particularly hydrolysis is a rate-limiting step (Parawira et al. 2004). Hydrolysis is catalyzed by the extracellular enzymes produced by acidogenic bacteria, which convert the hydrolysis end-products, i.e. various monomers, to VFA. Acidogenic bacteria are fast growing and tolerate elevated concentrations of VFA and low pH. Thus the hydrolysis and fermentation would benefit from high organic loading rate (OLR) and short solids retention time (SRT). On the contrary, methanogenic micro-organisms are slow growing and the methanogenic activity is inhibited by accumulation of VFA and low pH (pH < 6). The problem can be solved through the application of two separate reactors, i.e. a two-stage AD process. The first reactor has acidic pH and short SRT for cultivation of fast-growing acidogens. The second reactor has neutral pH and higher SRT for cultivation of slow-growing methanogens. In addition, the first hydrolysis and fermentation step is more efficient in higher temperature (thermophilic process), whereas the second methanation step benefits the larger diversity of species in lower temperature (mesophilic process) (Lv et al., 2010).

## 5.2 Volatile fatty acids as alternative end products in anaerobic digestion

Two-stage AD process improves the process stability and efficacy in biogas production but the process concept can be used to produce also other end-products than biogas. If the final methanogenic steps are fully inhibited, the end-product of the process is VFA (along with $CO_2$ and $H_2$) (Kleerebezem et al. 2015). VFA can be further used as raw material for the production of biomaterials, biochemical and biofuels (Figure 6).

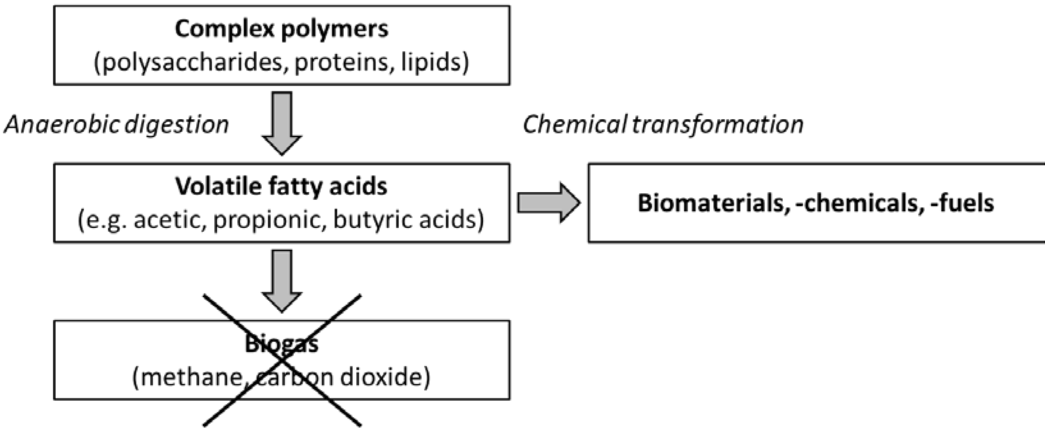

**Figure 6.** Volatile fatty acids (VFA) can be used as raw materials in the production of biomaterials, biochemicals and biofuels.

VFAs can be used for many applications (Table 7). One promising field is the production of polyhydroxyalkanoates (PHA) (Kleerebezem et al. 2015). PHAs have properties comparable to petrochemical plastics and they can be used in various applications, e.g. injection moulded products, foams, films and coatings. In addition, PHAs are completely biodegradable, which means that the accumulation of plastics in the nature could be avoided by using PHAs instead of petrochemical plastics.

**Table 7.** Applications of volatile fatty acids (VFA) (Lee et al. 2014; Singhania et al. 2013; Zacharof and Lovitt 2013).

| | |
|---|---|
| VFA used as such | • acidifiers in foods and beverages<br>• additional carbon source for biological nutrient removal in municipal waste water treatment |
| Building blocks for chemical transformation | • several organic compounds, e.g. alcohols, aldehydes, ketones, esters and olefins |
| Substrates for microbial production | • polyhydroxyalkanoates (PHA) production<br>• biodiesel production through the synthesis of single cell oils (SCO) by oleaginous yeast<br>• production of hydrogen via photofermentation by mixed microbial cultures<br>• microbial fuel cells |

## 5.3 Suitable raw materials and processing options for VFA production

Requirements for the raw material in VFA production are higher than in biogas production because of the higher production costs due to an additional separation and purification of the end product. Raw materials rich in organic matter, such as food waste, organic fraction of municipal solid waste (OFMSW) and waste activated sludge (WAS), provide opportunities for production of higher added value products (Table 8). Good results have been obtained also by mixing food waste and residual activated sludge. This raw material mixture combines the high organic matter content in food waste and micro-organisms in residual activated sludge, which are beneficial for the fermentation process (Hong and Haiyun 2010). However, due to the use of residual activated sludge, the use of digestate as a fertilizer may have some restrictions when used for cultivation of food.

**Table 8.** VFA yield from food and mixed waste.

| Raw material | Organic content mg TCOD/L | Organic content mg SCOD/L | VFA production mg CODL/L | VFA yield COD/ TCOD | VFA yield COD/ SCOD | Ref |
|---|---|---|---|---|---|---|
| Food waste | 91 900 | 49 900 | 16 900 | 0,18 | 0,34 | 1 |
| Food waste | 20 000 | 11 732 | 5 600 | 0,28 | 0,48 | 2 |
| Food waste | 166 180 | 53 180 | 36 000 | 0,22 | 0,68 | 3 |
| Solid potato waste |  | 32 000 | 19 000 |  | 0,59 | 4 |
| OFMSW | 196 700 | 32 100 | 23 110 | 0,12 | 0,72 | 5 |
| OFMSW | 150 600 | 23 100 | 19 580 | 0,13 | 0,85 | 6 |
| Vegetable and toilet waste | 27 000 | 11 500 | 6 000 | 0,22 | 0,52 | 7 |
| Food waste, WAS | 22 130 |  | 8 240 | 0,37 |  | 8 |
| Food waste, WAS |  |  | 29 100 |  |  | 9 |
| Food waste, PS | 29 050 |  | 3 610 | 0,12 |  | 10 |

TCOD = Total chemical oxygen demand, SCOD = Soluble chemical oxygen demand
OFMSW = Organic fraction of municipal solid waste, WAS = Waste activated sludge
PS = Primary sludge

1) Elbeshbishy et al. 2011, 2) Kim et al. 2006, 3) Zhang et al. 2005,
4) Parawira et al. 2004, 5) Sans et al. 1995a, 6) Sans et al. 1995b,
7) Poughon et al. 2013, 8) Feng et al. 2011, 9) Hong and Haiyun 2010,
10) Min et al. 2005

VFAs are difficult to extract and purify from water due to their high solubility. Currently, membrane separation seems most promising technology (Figure 7). VFA can be separated e.g. by nanofiltration with commercially available membranes (Teella at al. 2011). Another solution for the extraction of the end product is a secondary bioconversion either to medium chain fatty acids (MCFA) or polyhydroxy alkanoates (PHA). MCFA are obtained by increasing the chain length of VFA. MCFA are more hydrophobic compounds and thus easier to separate from water (Singhania et al. 2013). PHA storing bacteria extract VFA from the liquid phase and accumulate them intracellular. Further recovery of the end product can be done by solid-liquid separation (Kleerebezem et al. 2015).

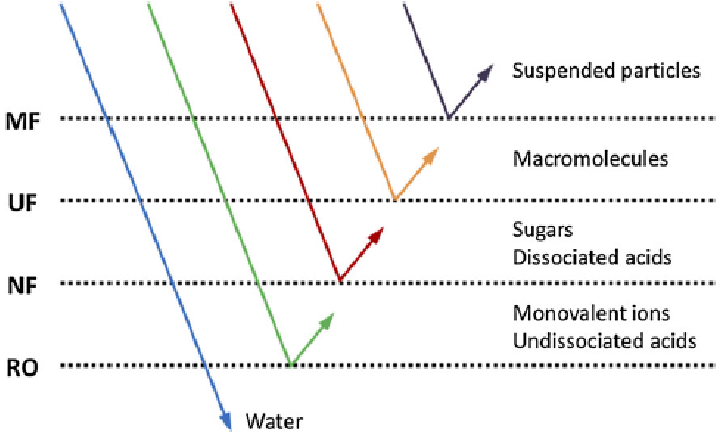

**Figure 7.** Principle of membrane separation using microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) (Kleerebezem et al. 2015).

Raw materials (type of carbohydrate substrate and concentration) and process conditions (pH, temperature, dilution rate, feeding pattern) have an influence on which fatty acids are produced. Acetic, propionic, iso-butyric and butyric acid are formed directly from the fermentation of carbohydrates, proteins and lipids (Parawira et al. 2004). However, the production of iso-butyric, butyric, iso-valeric, and valeric acid from non-proteinaceous raw material is minimal (Parawira et al. 2004). Furthermore, increased amount of butyric acid and total VFA is obtained through better cell wall hydrolysis, i.e. with higher temperature and longer reaction time (Lata et al. 2002).

The VFA distribution in fermentation medium can be shifted to shorter or higher average chain lengths. Which end products are desired depends on the market size and price (Table 9), but also the further use of VFA, e.g. preferred substrates for PHA synthesis are butyrate and lactate (Kleerebezem et al. 2015).

**Table 9.** Volatile fatty acids (VFA) market size and indicative prices (Zacharof and Lovitt 2013).

| Carboxylic acids | Chemical formula | Market size, t / a | Price, US$ / t |
|---|---|---:|---:|
| Formic | $HCOOH$ | 30 000 | 800 – 1 200 |
| Acetic | $CH_3COOH$ | 3 500 000 | 400 – 800 |
| Propionic | $CH_3CH_2COOH$ | 180 000 | 1 500 – 1 650 |
| Butyric | $CH_3(CH_2)_2COOH$ | 30 000 | 2 000 – 2 500 |
| Caproic | $CH_3(CH_2)_4COOH$ | 25 000 | 2 250 – 2 500 |
| Lactic | $CH_3CHOHCOOH$ | 120 000 | 1 000 – 1 800 |

One of the companies producing VFA by AD process from waste biomass is Earth Energy Renewables (www.ee-renewables.com). Typical fatty acid profile in their process is shown in Figure 8. Acetic acid is recycled in EER process and thus not shown in the figure.

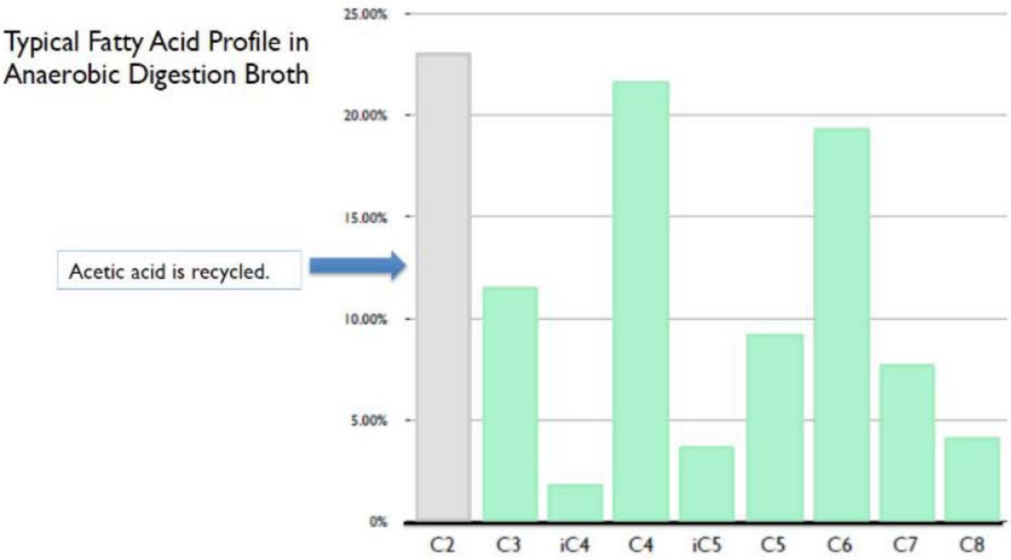

**Figure 8.** Typical distribution of C2 to C8 organic acids (The Digest's 2016 8-slide guide to Earth Energy Renewables, www.biofuelsdigest.com).

C2: Acetic acid
C3: Propionic acid
iC4: Iso-butyric acid
C4: Butyric acid
iC5: Iso-valeric acid
C5: Valeric acid (Pentanoic)
C6: Caproic acid (Hexanoic)
C7: Heptanoic acid
C8: Caprylic acid (Octanoic)

## 5.4 Case study: VFA production from separately collected biowaste

The feasibility of VFA production instead of biogas production was estimated by using a case example:

- Raw material: separately collected biowaste (i.e. municipal food waste) from Helsinki Metropolitan area
- Process: anaerobic digestion (AD) and membrane separation
- Products: volatile fatty acids (VFA)
- Side products: biohydrogen (H2), biogas (additional), nutrients

Around 1.1 million people are living in the Helsinki Metropolitan area. Separately collected biowaste (51 000 t) from the area is currently used as raw material for biogas production in Ämmässuo biogas plant, Espoo run by Helsinki Region Environmental Services Authority (HSY) (www.hsy.fi). The process is based on part-stream dry digestion where 70% of the biowaste is digested and 30% is directly composted (Figure 9). The total capacity of the plant is 60 000 t of biowaste.

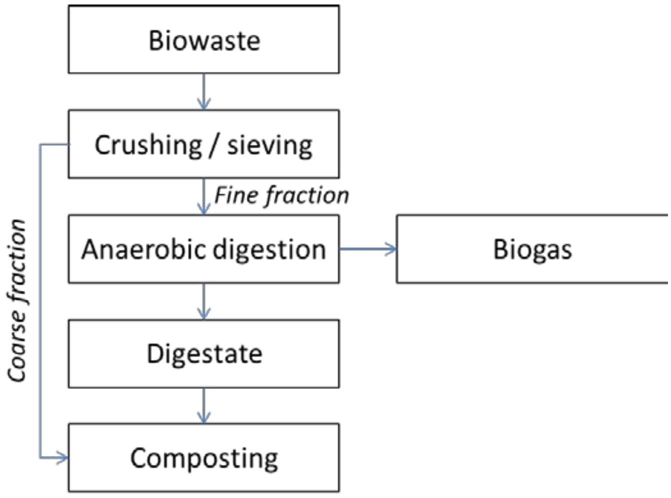

**Figure 9.** Current AD-process for biogas production. Coarse fraction after crushing/sieving goes directly to composting.

Mass and energy balance for the current biogas process were calculated based on the amount of biowaste treated in AD process (35 000 t) and biogas (6 milj. $m^3$) produced (Vantaan Sanomat 2015). The dry matter content of the biowaste was assumed to 30% (TS = total solids) and the share of organic matter in the dry matter 80% (VS/TS%, VS = volatile solids) (Bolzonella et al. 2005, HSY 2016). Furthermore, the share of methane in biogas was assumed to be 50 % and the biomethanepotential of the biowaste 500 $m^3$ $CH_4$ / t VS (Tähti and Rintala 2010). Based on these assumptions, 17% of the wet weight and 75% of the organic matter were converted to biogas (Figure 10).

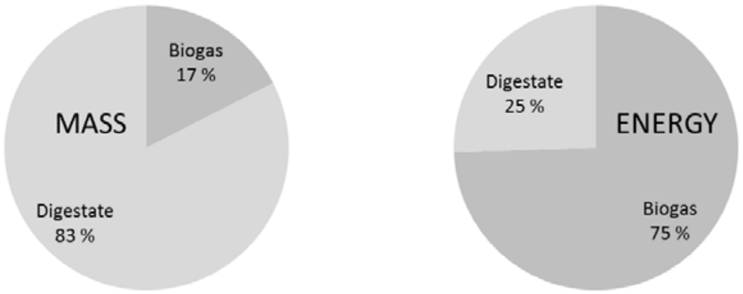

**Figure 10.** Mass and energy balance in biogas production. Mass refers to wet weight and energy to the share of organic matter which is converted to energy.

Separately collected biowaste is rich in organic matter and thus it could be feasible to use this raw material for VFA production. One example how the current process could be modified for VFA production is presented in Figure 11. First of all, the process conditions have to be optimal for VFA production.

Then instead of composting the digestate together with the coarse fraction of biowaste, the digestate would be separated with decanter centrifuge and VFA would be extracted from the press water with e.g. (micro- and) nanofiltration. The solid residues go to composting as in the biogas process.

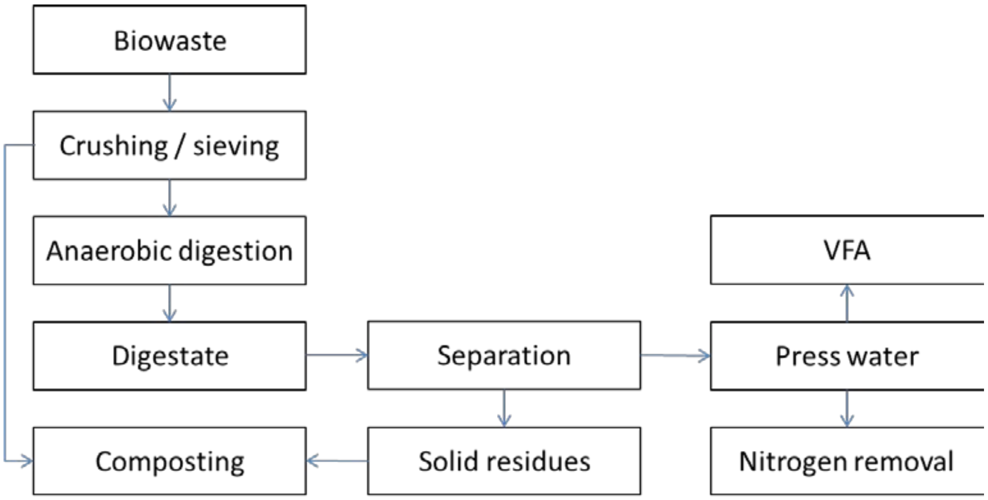

**Figure 11.** Optional AD-process for VFA production

Mass and energy balance for the optional AD-process for VFA production were calculated based on research done by Zhang et al. (2005). In their study VFA production from kitchen waste was 0.32 g VFA / g TS added. Separation of digestate was done with a decanter centrifuge. Separation indexes used in calculations were 17% for mass, 67% for TS and 67% for VS (Hjorth et al. 2010). In the optional AD-process, 10% of the wet weight and 41% of the organic matter were converted to VFA (Figure 12). The remaining solid fraction after separation of digestate could be used as raw material in an additional AD process for biogas processing since approximately 40% of the biodegradable organic matter of the original substrate is still left in the solid residues.

When looking at the mass and energy balances of biogas and VFA production, biogas production looks more efficient. But what would be more economically feasible? Starting from various references the economic feasibility was estimated both for biogas and VFA production (Table 10). With biogas production scheme, both the CHP-production and the CBG-production (compressed biogas for traffic fuel) were considered.

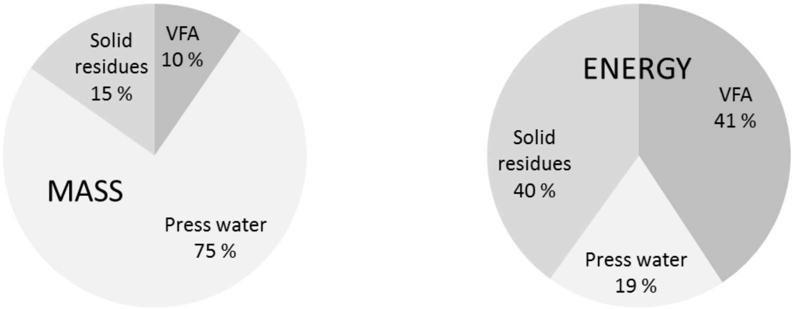

**Figure 12.** Mass and energy balance in VFA production. Mass refers to wet weight and energy to the share of organic matter which is converted to energy.

Operating costs were higher for CBG- and VFA-production than for CHP-production due to the higher energy need in production. Investment costs were estimated to be roughly at the same level. Surprisingly revenues for CHP-production were higher than for CBG-production due to the high price (133.50 €/MWh with heat premium) for sold electricity. Without the use of produced heat, the electricity price would be lower (83.50 €/MWh without heat premium) and the feasibility of CHP-production would be closer to that of fuel production.

**Table 10.** Feasibility estimations for different biowaste processing schemes

| | BIOGAS, CHP | BIOGAS, CBG | VFA | REF |
|---|---|---|---|---|
| **OPERATING COSTS** | | | | |
| Feedstock | 0 € | 0 € | 0 € | |
| Electricity | | 70 €/MWh | 70 €/MWh | 1 |
| AD reactor: 1 540 MWh | 0 €[a] | 107 800 € | 107 800 € | 2 |
| CBG production: 2 700 MWh | | 189 000 € | | 1 |
| VFA production: 2 700 MWh | | | 189 000 € | |
| separation: 100 MWh[b] | | | 7 000 € | |
| Heat | | 25 €/MWh | 25 €/MWh | 1 |
| AD reactor: 6 970 MWh | 0 €[a] | 174 250 € | 174 250 € | 2 |
| stripping: 1 530 MWh[c] | | | 38 250 € | |
| Labor, maintenance | 1 000 000 € | 1 000 000 € | 1 000 000 € | 1 |
| **Sum of annual operating costs** | **-1 000 000 €** | **-1 471 050 €** | **-1 516 300 €** | |
| **INVESTMENT COSTS** | | | | |
| AD reactor | 12 000 000 € | 12 000 000 € | 12 000 000 € | 3 |
| Biogas powerplant | 2 000 000 € | | | |
| Biogas purification and pressurizing unit | | 2 000 000 € | | 1 |

| | | | | |
|---|---|---|---|---|
| VFA extraction and purification unit | | | 2 000 000 € | |
| Total investment costs | 14 000 000 € | 14 000 000 € | 14 000 000 € | |
| Interest rate | 0,05 | 0,05 | 0,05 | |
| Operating years | 20 a | 20 a | 20 a | |
| **Annuity of the investment** | **- 1 123 396 €** | **-1 123 396 €** | **-1 123 396 €** | |
| **Total annual costs** | **-2 123 396 €** | **-2 594 446 €** | **-2 639 696 €** | |
| **REVENUES** | | | | |
| Biogas energy content | 38 657 MWh | 38 657 MWh | 4 224 t | |
| CHP operating efficiency, electricity | 0,42 | | | 4 |
| CHP operating efficiency, heat | 0,42 | | | 4 |
| Electricity price (with heat premium) | 133,50 €/MWh | | | 1 |
| Heat price | 25,00 €/MWh | | | 1 |
| Electricity for selling | 1 961 916 € | | | |
| Heat for selling | 231 650 € | | | |
| Traffic fuel operating efficiency | | 0,90 | | 1 |
| CBG price | | 50 €/MWh | | 1 |
| CBG for selling | | 1 739 571 € | | |
| VFA operating efficiency | | | 0,80 | 5, 6 |
| VFA price | | | 2,00 €/kg | 6 |
| VFA for selling | | | 6 758 400 € | |
| **Total annual revenues** | **2 193 566 €** | **1 739 571 €** | **6 758 400 €** | |
| **EBIT** | **70 170 €** | **-854 875 €** | **4 118 704 €** | |
| **Payback time** | 12 a | 52 a | 2,7 a | |
| **Production cost (no dep)** | 42 €/MWh | 42 €/MWh | 449 €/t | |
| **Production cost (with dep)** | 89 €/MWh | 75 €/MWh | 781 €/t | |

a) Electricity and heat used in the AD-process were produced by CHP.
b) Electricity needed in separation of digestate 2,5 kWh/t (Møller et al. 2000).
c) Electricity needed in stripping was evaluated through specific heat capacity of water (4,18 kJ/kg $^{o}$C) when the press water was heated from 40$^{o}$C to 80$^{o}$C (2).

1) Paavola et al. 2016, 2) Marttinen et al. 2015, 3) Vantaan Sanomat 2015,
4) www.hsy.fi, 5) Zacharof and Lovitt 2013, 6) Kleerebezem et al. 2015

The highest revenues were obtained with VFA production. Although many of the values were approximations, the estimated production costs were close to that announced by Earth Energy Renewables (The Digest's 2016 8-slide guide to Earth Energy Renewables, www.biofuelsdigest.com). With full scale commercial plant (80 t feed per day) they promise production cost of 507

US$/t without investment costs or 723 US$/t with investment costs. The first two full scale commercial plants are expected to be constructed in 2018 and 2019.

With Earth Energy's process VFAs are extracted and purified using patented extraction process, which is promised to have high product recovery as well as high product purity without complex or expensive purification techniques. Without any further information, it can be assumed that the chain length of VFA is increased to obtain medium chain fatty acids (MCFA) which are then separated by membrane separation. The technology is proven in a demonstration plant (3 t feed per day). Even with some unpredictable additional costs, VFA production would probably be the most feasible use for separately collected biowaste. Nevertheless, VFA production would need existing markets. In that sense CHP-production is an easy option because electricity and heat can be used on site.

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# 6 Non-wood biomasses in Southern-Finland

## 6.1 Case area

The amount of non-wood based biomasses was evaluated in Southern Finland from two different reports (Rasi et al. 2012, Tähti & Rintala 2010). The different case areas are presented in Figure 13 and 14.

AYK-jako SYKE
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**Figure 13.** Areal division (LOS = Lounais-Suomi, UUS = Uusimaa) used in Tähti & Rintala 2010 report.

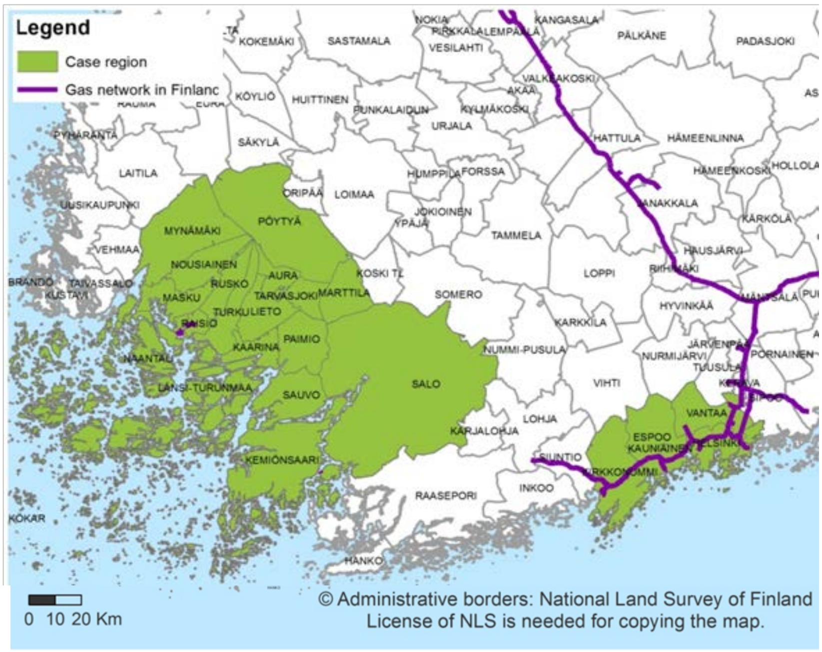

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**Figure 14**. Areal division used in Rasi et al. 2012.

In Tähti & Rintala 2010, the biomethane potential includes biomasses from municipal biowaste, municipal waste water sludge, food industry biowaste and sludge, pulp and paper industry sludge, manure and field biomass. Waste amounts were calculated from VAHTI database, meaning that waste amount are calculated from collected wastes that are informed in VAHTI system. Field biomass was calculated first based on all available field area after which assumptions are made for available land area for energy crop production.

In Rasi et al 2012 sludge data was gathered from municipal sewage treatment plants, from industry and industrial wastewater treatment plants and from wastewater treatment facilities in sparsely populated areas. The total amount of manure was calculated using values for the amounts of manure that can be produced per animal per year and the number of animals in the case regions by 2009 provided by the Agency for Rural Affairs and the Finnish Food Safety Au-thority Evira (2011). Biowaste in study by Rasi et al 2012 consists of biowaste generated in households and in public (schools, kindergartens, hospitals, other care facilities/nursing homes, universities and vocational schools) and private (restaurants, hotels, retail, ferryboats) services. The biowaste amounts include both kitchen and garden waste. Grass was considered as the potential energy crop. Sustainable amounts of energy crops were assumed to be cultivated on crop production farms only. Crop rotation of grass was assumed with cereal in sequence of 2 seasons of grass and 3 seasons of cereals. Field available for straw, i.e. cereals production, was estimated with a crop rotation approach described above.

The biggest differences between the results from these two studies come from amounts of municipal waste and field biomass because of the calculation principles. From both studies, the level of biomass amounts and their energy potential can be evaluated and the total amounts are in same range.

## 6.2 Amount of biomass and energy potential

The amount of municipal and industrial biowaste in Turku and Helsinki case areas is about 83 600 tTS/a (Rasi et al 2013). In Turku and Helsinki areas, the separately collected waste is about 24% and 43%, respectively (Rasi et al 2012). Amount of municipal sludge is about 56 900 tTS/a. The amount of energy in these wastes is from 360 (Tähti &Rintala 2010) to 425 GWh (Rasi et al. 2012), calculated as biomethane. Amount of energy from manures is from 153 GWh (Rasi et al. 2012) to 452 GWh in these areas (Table 12).

**Table 12.** Amount of biomass in case area (Rasi et al. 2012 & Tähti & Rintala 2010).

| | **Turku and Helsinki areas** | | **Uusimaa and Lounais-Suomi** | |
|---|---|---|---|---|
| Biomass | tTS/a | GWh/a | tTS/a | GWh/a |
| Municipal biowaste | 76 600 | 276 | | 95 |
| Municipal ww-sludge | 56 900 | 119 | | 145 |
| Industrial biowaste | 7 000 | 30 | | 28* |
| Manure | 83 700 | 153 | | 452 |
| Pulp and paper industry sludge | | | | 92 |
| Silage | 403 105 | 1 201 | | 3300 |
| Straw | 238 495 | 499 | | |
| Others ** | 15 196 | 46 | | |
| Total | 880 996 | 2 324 | 2 146 300 | 5990 |

*Food industry biowaste and sludge

**Vegetables, greenhouse, sugar beet and potato waste

In Turku and Salo regions, energy crops accounts for 57% and 62%, respectively, of the total theoretical methane potential and other agricultural materials (manure and agricultural waste and side products) accounts for 37% and 36%. On average about 36% and 66% of total vehicle fuel consumption could be replaced with biomethane in Turku and Salo regions.

Even though the calculated emission reduction of biomethane use is larger when biomethane is produced from waste materials than from energy crops, agricultural materials are to be considered as feedstock for domestic energy and chemical production mainly because of limited amounts of waste materials. Biomethane production from energy crops has a good energy balance, and perennial energy crops could be recommended to crop rotation for soil improvement. The largest energy use from crop production comes from nitrogen fertilizers meaning that the energy consumption in crop cultivation can be decreased by using organic fertilizers (e.g. digestate). However, in must be noted that energy production from energy crops is not totally $CO_2$ neutral due to fossil fuel related energy inputs and fertilization. The remarkable GHG reduction can still be achieved with choosing an effective energy production technique and using by-products to the greatest possible extent. Agricultural materials are noted as an important biomass resource also in other countries, e.g. in Germany the total energy potential of biomethane is estimated to be about 116 TWh, of which agricultural biogas systems account for 77-85% (Poeschl et al 2010). Agricultural materials are also potential raw materials for various biorefinery concepts, one of them is described in Rasi et al 2016.

## 6.3 Industrial food waste in Turku area

As an example, the amount of different types of industrial food wastes from Turku area were gathered from study from Rasi et al 2012 and the characteristics of waste was evaluated (Table 11).

**Table 11.** Industrial food waste from industry in Turku area.

| Amount of food waste kg/a | Characteristics | Estimated usefulness: main component | Other value compounds |
|---|---|---|---|
| 1 848 000 | Diverse by-products | wheat/oat proteins (whole seeds not a large fraction of the waste – other fractions contain less proteins?) | dietary fibers also in hulls and seed coats |
| 300 000 | Animal-based fats | meat/pork/chicken protein and peptides for special food and feed ingredients; but need to be collected species-wise | fats to biodiesel or other chemicals production |
| 978 000 | By-products and streams from spread processing (supposedly with process waters) |  | Lecithins (saponification residue). Fats to biodiesel or other chemicals production |
| 200 000 | Bakery residues | Cereal proteins and fibers, starch, mixed fats and oils |  |
| 350 000 | Bakery residues | Cereal proteins and fibers, starch, mixed fats and oils |  |
| 15 0000 | beetrot peals | Dietary fibers, sugars | betalain: pigment, antioxidant<br>betaine: nutrient, food and feed supplement |
| 1 255 000 | vegetable waste |  | betalain and carotenoid pigments/antioxidants |
| 60 000 | fish waste | fish protein and peptides for special food and feed ingredients | fish oil -> biodiesel? |
| 60 000 | berry marc |  | aromas, flavors<br>anthocyanin and carotenoid pigments/antioxidants<br>berry seeds as oil source |

Valuable compounds are in general easier to extract from waste materials if they are kept separately from other wastes. In industrial cases this could be arranged more easily by taking this into account in operational chain. From animal-based materials, the fats and chemicals are the most common valuable products while from vegetable and plant materials also fibers, food and feet supplements, aromas and flavors are possible to produce. Especially from vegetable and plant based waste the availability of raw material can vary seasonally bringing challenges to processing chain. Different collaboration chains between companies and industries would increase the amount of processing materials bringing economic feasibility to processes.

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# 7 Conclusions

The different pathways for using the available biomass were evaluated in this paper. As only couple of processing schemes were selected as examples, it must be noted that the most suitable processing pathway is always dependent on the raw material quality and quantity as well as the product quality and price. Realization of various process schemes depends also e.g. is there already a company capable of taking the new process into operation or can there be new business possibilities between different companies, how to control the seasonal variation in raw material supply, what are the real production cost compared to market and what is the political instruments in general when fossils based energy and products are replaced with renewable ones.

In chapters 3 and 4 the potential of multi-product processing approach was evaluated in the vegetable by-product case study. In this model system combination of fractionating and fermentation gave new options for adding value for this material. Energy-efficient bioprocessing equipment enabled the reduced processing costs, and value of the product, if utilized as feed, could be improved by beneficial microbes. In addition, relatively simple extraction and fractionation methods can be applied, still fitting for purpose. End-products such as food grade coloring /natural antioxidant, and probiotic product were shown to serve as promising alternatives for energy production or composting. Multiple end products provide flexibility, and improve the cost-efficiency of the processing. Although not studied in this project it is evident that further flexibility could be obtained using seasonal sequences of different raw materials in the processing plant. This would reduce the process standstill times, as the vegetable-based food processing by-products are often seasonal.

In the example of VFA production compared to biogas production, the VFA production seemed to be an interesting option as the value of chemicals is high and the price of energy in Finland relatively low. To find out the overall efficiency of the VFA process, the mass and energy balances should also be taken into account as after the extraction of VFA compounds the rest of the material still has energy value.

The current policy environment favors the use of agricultural side streams in energy production. There may not be much direct support to the collection and utilization of agricultural biomasses, but there are few policy or legislative obstacles, either. Energy and resource policies in Finland and in the European Union encourage a transition towards biological resources. This situation is likely to continue some time into the future. However, food security and avoiding indirect land use changes and carbon emissions are central in designing energy value chains. In addition, nutrient recycling is becoming an increasingly important topic, and the chosen energy solutions should reflect this. Waste of nutrients is unlikely to be sustainable or permitted for long.

There are many different types of agricultural and food waste biomasses in Finland, each with their own characteristics. In quantity, there is a lot of potential, but the materials are often produced in small lots, dispersed over large areas and not necessarily available in steady amounts over the year or across different years. Logistics becomes a challenge. Different biomasses are also distributed unevenly: manure and grass is often found in more northern and eastern areas, whereas cereals and straw are produced primarily in the south. This is a generalization, however, and there are e.g., poultry farms in Southwestern Finland. In any case, some farmers are struggling to find suitable fields for manure disposal and would benefit from alternative manure treatments.

A flexible production process that is able to use different kinds of biomasses would often be best, because there is seasonal and yearly variation in the availability of straw, manure and grass. Use of e.g. wastewater treatment sludge is also possible. Although Finnish Food Safety Authority Evira has accepted the use of wastewater treatment sludge on fields (with some restrictions), some farmers may refuse to accept digestate resulting from its use as they have doubts concerning e.g., trace amounts of medicines.

The currently low price of energy diminishes the feasibility of many schemes. Biogas and other transport fuels may become most important options, particularly as the fueling stations network develops. Local production and distribution of e.g., biogas would diminish logistic difficulties.

The farmers who have been contacted in previous studies have expressed interest in providing straw and grass for energy production. Manure is in some parts of the country a challenge to farmers, because adequate disposal methods are not available. Therefore, some farmers are willing to pay a gate fee for manure. Many policy, administrative and research activities are ongoing, aiming to increase productive uses of manure.

Many farms have invested into wood chips particularly for heat production. They have little interest in investing into additional energy production, if they have no use for it on their farm. They might, however, be willing to deliver agricultural biomasses for another energy producer.

In addition to the issues of price and available labor, farmers may have difficulty to rearrange their activities. A farm is a system that has been designed and developed over time and changing e.g. the way straw, manure or grass is managed takes some effort. Adjustments must be made to the total system, which may cause a barrier to even moderately profitable solutions to be taken to use. Extra work would need to be sufficiently compensated. On the other hand, farmers are entrepreneurs, to whom a search for alternative cash flows is not alien. Many farmers have no direct contact with end customers, however, which may reduce their skills in new business model development, marketing etc. Some farmers have expressed a wish to keep energy production in local hands. Farmers and villages often lack, however, affordable modular energy production systems and energy know-how. A joint company or cooperative might solve this dilemma.

The prices of biogas plants is considered to be very high in Finland, possibly as a result of the small number of biogas plants. Economies of scale have not yet brought the costs down. In addition, there is still lacking know-how in planning, constructing and operating biogas plants. Regional co-operation between farmers and possibly other actors such as local wastewater treatment facilities would be important for gaining sufficiently large biomass streams for profitable production scale. Co-operation would reduce investment costs of single farmers, allow for more advanced fertilizer production and more intensive use of equipment for harvesting, transporting and spreading organic materials.