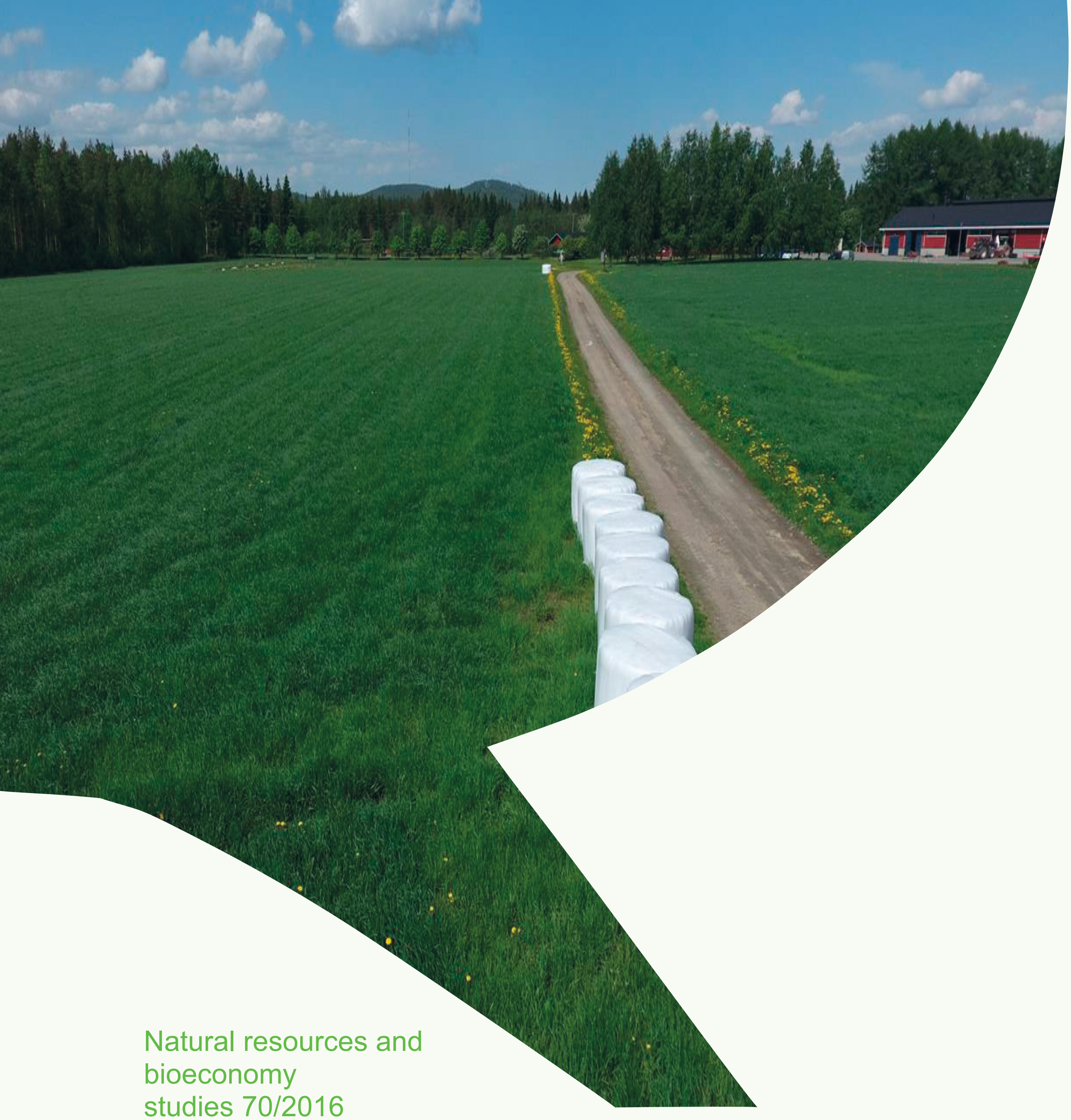

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Biorefineries in decentralized environment

Review

Saija Rasi (ed.)

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Summary

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As a result of food production and processing, considerable amounts of by-products are generated resulting in the need for finding appropriate alternative uses for this material. At the same time there is a need to move away from the use of non-renewable resources and to replace them with renewable ones. Different side- and waste streams can be utilized as new products, energy and nutrients. Depending on the biomass and its purity, a variety of processing possibilities can be used. On the other hand, the overall environmental effect from different processes can vary and in general the amount of side and waste streams should be minimized. As in all cases the total prevention is not possible, the most sustainable use from environmental, economic and social perspectives should be found.

The biorefinery concept is not new idea, but in recent years it has become an interesting option for various biomass treatments. Biorefinery has different definitions but, in principle, it means the processing of biomass for various different end products. In agriculture and in food production and processing, the concept of a biorefinery is relatively new, mostly because of the dispersed location of different biomasses. In many cases, increasing the number of processing steps also increases the cost of the end products. On the other hand, single processes are not necessarily profitable or feasible on their own, but may be sensible as a part of a larger system. With the growing interest and political mandates of utilising renewable resources for the production of new products, it should always be noted that biomass availability is limited. Therefore all production processes should be highly efficient, and the main driver should be the environmental, economic, and social sustainability, covering the whole life cycle.

This report gives a glance at biomass processing tehcnologies in agricultural and food sector. The processing options and example cases as well as the policy environment, sustainability, and economic issues reviewed here illustrate the knowledge and research interests at Luke in this field. The processing options described here are extraction and fractiation, fermentation, anaerobic digestion, and pyrolysis. All processes can be used for various materials either alone or combined with other processes, depending on the quality and amount of biomass. In all cases, Luke has the expertise to find out the ways to ensure the environmental, social and economic sustainability. Seeing the whole biomass value-chain and its possibilities is the core know-how in Luke.

Keywords: Biomass, Biorefinery, Sustainability

Tiivistelmä

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Ruoan tuotannon ja prosessoinnin eri vaiheissa syntyy merkittäviä määriä sivutuotteita ja jätejakeita, joille on löydettävä tehokkaita prosessointivaihtoehtoja. Tarve prosessoida sivu- ja jätejakeita tehokkaammin nousee sekä lainsäädännöstä (biohajoavien jakeiden kaatopaikkakielto) sekä tarpeesta korvata uusiutumattomia luonnonvaroja sekä kemikaalien että energian ja lannoitetuotteiden valmistuksessa. Riippuen biomassan puhtaudesta ja määrästä, useita eri prosessointi vaihtoehtoja voidaan valita sen mukaan, millaisia lopputuotteita halutaan valmistaa. Toisaalta, ympäristövaikutusten minimoimiseksi kaikkien sivu- ja jätejakeiden määrää tulisi minimoida mahdollisuuksien mukaan. Minimoinnista huolimatta, useissa prosesseissa sivuvirtoja kuitenkin syntyy, joten erilaisia ympäristölle, taloudelle ja yhteiskunnalle tehokkaita prosesseja tulisi kehittää.

Biojalostamo konseptina ei ole uusi, mutta kiinnostus erilaisiin jalostusketjuihin on noussut viime vuosina. Biojalostamolla on useita eri määrittelyjä mutta pääperiaate on, että biomassaa prosessoidaan erilaisiksi lopputuotteiksi. Maataloudessa ja elintarviketeollisuudessa biojalostamokonseptit ovat vielä melko uusia. Biojalostamot on tähän asti yleensä tarkoittanut suuren mittaluokan prosesseja, joihin maatalouden ja elintarviketeollisuuden massat ovat olleen liian pieniä virtoja hajallaan eri paikoissa. Usein prosessoinnin lisääminen merkitseekin suoraa kustannusten kasvua ja yksittäiset prosessikokonaisuudet eivät usein ole liiketaloudellisesti kannattavia. Uusia ratkaisuja voidaan löytää yhdistämällä erilaisia hajautettuja biomassavirtoja ja kehittämällä uusia tehokkaampia prosesseja. On kuitenkin pidettävä mielessä, että uusiutuvat luonnonvarat ovat rajallisia, joten uusien prosessien tulee olla tehokkaista sekä ympäristön että taloudellisuuden näkökulmasta.

Tässä raportissa tarkastellaan prosessointivaihtoehtoja maatalouden ja elintarviketeollisuuden erilaisille biomassoille. Tavoitteena on kuvata sekä Luonnonvarakeskuksessa tehtävää tutkimusta että tuoda esille eri mahdollisuuksia biotaloudessa. Raportin tarkoituksena ei ole arvottaa prosesseja, vaan tuoda esille vaihtoehtoja erilaisten esimerkkien kautta. Prosessointivaihtoehdoista esiin on nostettu erotus- ja fraktiointimenetelmät, fermentointi, anaerobinen hajotus sekä hidas pyrolyysi. Kaikki prosessit voivat käyttää hyvin erilaisia materiaaleja joko yksittäisenä prosessina tai yhdistettynä toisiin prosesseihin, jolloin toinen prosessi käyttää toisen ylijäämätuotetta tai jalostaa sitä edelleen. Oli prosessointiketju millainen tahansa, Luken tavoitteena on kehittää prosesseja, joiden vaikutukset ympäristölle, taloudelle ja yhteiskunnalle ovat mahdollisimman positiiviset. Kokonaiskuvan hahmottaminen, arvoketjujen muodostaminen ja eri vaihtoehtojen vaikutukset kokonaisuuteen ovat Luken osaamista parhaimmillaan.

Asiasanat: biomassa, biojalostamo, kestävyys

Contents

1. Introduction

Biomasses, whether being virgin biomaterial of plant or animal origin, or biowaste or side-products, are sources for biomolecules and organic and inorganic nutrients. As a result of food production and processing, considerable amounts of by-products are generated resulting in the need for finding appropriate alternative uses for this material. This kind of biomass usually contains significant amounts of potentially interesting compounds with nutritional and economic interest, thus having potential for recycling or for conversion into useful products of higher value. In circular economy the side-product biomasses could partly replace the use of renewable bio-materials, agro-food materials and even fossil-based materials. The potentiality of most common side-products and their EU wide volumes are already presented in many publications, e.g. by Mahro & Timm (2007).

The IEA Bioenergy Task 42 definition for biorefinery is: "*Biorefinery is the sustainable processing of biomass into a spectrum of marketable products and energy*", meaning that biorefinery can be a facility, a process, a plant, or a cluster of facilities (Fig. 1) (Jong & Jungmeier 2015).

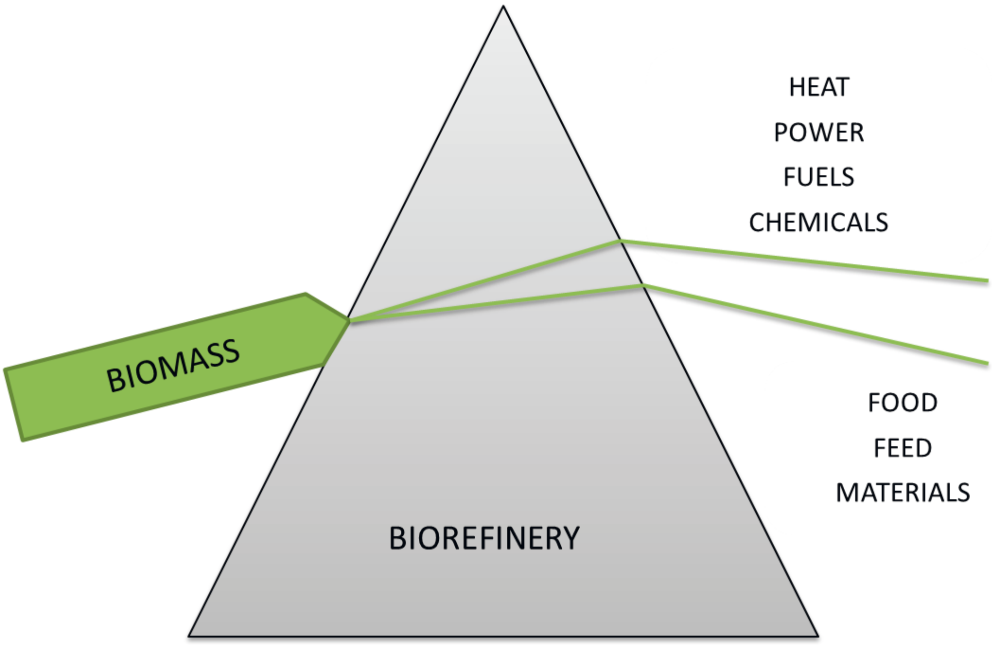

Figure 1. Biorefinery (Jong & Jungmeier 2015).

The concept of biorefinery is not new. The existing biorefineries will continue to grow and their future development will be towards increased sustainability and maximizing the utilization of biomass, improving energy efficiency and being less wasteful. For new biorefineries, selection of suitable biomass resources is extremely critical so that they can operate in symbiosis rather than in competition with food sector and other markets, e.g. those based on forestry. In order to be sustainable and also to avoid increase in the raw material prices, the future biorefineries will have to concentrate on lower quality renewables such as grasses, harvest residues from crops, and by-products and wastes from food industry, forestry and society (Hatti-Kaul 2010).

Biorefineries for integrated production of bioenergy, chemicals and materials hold promise for both short- and long-term sustainability for developing countries. As the use of biomass and implementation of biorefineries will increase with time, the issues of providing food as well as bioproducts while maintaining productive soils and effective infrastructure will become more and more important. In order to take advantage of the locally produced biomass, a major challenge for the developing countries will be to participate in technology development and application. Initial processing of biomass on small-scale close to the harvest location would provide several benefits in terms of minimal transportation, better recycling of minerals, new forms of integration in energy utilization and labor organization (Sanders et al. 2007). Production of an intermediate product bearing less water and a better shelf live that can be transported to lager processing plants would enable the production throughout the year and lead to lower capital and labor costs, as well as better prices for by-products.

Circular economy requires a systemic approach. This key challenge means that various products and services, as well as business models, need to be considered and designed together taking into account the sustainability of the chain. A single process is not necessarily profitable or feasible on its own, but may be sensible as a part of a larger system. This means that various professions, professionals, and organisations need to pool their resources to consider various biomasses, technologies, processes, business logics, and customers at the same time.

Biorefineries, as well as the whole circular and bioeconomy are constantly evolving. For example, legislation and technologies develop and change. In order to keep research relevant in the changing circumstances, as well as to direct both research and societal activities in a desired direction, foresight activities are needed. Mapping of future possibilities and barriers of emerging technologies, policies, and societal changes in the bioeconomy have been studied, for example, from the perspective of climate action in ILVAMAP and Polkeva projects (Rikkonen 2015, Uusivuori et al. 2015). In these projects handling of manure and biogas production emerged as significant tools for cutting down emissions, so it is possible that policy changes regarding them may be taking place.

Natural Resources Institute Finland (Luke) aims at being the central research organisation in this field. Luke has been organised into units that extend from biomass production to their utilisation, new businesses and societal, economic and sustainability research. Biorefinery concept has already brought together researchers in all Luke units. Our strength is having understanding of whole value chains, from fields and test tubes to barriers of commercialisation.

The aim of this review is to present examples of biorefinery concepts suitable for acricultural and other decentralized environment. These examples present also samples of the knowledge in Luke in this field.

More examples of biorefinery options from non-woow biomass can be found from Rasi et al 2016.

2. Policy and legislation

Vilja Varho, Erika Winquist

Biorefinery concept is based on a very strong political mandate. Key concepts in this mandate are bioeconomy and circular economy. The Finnish Bioeconomy Strategy (2014) defines bioeconomy as "an economy that relies on renewable natural resources to produce food, energy, products and services". Water resources, fish and game, leisure activities, and various ecosystem services are also part of the bioeconomy.

The Finnish goal is to reduce dependence on fossil resources, to preserve biodiversity, to create economic growth (increasing the bioeconomy output from 60 billion euros in 2011 to 100 billion in 2025) and to create new jobs (up by some 30% by 2025). Finland is not alone, as the European Union and many other EU Member States have bioeconomy strategies. The special strength of Finland is the abundant natural resources, particularly forest resources that have been used for centuries. In the EU and global level most bioenergy increases are expected to result from agrobiomasses (Kallio et al. 2015).

Recently even in Finland new attention has been paid to non-wood and non-food products, such as manure. Since the arrival of manufactured fertilisers, manure has been considered almost a nuisance and a waste. This is changing, in part due to the global scarcity of nutrient resources but also because of the eutrophication of lakes and the Baltic Sea (Ylivainio et al. 2014). For example, phosphate rock has been classified as a critical resource in the EU, which relies heavily on imports from outside the EU (European Commission 2014). Policies that improve the recycling of phosphorus and other nutrients are likely to be developed and enforced in the EU.

Circular economy is a term that is based on striving for sustainability. It encompasses also non-biological resources. It refers to a system where there is no "waste" but instead, resources for new products. It means closed systems, new collaboration between organisations, new products and technologies. The Finnish aim is not to just recycle large masses of materials, but to create new innovations, knowledge, technologies and products that can be exported. A central challenge in circular economy is to plan all products and processes in such way that productive use of various streams can be achieved. The idea is to avoid producing waste and to reduce the use of limited natural resources, particularly the non-renewable sources. An important initiative to facilitate efficient use of biomass in Finland is "Biomassa-atlas". It will bring detailed information about different biomasses and their locations to open use and will be available for use in 2017 (Lehtonen et al. 2014).

The circular economy concept is in wide use. For example, Finnish Environmental Industries have named circular economy as one of their goals (YTP 2015). The European Commission is renewing circular economy legislation. For example, a new proposal for regulating fertilisers from biowaste or other secondary materials was recently presented (European Parliament 2016), with the aim of increasing the production and markets of organic fertilisers. National recycling targets and eco-design guidelines are under discussion. Research is to be funded through the Horizon 2020 program (EU Office Helsinki 2015).

In waste management, policies aim to increase the recycling of organic waste. The Finnish Government regulation (VNa 331/2013) mandates that from the beginning of 2016 waste with higher than 10 percent organic content may not be placed in ordinary landfills. This means that there are various types of biomass that need to be processed, such as garden and park residues, waste streams from industry, and sludge from water treatment facilities. The waste hierarchy that promotes the reuse or recycling of materials over the retrieval of their energy content still stands, meaning that waste materials should not be burned if other uses are available.

Policies affect biorefineries in a crucial way. For example, new process development may receive some research, development and demonstration funding. Various subsidies are already available to e.g. small-scale energy production. Policies may also change the profitability of products more indirectly. For example, waste treatment costs may increase, which increases the profitability of processing wastes to useful products. Taxes on competing, non-biological products such as gasoline may rise. Policies affecting the global market may also affect competitiveness, such as oil production decisions of the OPEC. As many resources become depleted, the demand for alternative, bio-based products naturally increases. This is a slow trend at the moment, but it may reward the forerunners who now invest in biorefinery production.

Despite of this political mandate for biorefineries, direct political support is less straightforward. The field is regulated through e.g. food, agriculture and energy legislation which may cause unnecessary complications.

3. Economic feasibility

Erika Winquist, Vilja Varho

The economic feasibility of the biorefinery concept results from a more versatile and complete use of different biomass streams. A single process with a single end product may not be profitable on its own. However, when all side-streams and utilisation possibilities are considered together, a biorefinery concept may be profitable. Among factors affecting profitability are raw material costs and availability, logistics, selection of processing and end products, markets and legislation.

Many of the products that can be produced through biorefineries are used by other businesses. They can be finished products or raw materials for e.g., medicines, feed, or fertilizers. These business-to-business products face different challenges than products that are being marketed directly to consumers. Companies and entrepreneurs may not be willing to pay extra for products that are domestic or from renewable sources, whereas these values may affect consumer decisions. On the other hand, corporate responsibility and aims for sustainable production are strengthening trends.

3.1. Raw material costs and availability

A key concept that affects economic feasibility is whether the raw material for the pro-cess has to be grown or harvested specifically for the process, or whether it is easily available as a side stream or waste of another process. These side streams may be inexpensive, free, or even bring a gate fee with them. For example, much of the biogas production in Finland relies on waste streams, such as waste water sludge or waste from the food processing industry. Biogas plants are actually paid for the treatment of these materials, which naturally increases the profitability of the plant.

The quantities and year-round availability of raw materials can be central to economic feasibility. If the process can only treat a single material, and there are seasonal or other reasons why it is not constantly available, the process cannot be run all the time. The equipment that has been invested in is therefore in less than optimal use. A process that can use various kinds of materials, or materials that are available year-round or cheaply stored, is more likely to be profitable.

3.2. Logistics

Biomass has typically a high water content and low energy value. In addition, its availability may be spread to a large area. Even in the case of an inexpensive material, transportation costs may prevent its utilisation, such as the collection of straw for various purposes. The raw material stability may also be a problem and either fast processing or cold storage is required. Instead of a large centralised processing unit, decentralised processing located next to the raw material source may be an optimal solution. Decentralisation shortens both transport distance and storage time.

One success story is the bioethanol production by ST1 Biofuels. Its decentralised production plants are situated close to the raw material which can be food waste, biowaste or even sawdust. The bioethanol from these small plants is transported for further processing, but the amounts of transported freight are much reduced through the distributed production phase.

3.3. Selection of processing and end products

The raw material might provide possibilities to produce several end products. Purified chemicals may have use in medicines or cosmetics or as intermediates in production of industrial chemicals or materials. Biofuels (for transport) are typically less expensive than biochemicals and the lowest income is gained with bioenergy (heat and/or power) (Christensen et al. 2008). Both the recognition of the value components and the utilisation of all fractions are needed for feasible processing. In an optimal solution, the production of a lower value biofuel is supplemented with the production of a high value biobased chemical. The suitable processes are then selected based on the product portfolio. The recent growing interest in replacing fossil raw materials with renewable biomass resources can already be seen in technology development related to biomass processing (Bozell and Petersen 2010).

3.4. Market

A key question in biorefinery profitability is that of the market. Is there a natural and easily available use for the product and what are the competing solutions? For example, in the case of biogas, it is easier to find uses for electricity than heat, especially in the warmer months. There are high hopes that the use of biomethane as a transport fuel will increase, improving the market demand. The main benefit in the use of biomethane in transport is that no extra heat is produced as in CHP production (Winquist et al. 2015). In cities, there are already some buses that run on biomethane. Increasing the number of gas vehicles requires more methane stations in the countryside and also outside the natural gas pipeline network. New gas stations are being opened by e.g. the firm Gasum. It is in part a response to the EU Directive on the deployment of alternative fuels infrastructure (Directive (EU) 94/2014). LNG (liquefied natural gas) technology and infrastructure are improving, which will gradually also increase the demand for biogas.

Markets for other biorefinery products may also change in the future. Market prices may increase, or new uses for the products may be discovered. Policies may also remove market barriers, as is the aim in the new organic fertilizer proposal (European Parliament 2016).

4. Treatment processes for various biomasses

4.1. Extraction and fractionation techniques for biomass refining

Eila Järvenpää

Extraction and fractionation techniques are a wide group of chemical and physical methods, which are utilised to simplify the biomass or raw material to fractions owing different chemical or physical properties. The methods are used often in combination, depending on the specific need of fraction of simplicity. The most simples one could be just sieving of dry material, yielding fractions of different particle sizes, or by sedimentation of insoluble compounds from a liquid solvent. Simple extraction and fractionation techniques have been used in small and larger scale, and utilised e.g. in the production of foods and feeds (e.g. water or ethanol extraction, distillation, centrifugation, filtering). Actually, an extraction process is one example of a simple fractionation process, because after extraction one has at least two fractions: a soluble and an insoluble fraction of the original material. More specific separation techniques can be used to yield specific chemical compounds, e.g. enantiomers of plant biomolecules, owing different chemical characteristics. The latter technologies are often called purification methods.

Traditionally, specific extraction and fractionation methods have been developed to be used in analytical or preparative scale, because they make an analytical problem easier to resolve. In these exercises of analytical chemistry, traditionally, virgin and intact materials of plant or animal origin have been used as a raw material. From literature, it is possible to find several techniques for most of the biomolecules, e.g. by reviewing journals in the fields of food (bio)chemistry and and (bio)technology, food engineering and separation sciences. The major technological issue is how the material has been changed during its transfer from intact material to a biomass and how well its components and their quality have been preserved.

In this review typical extraction and fractionation methods are presented very shortly, focusing on environmentally benign methods. In practice, the selection of the method is always based on the balance of three needs: what biomolcules should be extracted and how well they should be fractioned from the other components of the biomass, and how the rest of the biomass will be used.

4.1.1. Extraction methods

Extraction takes place in a container, where the biomass is mixed with the solvent(s) and possible additives. The type and size of the contained depends upon the operative conditions and materials used, for example acids and bases and organic solvents have different restrictions to the container materials. Container type also is determined by how the mixture of solvent and biomass is to be mixed and finally, how the solvent and the residual biomass are to be separated from each other.

As some of the sources of biomass may produce rather large volumes of biomass, continuous systems might be useful. Such containers are equipped with a conveyor, screw or pumping systems for transport of biomass, solvent(s) and their mixtures.

Typical liquid solvent extraction

Extraction with liquids is versatile technique, because many different liquid solvents can be used, and the obtained extract is characterised by the solubility to said solvent. For agro-food biomasses, aqueous solvents can often be used. Aqueous solvents are also enlisted as green solvents, i.e. probability of pollution caused by these solvent is rather low. Less toxic solvents (for humans and environment) are also preferred due to occupational health issues. Depending upon the use several lists of green solvents have been formulated, and lately the effort of purification and recycling has obtained the attention. In a recent review, typical chemical synthesis and extraction solvents are classified by their usability, overall toxicity and occupational health issues (Byrne et al., 2016). One could also think how much a solvent is needed per amount of the extract obtained. Low solubility of the desired component in the solvent often results in use of larger volumes of solvents. Enzyme-assisted extraction releases the target biomolecules from the bulk biomass by enzymatic hydrolysis simultaneous to the extraction step enhances the extraction yield of such biomolecules, which are bound to or adhered to larger molecules structures such as pectins and other fibers or proteins. By this technique, the solvent can be less strong, but the enzymes modify the bulk of the biomass and remain in the biomass, unless immobilized enzymes can be used. In addition, additives, such as salts, acids and bases are utilised to refine the properties of the liquid solvents, especially aqueous systems, to obtain more refined extracts and improve the solubility. The solubility can also be modulated using temperature and pressure controls. Elevated pressure processes are briefly described below. Nevertheless, large volumes of liquid solvents are often necessary.

One of the most important parts of the extraction process development in larger scale is to define how to achieve effective mixing between the biomass and the extraction solvent. If the biomass has particulates, it may be necessary to use any size-reduction device for milling or grinding or pressing the biomass to a more homogenous particle size. Different kind of mixers, paddles and vortex-mixers are often in use. Some biomaterial applications would benefit from the enforced circulation of the solvent through the material, e.g. by counter-current flow systems and pump/vacuum systems. In addition, ultrasound and microwave energies mix solvent very efficiently with the biomass particles and within the particles. These have been shown to improve the extraction efficiency and shortening the extraction time in analytical scale processes, however some of the techniques are also proposed for industrial use.

After extraction the biomolecules will be recovered in the solution, and the rest of the biomass remains behind. This can be achieved using relatively simple techniques such as sedimentation and sieving/filtering. Recovery of biomolecules from solvent - water and other solvents - often necessitate the use of energy, such as heating to achieve the evaporation of solvent, but also techniques with lower energy impact are available (see below).

If any of the additives, e.g. salts are used, they need to be removed from the refined extract or from liquid phase before the liquids can be recycled or reused. Industrial processes almost always include reuse and recirculation of the solvents after purification, which is most often achieved by adsorption and distillation.

Alternative solvents and pressurised solvent systems

Fats and oils included in many of the biomasses can be used as a solvent, too. They dissolve fat-soluble vitamins and antioxidants, and other non-polar biomolecules. As well, the extraction and purification of more polar biomolecules within the biomass may be enhanced if the oil phase is first removed. Separation of fat from the biomass is rather easy when the fat is in liquid (oily) form, and the other part of biomass is very wet. One typical example is steam extraction, which has the benefit of increasing the temperature of the biomass rapidly and evenly. Oil and water phases can most cases be separated, and in difficult cases the phases are better separated by adding suitable additives, e.g. enzymes/salts/acids, which modify the structure of the aqueous phase of the biomass.

It has been also proposed, in specific cases, that the addition of vegetable oil to a biomass may result in the extraction with the fat. This could be good option, if the biomolecules within the biomass would be utilised with the added fat phase. Such compounds could be e.g. yellow-red carotenoid pigments such as found in carrot, tomato, and algae (Sun & Temelli 2006, Vasapollo et al. 2004, Krichnavaruk et al. 2008).

Supercritical carbon dioxide (CO_2) extraction has been used long time for decaffeination and aromatic volatiles extraction. In these cases the CO_2 extraction replaced the use of chlorinated solvents and hexanes, which was huge benefit in reduction of use of environmentally harmful solvents. In addition, (vegetable) oil extraction for food and nutraceutical use is performed in many locations globally, and also in Finland (Aromtech LTD, Tornio). In addition, Fazer Mills & Mixes (Lahti) is building a new mill, including an industrial oil extraction plant in order to facilitate the fractionation of oats to value-added fractions owing special properties. Such process has been also tested in pilot scale in MTT-Luke (Aro et al., 2007). Supercritical CO_2 is a non-polar solvent, so it fits best to above mentioned use, however more polar biomolecules, such as certain phenolic compounds and polar lipids can be extracted using ethanol or aqueous ethanol as cosolvent. The benefit is that the extract does not have any solvent residues, or the extract is biomolecules in ethanol. The technique could be well suitable for recovering of volatile aromatic compounds as well as nutritionally important oils from food-grade waste. There is however sometimes a need to dry the material prior extraction and it will affect the environmental impact of the whole process.

The supercritical fluid extraction (SFE) process uses electricity for pressurization and pumping of high-pressure carbon dioxide, and the equipment and the facility has to be made and certified pressure-proof. The solvent – carbon dioxide liquid – is most cases circulated even in pilot-scale equipment, thus the solvent itself does not have large impact, because the carbon dioxide is often collected from industrial fermentation processes. As SFE is an industrial processing method, several applications are described in the literature. The topic of this review, by-product processing is considered e.g. Casas et al (2009), Martinez (2007) and del Valle (2015).

Pressurised hot water extraction (PHWE) involves an extraction chamber, which is filled with the material and water. After closing chamber tightly, the temperature is increased, thus increasing the pressure inside the chamber. After extraction process is finalised, the pressure is released, and the extracted compounds will flow out in an aqueous solvent. PHWE has been demonstrated useful for fractionation of wood components: cellulose, hemicelluloses and extractives (e.g. Kilpeläinen 2015), as well as other lignocellulosic biomasses. One Finnish start-up company has established its use, however the utilisation of the fractions in the products is still on its way. For food-based biowaste most effort has been made to develop a process for fractionation of polyphenolic compounds from pectins and other fibre components, e.g. in fruits, onions and spent coffee (Turner et al., 2006;Plaza & Turner, 2015; Xu et al., 2015) The equipment does not have as strict occupational healt rules as SFE, because pressures are lower and there is no risk of carbon dioxide poisoning (as in SFE).

Pressurised liquid extraction methods are becoming more popular after a lag phase – as an analytical scale extraction method. By increasing the pressure and temperature, the extraction step becomes faster and more effective, thus for easily deteriorative biomolecules this technique might be useful also in a larger scale, but such example has not been shown, and the process facility involves safety issues similar to the above pressurised systems. Pressurised extraction systems have been proposed as a part of biorefinery concepts now, because they use solvents which are benign for environmental point of view, and at the same time novel techniques and high-tech. Actually, the processes itself can be rather easily modulated for the actual need. Some examples for food processing side-products and similar raw materials has been recently discussed e.g. by Brunner 2015, Duba & Fiori 2015, Temelli & Ciftci 2015, del Valle 2015 and Vardanega et al 2015.

Pressurised carbon dioxide and hot pressurized water systems have been and are still are of research interest, as a replacement of organic solvents and other complex solution systems in the chemical processes and biorefineries. Ionic liquids and their use as solvents have showed interest lately and are now studied in numerous research projects, because some of them are considered green, environmentally benig extraction solvents and reaction media. They are proposed for valorisation of cellulosic compounds, biodiesel and other biofuel production as well as refining of algae compounds. Examples can be found in the literature (e.g. Bogel-Lukasik, 2015; Xu et al., 2016). As well, a range of different ionic liquids have recently showd to be attainable from lignocellulosic biomasses, thus replacing the fossil-based organic solvents (Socha et al., 2014).

4.1.2. Fractionation and purification methods

There exists several fractionation and purification methods suitable for biomolecules and again the selection is made by characteristics both the target and unwanted compounds in the solution. Below, are presented short lists of available techniquees, and examples of compounds, which have been isolated using the technique.

Fractionation based on volatility

Volatile constituents of biomass or processed biomass could be separated first before further fractionation and purification processes. Evaporation of volatiles can be achieved by purging air/purified gas or steam through sample bed. Depending on the total biomass utilization, the heating of material necessary to obtain the steam is useful, although this process consumes a lot of energy. Evaporated compounds can be collected using cooled condensers, and in the industrial scheme energy can be saved by heat exchangers

Inverse process deodorises the desired fraction by removing undesired aromas and flavours.

Examples of volatile compounds attainable this way are e.g. small molecular weight alcohols, aldehydes, terpenes and some of the organic and fatty acids.By increasing the temperature more compounds can be volatilized, thus the process is used e.g. in the de-odorisation and fractionation of vegetable oils.

Fractionation of dilute aqueous solutions

Dilute aqueous solutions are obtained using normal aqueous extraction or PHWE. edimentation of precipitating compounds and filtration is a convenient way to simplify the solution before further fractionation and purification. Sometimes using precipitation aids (solids or solvents) are used.. It can be used also opposite way, i.e. sedimenting the desired component, e.g. protein aggregate or pectins. More clean fractions are obtained using membrane filtration and concentration. Membranes separate compounds based on the molecular size – molecules able to flow through the pores of the membranes and molecules which will remain in the main flow.

- Example1: pigments and flavonoids concentration from a diluted juice.
- Example 2: Desalting and removal of sugars of solution containing proteins and peptides (after extraction using pH –controlled aqueous solution).

Sometimes added liquid or solid phases are necessary to achieve partitioning between two or more phases. Such process in chemistry are liquid-liquid (e.g. oil-water), and solid-liquid partitioning. Solid-liquid partitioning is one of the different chromatographic techniques, which makes it possible to fractionate and purify the mixture of compounds by molecular size, molecular mobility, molecule polarity and their combinations. Although more complex and laborious to perform, industrial chromatographic separation is in use for value-added natural and synthetic compounds in the pharmaceutical, cosmetics and food and feed ingredient sectors.

4.2. Fermentation of vegetable and fruit processing residues

Minna Kahala, Vesa Joutsjoki

Fermentation is a process in which microbes- bacteria, yeasts or sometimes molds - convert carbohydrates of organic material to organic acids, alcohols and/or carbon dioxide. Fermentation process has a long history and has been used world wide for food processing and preservation. Industrial fermentation is performed on bioreactors with the option to control aeration, stir rate, temperature, pH and other parameters of interest, depending on the application.

Fermentation processes enable conversion of by-products into an extensive range of valuable fine and bulk chemicals, enzymes, biofuels, organic solvents, aroma compounds, organic acids etc. (Vandamme 2009) (Fig. 2). Once produced, final product recovery and purification methods are dependent on the product and the concentration of the product. Biochemical, mechanical and chemical processing steps can be usefully connected.

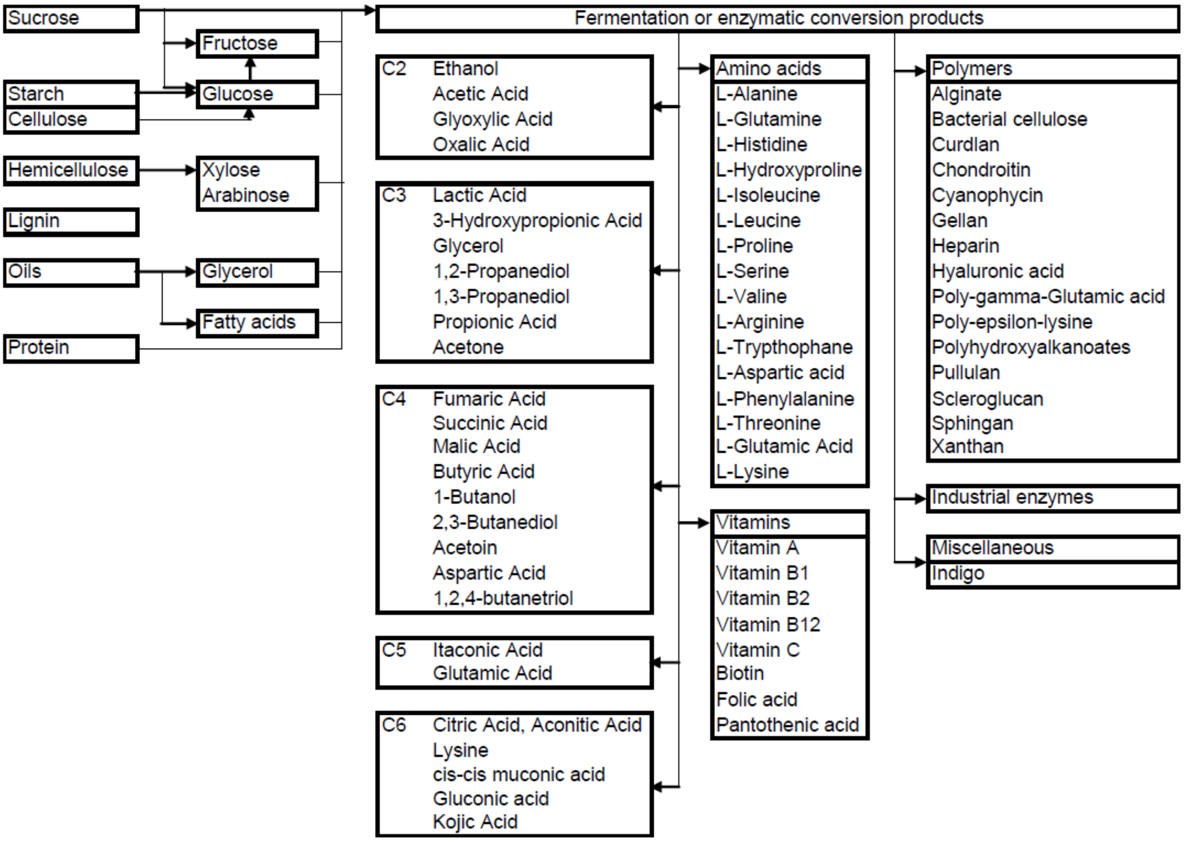

Figure 2. Overview of chemicals that can be obtained from major biomass conctituents by established or possible biotechnological processes. (http://www.bio-economy.net/applications/applications_chemicals.html)

Vegetable and fruit residues include trimmings, pressing fluids, peels, rotten, shells, or slurries posing increasing waste and pollution problems, and furthermore, considerable losses in vegetable production worldwide. Storage losses of root vegetables can be 30% of the harvested yield and when root vegetables are peeled about 40 – 60% of the material turn into the by-products. As an example, in carrot production in Finland it means 39 000 t residues in a year.

Vegetable and fruit by-products often have high content of nutrients, such as vitamins, minerals, saccharides and other organic compounds, providing also good medium for micro-organisms to grow. Thus, these residues are easily decomposed in an uncontrolled way because of numerous spoilage bacteria on the surface, particularly if stored in the production unit prior to use (Laufenberg et al. 2003). Practical and cost-efficient methods are needed for storage, preservation and utilization of by-products.

Utilization of the by-products can be enhanced by fermentation. Lactic acid bacteria have a major potential for use in preservation of the vegetable residue because they are safe to consume and during storage they naturally dominate the microflora of many foods. Fermentation with lactic acid bacteria leads to a suitable transformation of low molecular materials, like sugars and to a microbial stabilisation, because enterobacteriaceae and moulds present on the biomass are inhibited by the lactic acid formed (Stiles 1996). The fermentation process can simultaneously improve stability and add value of the product. Depending on the amounts of the by-products, it could be advantageous to set up and utilize biorefinery in the vicinity of the vegetable production and processing plant.

Fruit and vegetable by-products have been found to have potential also for higher value products. Several studies for utilizing plant based waste as a starting material for producing organic acids, flavours etc. have been carried out both in lab and in pilot scale. In an EU funded project (www.transbio.eu) biotechnological solutions like fermentation and enzyme-conversion strategies with the aim to obtain valuable bioproducts like plastics (PHB), nutraceuticals/platform chemical succinic acid and enzymes for detergent applications were investigated. Fruit and vegetable waste were studied as raw materials in these processes. Also big companies producing biobased products, such as succinic and lactic acid, have announced the longer-term goal to move to agricultural, forestry and industrial waste as alternative feeding materials for processes**.**

4.3. Slow pyrolysis

Kimmo Rasa, Kari Tiilikkala, Saija Rasi

Thermochemical conversion takes place in elevated temperature, under restricted or controlled oxygen supply and in some cases under elevated pressure. One of the major differences between technologies lies in their requirements for the feed stock. Torrefication, pyrolysis and gasification are suitable for relatively dry or dried feedstocks whereas hydrothermal carbonisation (HTC) can handle also wet materials.

Pyrolysis is a thermochemical conversion technology where biomass is slowly heated under oxygen free or oxygen limited atmosphere at temperature generally over 350 °C. The products of the pyrolysis process are non-condensable gases, liquid fraction and remaining char fraction. Pyrolysis technology is commercially available for dry feedstocks, however, in the case of biomasses with high moisture content additional pre-treatment steps are needed.

Before pyrolysing initially wet biomasses, the solid part of wet biomass should be separated e.g. by pressing or centrifugation and further dried as well as possible. Useof waste heat from some other process should be prefered in order to suppress drying costs. In general, pyrolysis system can treat a feedstock with moisture content up to 30 wt%, but moisture content less than 10 wt% is preferred. High moisture contents affects the pyrolysis process energy balance and end product quality, e.g. lower char yield and lower caloric value on gases and liquids are obtained. Depending on pyrolysis system, the feedstock composition as e.g. particle size has to be taken into account (Ronsse 2013).

In order to minimize transport costs of feedstock material mobile pyrolysis technologies have been developed. Economic analysis of the technologies have proved that pyrolysis systems could be economically sound if labor cost can be minimized in the production (Brown et al. 2011) and all the products (energy, liquids, char) are sold. An on-going EU project Mobile Flip address challenges related to mobile units aiming to convert underexploited agro- and forest based biomass resources into products and intermediates.

The pyrolysis temperature, as well as heating rate has an effect on pyrolysis products. With increasing temperature, gas yields usually increases. In the higher temperatures, ash content in char increases and more carbon, nitrogen, hydrogen and oxygen from the feedstock end up in the pyrolysis liquids and gas (Azuara et al. 2013). For maximizing char and syngas yields, a slow heating rate and a long residence time, e.g. slow pyrolysis, should be applied. Fast pyrolysis is required to maximizing the tar yields (Cantrell et al. 2012).

Slow pyrolysis can be considered the process of choice for biochar production, as the char itself is considered the primary product and consequently, the choice of process conditions (with respect to the quality of the resulting biochar) is less constrained by the optimization towards bio-oil quantity and quality (in case of fast pyrolysis) or syngas quantity (in case of gasification).

Increasing number of research and publications dealing with pyrolysis and its end products has emerged extensive scientific discussion about characterization of the char fraction. Not only the vast variation in char quality depending on raw material and process parameters, but also several possible uses of the end products makes it challenging to establish “generally accepted methods for char analysis”. As an example, two international approaches have been actively developed to standardize appropriate tests for biochars, which main use is soil application on agricultural purposes. These are European Biochar Certificate (EBC) and International Biochar Initiative (IBI), which have common interest to harmonise guidelines. Though both approach are mainly consistent regarding basic properties to be studied and declared, there are still variation in the specific analytical methods. The same methodological variation applies to scientific papers, which makes sometimes comparison of the result rather difficult.

Considering the quality of the remaining char fraction, its carbon content is one of the fundamental properties (cf. carbon sequestration). Carbon content of the char fraction can be expressed on the basis of the total carbon content (C_{tot}) or organic carbon content (C_{org}). The main difference is that inorganic carbon, e.g. in the form of $CaCO_3$, will be accounted for Ctot if present, whereas Corg accounts only for carbon associated to organic material. Both EBC and IBI guidelines rank charcs according to their carbon content, for example EBC divides chars with C_{tot} > 50% as biochar, <50% pyrolysis ash containing biochar.

Although pyrolysis of wood based materials has the longest research history, recent studies have proposed various types of biomasses as potential raw materials for the process. For example, pyrolysis of different types of manures, sewage sludge from waste water treatment plants and other industrial waste streams rich in nutrients have been tested (Rasa & Ylivainio, 2014; Rasa et al. 2015; Ylivainio et al. 2015). In general pyrolysis of nutrient rich biomass is seen as a way to concentrate phosphorus in the biochar while nitrogen and carbon divides in all pyrolysis products. Therefore pyrolysis is considered as a potential method to produce recycled bio-based fertilizers with relatively high concentration of phosphorus and carbon; the latter bearing potential to improve soil physical properties in addition of fertilization value of phosphorus. However, research on the short and long term plant availability of phosphorus enriched into different types on biochars is required. This data is needed to enable appropriate use of these recycled fertilizers in plant production as well as to provide relevant information for marketing purposes (cf. informative label in commercial NPK-fertilizers).

In slow pyrolysis, bio-oil product is bi-phasic with an aqueous phase containing large amounts of organic acids and smaller amounts of heavy, water-soluble tars (Ronsse 2013). If pyrolysis liquids are considered for fuel products, the low nitrogen content in pyrolysis feedstock is required as presence of nitrogen is considered as a disadvantage in pyrolysis oils. Pyrolysis liquids contains usually also aqueous phase and as also this phase commonly contains nitrogen, some applications as nitrogen fertilizer could be possible (Azuare et al 2012). Use of pyrolysis liquids as pesticides has been known for a long time but many bottlenecks in the registration of botanical pesticides limit the marketing in Europe (Tiilikkala et al. 2010). According to Ronsse (2013) in small scale pyrolysis units bio-oil production is not currently economically viable and new applications are needed especially for small scale units.

The composition of pyrolysis gas depends on e.g. the characteristics of feedstock and the pyrolysis temperature and heating rate. Pyrolysis gases can usually be used as primary fuel for direct combustion. The main components of pyrolysis gases are carbon dioxide (CO2), carbon monoxide (CO), hydrogen (H2) and methane (CH4). Gases may also contain some minor amounts of light hydrocarbons (HC), as ethane and propane (Azuara et al 2013, Lima et al 2009). Pyrolysis gases can be used for energy production but overall energy balance of the process depends on process parameters (amount of heat needed versus gas produced).

In general, many research papers focus on throughout analysis of one pyrolysis product at the time. Less documents describing potential use of all three end products is available. However, such research is of great value due to optimization dilemma related to pyrolysis process; by optimizing quality of one end-product (e.g. biochar) the quality of liquid and/or gaseous fraction may suffer. Accounting the statement that all end-products should be utilized to make pyrolysis economically viable (see above), broader research approach should be addressed.

4.4. Anaerobic digestion

Elina Tampio, Saija Rasi

4.4.1. Biogas process

The anaerobic digestion (AD) and formation of biogas is a combination of multiple microbial processes under absence of oxygen. AD consists of four stages: hydrolysis, acetogenesis, acidogenesis and methanogenesis, which function in symbiosis, producing substrates for the subsequent process stages. During hydrolysis, the insoluble macromolecules of the substrate; proteins, long-chain carbohydrates and fats, are degraded into smaller compounds such as sugars, amino acids and long-chain fatty acids, which are further broken down into volatile fatty acids (VFAs) such as propionic and valeric acids during acidogenesis. In the third stage of the AD, acetogenesis, the VFAs and other intermediates from the previous stage are converted by bacteria to acetate, CO_2 and H_2, where the synergy between hydrogen-converting methanogens prevents the accumulation of intermediate VFAs. Intermediates from acetogenesis are transformed into CO_2 and CH_4 by acetotrophic or hydrogenotrophic methanogenic micro-organisms, i.e., archaea, during metanogenesis. The acetotrophic methanogens consume the acetate to produce CO_2 and CH_4, while hydrogenotrophic methanogens are dependent on the CO_2 and H_2 (reviewed in Jain et al. 2015, Merlin Christy et al. 2014).

AD is a widely used technique for the treatment of various organic waste materials such as manure, food waste, sewage sludge and agricultural by-products, as it recovers energy in the form of biogas for use in combined heat and power plants, in vehicles and for grid injection. AD also allows recycling of nutrients through application of digestion residues in crop production. Both the Renewable Energy directive (2009/28/EC, European Council 1999) and the Landfill directive (99/31/EC, European Parliament and the Council 2009a) have been strong drivers in promoting the use of anaerobic digestion for this application in recent years. Additionally, the EU Action Plant for the Circular Economy will strengthen the role of AD as a part of nutrient and material cycles (European Commission 2015).

Theoretically anaerobic digestion produces 50 % CO_2 and 50 % CH_4. Thus, the composition of the substrate affects the methane content (Angelidaki & Sanders 2004). Also other components can be formed during anaerobic digestion, e.g. hydrogen sulphide (H_2S), which affect the biogas composition due to different substrates, microbial consortia and digester conditions (Möller & Müller 2012). Typically biogas contains 50-70% methane and the highest methane production can be achieved with materials with high fat and protein content (Angelidaki & Sanders 2004).

The biomass treated in anaerobic digester degrades during the microbiological processes but all the nutrients are conserved which increases the agronomical value of the produced digestate (Tambone et al. 2010). Phosphorus and potassium are partly solubilised during anaerobic digestion, and the organic nitrogen is degraded and ammonium nitrogen is formed. However, the nitrogen and other nutrient content of the digestate are dependent on the nutrient content of the substrate (Haraldsen et al. 2011). The application of nutrient-rich digestate to agricultural land produces similar and even increased crop yields compared to mineral fertilisers (Alburqueque et al. 2012, Haraldsen et al. 2011, Svensson et al. 2004, Vaneeckhaute et al. 2012) and digestate based compost (Tambone et al. 2010). In Europe the total digestate production in 2010 was 56 Mtonnes per year of which 80–97% was used in agriculture (Saveyn & Eder 2014). The use of digestate in agriculture has been acknowledged as an efficient way to mitigate greenhouse gas emissions through material recycling, avoidance of mineral fertilizers and improvement of soil properties as reported in several life cycle analyses (Bernstad & la Cour Jansen 2011, Boldrin et al. 2011, Evangelisti et al. 2014).

4.4.2. Different AD technologies

Two-stage AD for VFA production

AD is a flexible microbial process, which can be modified to produce different energy carriers, e.g. CH_4, H_2 and VFAs. AD process can be divided into two stages, where hydrolysis/acidogenesis are taking place in the first stage and methanogenesis in the second stage. First phase is thus optimised for hydrogen and VFA production, and in the second stage VFAs are further degraded into methane (reviewed in Budzianowski 2016). Compared to CH_4 formed during anaerobic digestion of biodegradable biomasses, the yields of VFAs has been reported to be higher, and also the applications for VFA use are more comprehensive compared to CH_4 (Yin 2014). When the aim is to produce only VFAs, the methanogenesis phase is hindered, while only VFAs and H_2 are produced as an end product of which H_2 can be captured and used for e.g. renewable energy production.

The resource- and cost-effective production of VFAs from waste materials has become an interesting option for the production of e.g. bioplastics and bioenergy. These renewable substrates could replace the extensive industrial use of oil-based chemical processes and fossil fuel production. VFAs act as substrates and intermediate products for anaerobic digestion, fermentation and microbial polymer synthetization, where the interest of using waste and other bio-based raw materials has increased in recent years. Different biomasses, for example, food waste, wastewater sludge, differ-

LCA and LCC of anaerobic digestion

Taija Sinkko & Karetta Timonen

Environmental LCA studies of anaerobic digestion are abundant. Singh et al. (2011) compared three different anaerobic digestion plants: dry continuous, wet continuous and two phase system. They assessed energy balance and greenhouse gas emission savings compared to diesel. The functional unit was 1 m^3 of biomethane per annum. Greenhouse gas emissions were also assessed per km vehicle travel. They used the methodology proposed in the EU Renewable Energy Directive (2009/28/EC), but they also used consequential approach which is not in line with the Directive. With this approach, they took into account nutrient value of digestate which replaces mineral fertilizers. Results of the study showed that even though dry continuous digestion produces least gas, the emissions per km are the lowest compared to other two systems. The reason for that is that heat demand is lower with dry digestion, and heat was produced with natural gas which has quite high emission factors compared to use of renewable sources.

Martinez-Sanchez et al. (2015) assessed life cycle costing of co-digestion of source-segregated organic waste from 100 000 Danish households with animal manure and compared it to incineration of all household wastes. Study provided a detailed and comprehensive cost model for the economic assessment. Functional unit was tonne of waste input. Cost items were classified into: budget costs, transfers and externality costs. Each cost item was defined by two parameters: a physical and an economic parameter related to the specific waste technology in question. The cost model allows calculation of Conventional LCC, Environmental LCC and Societal LCC. According to Martinez-Sanchez et al. (2015) any associated externality costs could be discounted to a present value due the reason emissions occurring now have damage effects distributed over time. Also future emissions should be accounted for within the LCA but the annual damage cost (representing damage costs at the moment of emission) should be discounted to present value (or the value at the time of treating/disposing of the waste).

The source segregation resulted in higher financial costs than the alternative of incinerating the organic waste with the residual waste. Organic waste source segregation and subsequent activities resulted in an extra financial cost per a household but then provided environmental savings for noncarcinogenic human toxicity, freshwater eutrophication, freshwater ecotoxicity and photochemical oxidant formation. Also they contributed with environmental loads to carcinogenic human toxicity, global warming, terrestrial acidification and resource depletion. The case study demonstrated that valuing the time households spend on source segregation may significantly affect the results of the Societal LCC, though assigning a cost (€/h) would eliminate the overall difference between the two scenarios, i.e. households should experience a benefit from sorting (Martinez-Sanchez et al. 2015).

ent industrial wastewaters and plant materials, such as grass, straw and algae have been used as raw materials in biological VFA production (Huang et al 2014, Zacharof & Lovitt 2013, Zhou et al. 2013, Cerrone et al. 2012, Pham et al. 2012, Maharaj & Elefsiniotis 2001). Because the use of biomasses for the production of energy and value-added materials is increasing, the resource-effectiveness of the VFA production is increasingly important to ensure the availability of raw materials.

Solid-state AD

For example in Finland, the most common AD method has been wet-type digestion, where the total solids content of the feedstock biomass must be under 15%. Wet-type digestion is suitable for biomasses with initially high water content, for example manures and sludges. However, with e.g. food wastes and plant biomass, the total solids content is usually higher, around 20-30%, which requires dilution to achieve suitable conditions for wet-type digestion. For these types of dry feedstocks, solid-state digestion process (also known as high-solids digestion or dry digestion) is more suitable as no water additions/biomass dilution is needed, facilitating also the digestate handling and post-processing (reviewed in Budzianowski 2016, Xu et al. 2015, Yang et al. 2015).

Water content is thus critical in enabling mass transfer affecting the interaction between AD micro-organisms and feedstock. With e.g. leachate recirculation the mass transfer and liquid surfaces inside the reactor can be increased, which increases the biogas production. The high solids content and high viscosity of the feedstock can hinder the mechanical agitation of solid-state digesters which can be enhanced with leachate recirculation. Compared to wet-type digesters, a higher organic loading rate and thus smaller reactor volume can be achieved as the solid content of the feedstock can be higher. Solid-state digesters have also higher volumetric methane productivity and lower energy demand for heating as there is less water to be heated (reviewed in Xu et al. 2015). Additionally, problems related to stratification and floating of fibrous material do not occur in solid-state AD, which is also more tolerant against inerts, such as sand and stones, compared to wet-type AD (reviewed in Xu et al. 2015, Yang et al. 2015). Solid-state digesters can be operated both in batch and continuous mode, where batch is more commonly used in full-scale applications while the interest towards continuous solid-state AD is still increasing.

AD enhancement

The process performance, e.g. methane yield, energy efficiency, feedstock degradability and process stability, can be enhanced in different ways. The most promising recent technologies are pre-treatment of ligno-cellulosic feedstock, microbiological engineering and bioaugmentation as well as carbon management and different biorefinery concepts. Different pre-treatment technologies have been applied for various feedstocks to increase the quality and biodegradability through e.g. mechanical, biological, chemical and thermal treatments. Recently, the attention has been directed to the treatment of lingo-cellulosic materials, which without pre-treatment are not seen profitable feedstock for AD. For these materials the latest pre-treatment strategies include e.g. the use of enzymes and fungi, which are able to degrade and hydrolyse lingo-cellulosic complexed enabling further degradation in AD (reviewed in Budzianowski 2016, Romero-Güiza et al. 2016). With microbial engineering and bioaugmentation the balanced microbial population can be achieved to ensure efficient and stable AD process and to optimise the biodegradability of certain feedstocks (reviewed in Romero-Güiza et al. 2016). Carbon management, however, aims to maximize energy efficiency and carbon (CO_2/CO) capture through biomethanation during AD. The biomethanatation increases the CH_4 yield of the digester. Carbon management also connects AD to different biorefinery concepts, where e.g. combination of AD with pyrolysis treatment facilitates carbon management and digestate post-treatment as well as the utilization of pyrolysis liquids in AD (reviewed in Budzianowski 2016, Fabbri & Torri 2016).

4.4.3. Digestate processing options

Digestate post-treatment may be needed as in most cases the digestates have unbalanced nutrient ratios for plant growth leading to the need for additional mineral fertilizer supplementation (Svensson et al., 2004). Raw digestates, depending on the feedstock, digester type, and operational parameters, can be relatively diluted, which increases the spreading amounts to achieve the desired fertilization level. The transportation of large quantities of water is inefficient, and large digestate volumes increase the transportation costs, especially over longer distances (Rehl and Müller, 2011). Digestate post-treatment can be divided into processes where i) the nutrient concentration of the material is increased in comparison with the original digestate, or where ii) the aim is to produce separate nutrient containing mineral fertilizer-like material. The nutrient concentration can be increased, e.g., by the solid-liquid separation of the digestate. Separation either with screw press, belt press, or decanter centrifuges transfers most of the digestate volume into the liquid fraction, along with the water-soluble nutrients (N and K) (Hjorth et al., 2010). The solid fraction contains most of the P, and the decreased volume makes the solid digestate easier to handle and transport. The solid fraction can be also further dried, pelletized (reviewed in Möller and Müller, 2012), or composted to increase transportability and marketing value.

The liquid part of the digestate containing the majority of digestate N and K has high water content and volume, as well as low nutrient concentrations, which complicates its usability in agriculture (Hjorth et al., 2010) by increasing application volumes and transportation costs. In liquid part of the digestate, the N is mainly (45–80%) in the soluble NH4-N form (Möller and Müller, 2012), which is easily volatilized during liquid spreading. The digestate liquid can be further processed to remove water and simultaneously concentrate nutrients with e.g. ammonia stripping, evaporation, struvite precipitation and membrane techniques. Combining the solid-liquid separation and digestate liquid treatment technology provides an opportunity to produce fertilizer products with optimal composition of nutrients (Hjorth et al., 2010) to match the nutrient requirements of crops and achieve better control of the applied fertilizer.

4.5. Organic fertiliser products

Petri Kapuinen

Organic fertiliser products are classified either as fertilisers or as soil amendments (MMMa 2011). A fertiliser works as a source of nutrients and a soil amendment improves the quality of soil as a growing media. They can, however, have qualities of the other group. One basis of classification is nutrient content. Products having lower contents of nutrientts are classified as soil amendments (MMMa 2011). The products containing sewage sludge more than 10% as raw material are also soil amendments. When the bulk of organic fertiliser products are different kind of soil amendments made of different kind of recycled by-products the organic fertilisers are mainly made by purpose for special applications like organic farming. In organic farming, however, no sewage sludge is allowed as raw material.

The Finnish classification system for organic soil amendments (MMMa 2011) is rather sophisticated compared to those in other European countries. In Finland, the soil amendments belong to different designation types mainly according to the manufacturing process but also the raw material. The restrictions for the use of the fertiliser product usually decrease when treatment processes are increased. The processing costs usually increase as well and the end-use of the fertiliser product must be one where its value is higher than in landscaping.

The characteristics of fertiliser products like digestate are closer to a fertiliser than soil amendment especially when not dried (e.g. Tontti et al. 2015). A soil amendment compost is closer to a soil amendment. The main classification is between actual organic soil amendments and those which are used as such as a soil amendment (MMMa 2011).

The fertiliser products belonging to the soil amendments used as such and containing more than 10 per cent of sewage sludge as raw material are considered to be sewage sludge meant in the Sludge Directive and the Finnish implementation of the Sludge Directive (European Council 1991a) (is realised in paragraph 11 a of the fertiliser product decree MMMa 2011). In practical agriculture these fertiliser products can be used in large extent on fields growing barley or wheat. The use of fertiliser products having sewage sludge as a raw material can be limited more by the buyers of the agricultural products than by the legislation (Rikkonen & Soderlund 2015, Kivelä 2016).

The agricultural use of organic soil amendments usually made of sewage sludge was profoundly researched in Finland after the introduction of fertiliser product legislation in 2006 to 2007 in field experiments in barley and wheat (Parliament 2006, Regina et al 2006, MMMa 2007, Kapuinen et al 2010, 2011, 2012, Paavola et al 2011a, b, Salo et al 2010, 2011, 2012, 2013, Ylivainio & Kapuinen 2011, 2012, Kapuinen 2013, Marttinen et al 2013, Tontti et al 2014, 2015, Tontti & Kapuinen 2015, Kapuinen & Ikäläinen 2016a, b). The main scope was their yield response to nitrogen. Fertiliser products made of sewage sludge are, however, mainly a source of phosphorus. They have, however, not had any yield response in normal situations because there is more than sufficiently phosphorus in Finnish fields. That is because of large use of manure and phosphorus of mineral fertilisers in the end of last decennium until the introduction agri-environmental subsidy schemes in 1995 when Finland joined the EU. The latest version of the subsidy scheme was introduced in 2015 (Maaseutu 2020). The main finding in the studies was that only the analysed soluble nitrogen contributed to the yield when no milk waste or meat-bone meal was present (Chen et al 2011, Kapuinen et al 2012, Kivelä et al 2015, Tontti et al 2015). In dry fertiliser products (DM > 90 %) the response of those two raw materials was more. In practise, the variation of application rates, too large proportion of soluble nitrogen from these fertiliser products and rather large variation in content of soluble nitrogen resulted yield losses. Better results could be obtained when about half of soluble nitrogen was placed as mineral fertiliser when seeding with a combi-drill (Tontti et al 2015). A typical content of soluble nitrogen in the digestate used in this above studies was about 1.0 kg/t, with value about 0.80 €, which is much less than the application cost about 3.00 €. The agricultural use of these products is in these circumstances rather a legal end-use than a great advantage for a farmer. The situation would be much different if there were a general need for phosphorus in agriculture because the main value of these products lies in there phosphorus. Moreover The Central Union of Agricultural Producers and Forest Owners is against the use of sewage sludge on the fields (MTK 2015).

In anaerobic digestion, the formation of ammonium nitrogen from the organic nitrogen is a positive process because the organic nitrogen has no direct growth response in plants as mentioned above. In Nordic, short season mineralisation of organic nitrogen in soil usually takes place too late for the most relevant and common crops to gain. More south, in Central Europe, there is some growth all round the year and the situation is different in that sense. There the plants are able to collect the mineralised nitrogen.

A low proportion of organic nitrogen in organic fertilizer products is an advantage in plant production of common crops such as barley, oats and wheat because their response to nitrogen fertilisation is great and a low content of organic nitrogen helps to reach a reasonable control over the apparent nitrogen availability. Barley is the most common grain cultivated on crop farms in Finland when wheat is the next one (Luke's Statistics 2016). Although oats is the second common grain in Finland, it is mainly cultivated on cattle farms, which have got more than sufficiently manure by themselves. They need mainly soluble nitrogen on the top of that.

In agriculture, the potential use of organic fertiliser products is on crop farms growing barley and wheat. In wheat, a late mineralisation of organic nitrogen of organic fertiliser products could be an advantage because it potentially increases the crude protein content which is an advantage in mill wheat production but disadvantage in malt barley production. Furthermore, the proportions of components of soluble nitrogen: organic soluble nitrogen, ammonium nitrogen and nitrate nitrogen have got a great significance in the suitability of an organic fertilizer product in fertilisation of such a crop which has got a great response to nitrogen fertilisation (Tontti et al 2015). The uptake takes place either as nitrate or ammonium. In soil, ammonium nitrogen is degraded to nitrate in couple of weeks. The availability of the nitrate nitrogen is the best because it moves rather easily in soil diluted to water to the zone where the uptake takes place. Therefore the crops growing on the fields take nitrogen mainly as nitrate although the uptake as ammonia would consume less energy.

Nitrate nitrogen exists only in such organic fertiliser products which have been composted (Tontti et al. 2015). The soluble organic nitrogen of an organic fertiliser product is degraded to ammonium when applied to soil and further to nitrate. Most of the organic fertiliser products are solid and there is no machinery to place them. In that sense solid organic fertiliser products which have been pelletized or granulated are an exception. However, their specific gravity is usually less and the typical application rates greater than those of mineral fertilisers. Therefore the machinery intended to place mineral fertilisers might work poorly when organic fertiliser products are used instead.

The growth in the beginning of the short season is hasty and shortage of nitrogen could result just because of a wrong position of nitrogen in soil. Therefore the combined drilling was developed in late 60s and is the prevalent drilling method in Nordic countries but not in Central Europe. Some organic fertiliser products are, however, liquid and they can be injected like liquid manure with the very same machinery. Injection provides a better possibility to place the nitrogen in a correct position in soil from point of view of uptake. However, injection not combined with drilling of seed is a worse technique and usually results a lower yield when an organic fertiliser product is the only source of nitrogen. Good result could be reached with shared use of organic fertiliser and mineral fertiliser which is placed with a combi-drill when seeding (Tontti et al 2015).

The legislation and subsidy schemes related to application of organic fertiliser products in agriculture vary by Member State. In all the Member States the Sludge Directive is implemented (European Council 2011a). The implementations limit the rate of heavy metals on agricultural land. The allowances of nitrogen and phosphorus vary by Member State. On the nitrate vulnerable zones declared according to the implementation of the Nitrate Directive (European Council 1991b), there may be maximum rates for nitrogen. In addition to the limitations set by the legislation, there are subsidy schemes which limit the rates of nitrogen or phosphorus even more. The Finnish agri-environmental subsidy scheme is the widest (Maaseutu 2020). The maximum application rates of phosphorus usually limit the application rates of organic fertiliser products to the same level as the limits of heavy metal. In the Finnish agri-environmental subsidy scheme, the application rates are evaluated as an average of five years. Therefore the dose of five years could be applied at one time. Typically the application rate of a solid fertiliser product is only 20 tons per hectare during five years (Tontti et al 2015). It means a layer of about 3 mm and about 6 tons per hectare of dry matter. The amount of organic matter from this dose is about 3 tons per hectare. Although the Finnish fertiliser product legislation (MMMa 2011) classifies these fertiliser products as soil amendments, phosphorus and heavy metal contents limit their application rates in agricultural purposes rather low resulting rather insignificant effect as a soil amendment compared to their significance as a source of nutrients.

When organic soil amendments are used as a component of growing medium e.g. in landscaping there is no legislation limiting the rate of nutrients or heavy metals but only the contents (MMMa 2011). When a layer of growing medium could be even 20 to 40 cm the rates of nutrients and heavy metals are much greater than in agriculture and they have a large significance as a soil amendment as well.

Environmental and social LCA and LCC of organic fertilizer products

Taija Sinkko & Katri Joensuu

Rehl and Müller (2011) compared several digestate processing technologies to the storage and application of untreated manure. Digestate processing technologies were composting, mechanical drying, thermal vaporization and physical-chemical treatment. Functional unit was 1 kg digestate from biogas plant. All necessary operations were included to the system boundary: extraction and processing of raw materials, digestate production and use of the products. Biological degeneration and soil activation by digestate application was not taken into consideration. Also capital goods were excluded. They used consequential approach to take into account credits from substituted fertilizer production. Solar drying, composting and physical-chemical treatment were identified to be the most suitable options to reduce the use of resources and environmental impacts compared to storage and application of untreated manure. Belt drying had the highest primary energy demand, climate impact and acidification potential among the compared options. Environmental impacts depend largely on nitrogen related emissions from digestate treatment, storage and field application. Also, the amount and fuel used for heat supply were important aspects.

Martinez-Blanco et al. (2014) have studied the social effects caused by the production and application of municipal biowaste based compost and two mineral fertilizers (nitric acid and potassium nitrate) in tomato cultivation. They considered four of the stakeholder categories mentioned in the S-LCA guidelines (worker, local community, society and consumer), and added a new stakeholder category (citizens collecting the biowaste). The choice of categories was made based on their importance noted in previous studies of the studied systems and on data availability. The assessment was done at three geographical scales: country, sector and company (between which the choice of indicators and subcategories varied). The authors used the activity variable working time (seconds of work per functional unit) for weighting the indicators. According to results, the total working time for the compost alternative was more than 20 times higher compared to nitric acid. They also made environmental LCA and LCC assessment to same three fertilizer products. According to the environmental assessment, compost was the worst fertilizer option, regardless of the impact category. Regarding to LCC evaluation, the price of compost was lower compared to mineral fertilizers, but transportation and application costs were higher for compost.

5. Example: Grass biorefinery

Arja Seppälä, Erika Winquist, Oiva Niemeläinen, Marketta Rinne

Grass sward is an abundant, nutrient rich and competitive crop in the Northern European areas, but currently an underutilized resource (Seppälä et al. 2014). Grass has traditionally been a primary feed for ruminants. Currently, in many European countries grassland utilisation is decreasing due to a trend towards controlled animal production systems using high amounts of concentrate feeds in ruminant diets. The decreasing number of ruminants further accelerates this trend (McEniry & O'Kiely 2014). The potential of surplus grass as raw material for the production of renewable energy, chemicals and materials has been evaluated in several research projects during last decades (e.g. Grass 2004, Kamm & Kamm 2004, Kromus et al. 2004, Mandl 2010, Sieker et al. 2011), and pilot plants have been built in Austria, Germany, The Netherlands and Switzerland (Kamm 2010, Keijsers & Mandl 2010).

5.1. Availability of grass biomass for biorefineries in Finland

Perennial grass swards fit well to the Finnish growing conditions as the grasses start growing early in the spring when solar radiation is abundant and soil water situation is good. Grass is mainly cultivated for silage or hay, or for grazing. Since the yields per hectare vary from year to year and the livestock farmers want to secure adequate amount of forage for their animals even on poor years, the area of grass devoted for silage production tends to be higher than needed even on an average year. This leads to a situation where during most years some surplus silage could be available for bioprocessing if the grass growth potential would be fully utilized. In good production years the second or third cut of the grass is typically not fertilized as intensively as it could be. There would be a possibility to increase grass biomass yields if there would be demand for it.

Grass sward yields per hectare are challenging to estimate accurately as the dry matter (DM) concentration of the herbage varies and the same field is typically harvested two or three times per season. Statistics of year 2015 (Luke 2016) show, that silage production area was 492 300 ha and that of hay 85 700 ha. The long term yield estimate for 2004-2013 was on average 3 460 kg/ha for hay and 16 780 kg/ha for silage. The DM concentration of hay is around 85 % and that of silage typically 25 to 35 %, but it can be highly variable based on the weather conditions and the length of wilting period (from 15 to 80 %).

Using the values from above would result in an average grass DM yield of 3000 to 5000 kg DM/ha in Finland. However, the best timothy and tall fescues cultivars produce over 11 000 kg DM/ha as a long term average in official variety trials (Laine et al. 2015). Although the official variety trials are carried out on best fields and harvest losses are minimal the large gap between yield estimates from commercial production and yields obtained in them support the view that considerably higher total yield could be produced from current grass production area.

In addition to feed production, grasses are grown in as perennial green fallows and in buffer zones where environmental objectives play a major role and e.g. fertilizer application is not allowed.The area of these grass production types was 177 145 ha in 2013. This type of fields had on average 5 000 kg DM/ha biomass, assessed in late summer (Niemeläinen et al. 2014) but variation in the biomass was high, from 1 300 to over 10 000 kg DM per ha. Removing the biomass is obligatory from buffer zones but would be environmentally beneficial also from the other fallow areas. However, in most cases the biomass is cut and left on the field unutilized. Mowing is recommended to take place in the latter part of the growing season resulting in a high fibre concentration and low nitrogen concentration in the yield (Fig. 3,4). The cultivation guidelines provide a possibility to use nitrogen fixing clovers in the stand which would increase the yields and improve the quality of the harvested biomass. The small size and conformation of many of the fallows field parcles prevents use of efficient harvesting technology. However, Niemeläinen et al. (2014) estimated that around 105 000 ha of green fallow area in 2013 would have been available for biomass harvesting. Using the 5 000 kg DM/ha yield estimate this would have resulted in a total biomass yield of 525 million kg DM.

Silage production is closely connected to milk production and the additional biomass generated from more efficient grass production would be available on areas where milk production is high. Green fallows are located quite evenly around the country in relation to overall field area.

Figure 3. Silage swards are harvested twice or three times in season and sward age is up to 4-5 years. Legume based swards (on the right) manage at very low fertilizer application. Acreage of silage and hay fields is around 580 000 ha. Variation in annual hectare yield provides occasionally surplus for biorefinery use.

Figure 4. Perennial green fallow fields are a resource which is currently not much used. Biomass varies greatly between different perennial green fallows fields. Acreage of perennial green fallow type fields was around 175 000 ha in 2013 of which around 105 000 could be harvested relatively efficiently. Same harvest-ing chain could be used in silage harvesting.

5.2. Ensiling

Fresh grass that has been cut has a short shelf life of only a few hours. Biological processes, due to microbes and plant enzymes, continue after cutting and consume valuable nutrients such as sugars and proteins (McDonald et al. 1991). Since fresh grass is only available in the summer, the all year round availability of the biomass requires preservation of it by fermentation (silage) or drying (hay or pellets).

Ensiling is a cost efficient storage method for moist biomaterials, which combines the anaerobic environment and low pH. Low pH is achieved by the naturally occurring lactic acid bacteria which produce lactic acid from water-soluble carbohydrates present in the fresh grass. The process may be improved by the use of silage additives which can be chemical (under Finnish conditions typically formic acid) or selected strains of lactic acid bacteria.

In ensiling, grass is typically cut using mover-conditioner, prewilted at the field and picked up using precision chop forage harvester, forage wagon or baler. Silage additive is sprayed into the forage during pick-up. The harvested grass is immediately transported to the silo, which is packed and finally closed airtight when full, or stored in bales covered with plastic. The time span from cutting to the airtight silo can be just a couple of hours depending on the prewilting time. To minimize losses, the optimal DM concentration of silage is typically between 25 – 35 % which results in minimal effluent losses and as well as minimal field losses (McDonald et al. 1991). Silage has replaced hay in cattle feeding. Modern ensiling technologies enable fast harvesting of large areas, e.g. with self-propelled harvester 6.5 ha/h or 53 t/h (Seppälä et al. 2014).

5.3. Composition of grass silage

The chemical composition of a biomass feedstock will determine the potential range of products produced in the biorefinery (McEniry and O'Kiely 2014). Various factors such as grass species, soil characteristics, nitrogen fertiliser application, environmental factors (e.g. rainfall and temperature), growth stage at harvest, prewilting time and ensiling method have a significant impact on the yield and chemical composition of grass silage. Some of these factors can be controlled. When e.g. the recovery of plant protein is the main focus, the composition of grass silage can be optimized to contain e.g. 180-250 g crude protein/kg DM by grass species selection, plant growth stage at harvest and ensiling procedures (Table 1).

Table 1. Factors affecting the composition of silage (www.luke.fi/rehutaulukot).

Variable	Typical range	Factors
Dry matter	200 – 500 g/kg	prewilting time
Crude protein	120 – 200 g/kg DM	grass species, N fertiliser application, growth stage
Digestibility	650 – 700 g/kg DM	growth stage at harvest
Sugars	40 – 120 g/kg DM	grass species, ensiling method
Lactic acid	10 – 130 g/kg DM	ensiling method

Choice of grass and forage legume species enables varying the raw material composition as well as introducing other benefits in crop cultivation, e.g. nitrogen fixation ability of legumes or vigorous autumn growth of ryegrasses. The typical species in Finnish swards are timothy (Phleum pratense), meadow fescue (Festuca pratensis) and red clover (Trifolium pratense). Winter hardiness providing sustained yields and good nutritional characterisics have been the primary selection criteria for these species. However, biorefinery may change the selection criteria, e.g. high protein concentration may have a greater value than in ruminant feeding. Forage legumes as pure stands may be an interesting option for maximising protein content in the harvested biomass.

5.4. Processes and products

Only mild processing is needed to efficiently fractionate and modify grass to valuable components. In comparison to pre-treatments required in processing of e.g. straw or wood-based biomasses, mild treatments based on milling, lower temperatures and minor use of chemicals are sufficient for liberating sugars in grass and increasing the bioavailability of proteins and amino acids (results of Ruohosta proteiinia project, IBC Finland 2014).

The first unit operation for most process options is fractionating green plant biomass into a fibre-rich press-cake and a nutrient-rich press-juice. The press-cake fraction consists mainly of the cell wall fraction of the grass, which is rich in cellulose, hemicellulose and lignin. The press-juice fraction consists mainly of the cell contents and therefore contains proteins, water-soluble carbohydrates, organic acids, minerals and other substances (Kamm & Kamm, 2004). Depending on the end product, the following unit operations may include enzyme hydrolysis, microbial cultivation (single cell protein), anaerobic digestion, and chemical separation.

Due to different national interests, the process chains explored and the primary end products have varied including ethanol (Sieker et al. 2011), insulation boards (Grass 2004), purified lactic acid and amino acids (Ecker et al. 2012) or biogas and insulation (O'Keeffe et al. 2011). An ongoing project in Denmark (BioBase, DCA – Danish Centre for Food and Agriculture) uses fresh grass or clover as raw material for separating protein. VTT, Luke and Aalto University were involved in Ruohosta proteiinia project led by Valio Ltd, which focused to produce Pekilo-biomass from hydrolysed silage (IBC Finland

2014). At present, Innofeed-project (VTT, Luke, companies) focuses on liquid pig feed rich in protein (Tekes funding for 2015 - 2018).

For economically feasible production, the biorefinery concept must be carefully planned. Suitable applications with existing / potential markets need to be identified for the separated fractions. Approach with multiple products rather than one main product helps to design a process with efficient utilisation of all process residues. Whether to build a local or central biorefinery depends on the main end product (Fig 5). With a low added value product requiring only basic processing, local biorefinery offers savings in logistics. Furthermore, a high added value product produced by advanced processing technology needs larger capacity from the unit and the transportation costs are in minor role. Cost efficient management of the process residues has also to be solved as transportation of both the silage and the residues.

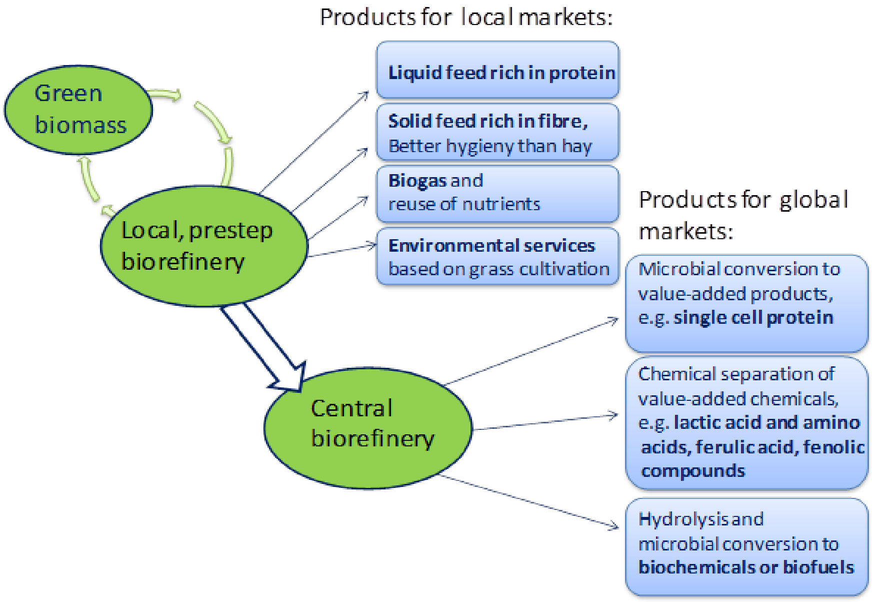

Figure 5. Local and central biorefineries and product

Innofeed grass biorefinery

The need for Innofeed-project (Tekes 2015 - 2018) emerged from the earlier Bionurmi-project, where the utilisation of grass as raw material for biogas production was studied (Seppälä et al. 2014). Grass is becoming more and more a surplus resource in Finland due to the decreasing number of ruminants. There are approximately 500 000 hectares of grass swards in Finland that are not fully utilised. In addition, perennial green fallows and buffer zones could be more efficiently utilized. However, based on the Bionurmi-project, the profitable use of grass as raw material for biogas production is challenging, because of cultivation and transportation costs and the rather low prices of the competing energy products: electricity from the grid or natural gas.

Nevertheless, grass has several advantages as a raw material for a biorefinery. It has low lignin content and thus is easy to hydrolyse to sugars, and it is a source of various biochemicals (e.g. amino acids, lactic acid, minerals, and vitamins). From the several possibilities, Innofeed focus on producing protein rich feed for pigs, which would replace soy in pig feeding and thereby improve protein self-sufficiency. The approach is local, decentralised production that utilises simple pre-treatment methods. In addition, the fibre-rich side-stream not suitable for pig feeding would be used as raw material for biogas production. In this way, grass could also be used for biogas production without being too costly raw material for that purpose.

6. Sustainability

Taija Sinkko, Katri Joensuu, Karetta Timonen

There is no universally agreed definition on what sustainability means. However, the idea of sustainability stems from the concept of sustainable development which means “Development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland 1987). The concept of sustainability defined by the Brundtland commission includes three ’pillars‘: environment, economy and society. To find a solution to support progress in and between these aspects is challenging.

Ecological sustainability means the maintenance of the factors and practices that contribute to the quality of environment on a long-term basis. It is also stated that ecological sustainability is a prerequisite for existence, and smart usage of natural resources are a key issue in terms of the continuation of life (Sitra 2014). Economic sustainability is often seen as prerequisite for realization of ecological and social sustainability. It is observed that economic sustainability is often very much linked to ecological and social sustainability.

Social sustainability is the least developed of these three concepts and it has currently no established definition. Kautto and Metso (2008) have identified some common features of the existing definitions. Firstly, social sustainability means in most cases fairness and equality, regardless of which matter is considered. Secondly, it is seen to support such development that strengthens people's ability to influence their own life. Thirdly, socially sustainable development should maintain and strengthen people's communal identity. The concept of social sustainability has been mainly used when talking about social sustainability of cities and regions, importance of social capital in the development of regions, public participation in decision-making and business responsibility.

6.1. Life Cycle Sustainability Assessment

Life cycle perspective considers all life cycle stages from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end-of-life treatment and final disposal. Life Cycle Sustainability Assessment (LCSA) means evaluation of all environmental, social and economic impacts and benefits in decision-making process towards more sustainable products throughout their life cycle (UNEP/SETAC 2011). Life cycle sustainability assessment consists of three sub-methodologies: environmental LCA (e-LCA), social LCA (s-LCA) and Life Cycle Costing (LCC) (Fig 6). In addition, even when there is not widely accepted specification for LCC and interpretations may vary substantially in the literature, there seems to be three types of LCCs: conventional LCC (c-LCC), environmental LCC (e-LCC) and societal LCC (s-LCC) (Hunkeler et al. 2008).

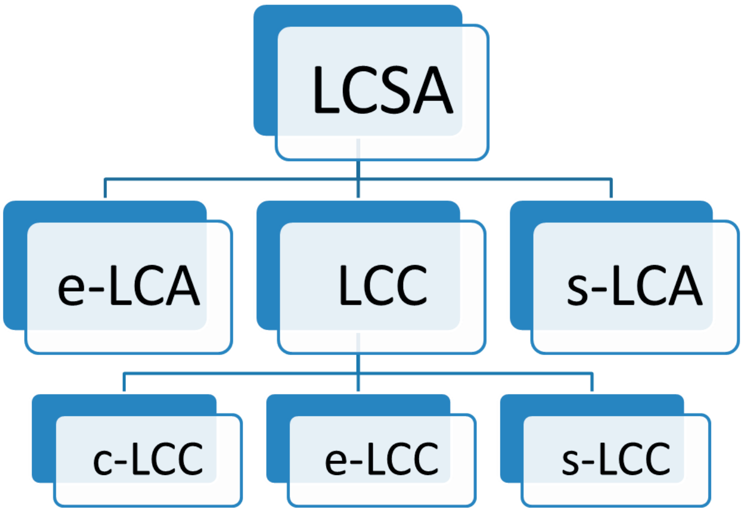

Figure 6. Hierarchy of Life Cycle Sustainability Assessment (LCSA).

Life cycle sustainability assessment has a great potential to help produce and consume more sustainable products which reduce environmental degradation and use natural resources in a cost-effective manner, while contributing to social welfare.

6.1.1. Environmental LCA

Environmental life cycle assessment has a long history and often term LCA is considered only in case of environmental LCA. ISO 14040 (2006) and ISO 14044 (2006) provide the standardized framework for environmental LCA studies. Also some methodological guidelines have been published, e.g. International Reference Life Cycle Data System (ILCD) handbook (JRC 2010). Environmental LCA is carried out in four phases (ISO 14040). These phases can also be adapted to LCC and s-LCA. LCA phases are:

1. Goal and scope definition: This step provides the context for the assessment and defines the functional unit, system boundaries, assumptions, impact categories and allocation method selection.
2. Inventory: All resources extracted from the environment and emissions released into the environment along the whole life cycle of a product are inventoried.
3. Impact assessment: Inventory results are translated into impact categories (midpoint or endpoint) with the help of an impact assessment method. This means that all elementary flows within same category (e.g. climate change) are converted to a common unit using characterization factors.
4. Interpretation: In this step, the results of the inventory and impact assessment is checked and evaluated. It should generate a set of conclusions and recommendations.

Functional unit is the unit for what emissions of the system are calculated for and describes the function of the system. It allows making comparisons between two or more systems with same functional unit. System boundaries define which parts of life cycle and which processes belong to the analysed system. It is important that all relevant processes are included to assessment.

Some processes produce more than one product when the question is of what impacts are caused because of different products. If the production processes cannot be separated, there is a need to allocate impacts between products. Several different allocation methods exists which are:

- economic allocation (based on market prices of products)
- mass allocation (based on masses of products)
- physical allocation (based on physical properties, e.g. energy contents of products).

One way to avoid allocation is to use system expansion which means that co-product replaces production of some other product, which impacts are reduced from impacts of the original system.

Although LCA is a widely used methodology to assess environmental impacts of systems and products, only limited amount of environmental LCA case studies were found in the field of biorefinerys in the decentralized environment. Environmental LCA studies related to this topic are presented as examples in connection to the descriptions of treatment processes to various biomasses.

Environmental impacts of potato waste starch fermentation
Taija Sinkko

Harbec (2010) compared lactic acid production using direct fermentation of potato waste starch recuperated from the wastewater of potato chip facility to the conventional process which uses dextrose from corn. Study includes all steps from production and extraction of raw materials and fuels until the product is delivered out of the factory gate (cradle-to-gate LCA). Also transportation of sludge to the landfill, wastewater treatment and final disposal of biomass are included. Processes that are identical to both processes are excluded (e.g. polymerization steps following the lactic acid purification). Also processes that have low environmental effect are excluded (e.g. minerals and other chemicals added to the media). No emissions from potato chip process are allocated to wastewater since wastewater has no economic value. All emissions from waste starch concentration were allocated to potato waste starch. In case of corn based production, system expansion was used for multiple products that wet milling produces.

Results showed that lactic acid produced from potato waste starch has higher impact compared to corn based lactic acid. However, with proper energy and nutrient concentration optimization it could have approximately same impact as conventional process. The purification and the media pre-heating are highly energy consuming in case of potato waste starch based process; therefore the energy utilization needs improvements.

6.1.2. Life Cycle Costing (LCC)

There is no standard or widely accepted detailed specification for any of terms used when estimating life cycle costs, so interpretations may vary substantially in the literature and make clarification as to what the terms actually imply difficult. All the terms can in theory be used for economic life cycle analysis of a system or function: it is just a matter of defining the system boundaries so that they coincide with an LCA. In order to avoid confusion we decided to use the term LCC (Life Cycle Costing).

ISO 15686 (2008) defines LCC as “a technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors, both in terms of initial costs and future operational costs”.

The traditional LCC methodology is developed only for financial analysis so it is purely economical and does not take into account environmental aspects like traditional LCA methodology does.The foundation of LCC theory was properly developed by Flanagan et al. (1989) and Kirk & Dell’Isola (1995) along with essential decisions and activities to undertake an LCC analysis:

1. Defining alternative strategies to be evaluated: specifying their functional and technical requirements
2. Identifying relevant economic criteria: discount rate, analysis period, escalation rates, component replacement frequency and maintenance frequency
3. Obtaining and grouping of significant costs: in what phases different costs occur and what cost category
4. Performing a risk assessment: a systematic sensitivity approach to reduce the overall uncertainty

Costs in LCC can be distinguished between internal and external costs or between different cost items: budget costs, transfers (taxes, subsides, fees) and externality costs (emission and disamenity related damage costs, abatement costs) (Hunkeler et al. 2008 & Swarr et al. 2011). According to Hunkeler et al. (2008) and Martinez-Sanchez et al. (2015) there are three types of LCC's: a conventional, environmental and social LCC:

- A Conventional LCC (C-LCC) represents traditional financial assessments (i.e. accounting for marketed goods and services) carried out typically by individual companies focusing on their ''own'' costs. It is for the assessment of financial costs and may often exclude specific parts of the lifecycle, thereby reflecting the specific goal of the Conventional LCC.
- The Environmental LCC (E-LCC) expands and provides a complement to a financial C-LCC and in order to be consistent with the system boundaries of the LCA. It is typically intended to supplement an LCA with an economic performance assessment and in other words E-LCC is for the assessment of financial costs whose results are complemented by LCA for the same system (includes budget costs and transfers). Here costs incurred by all the affected stakeholders are included.
- The Societal LCC (S-LCC) further includes externality costs (i.e. it ''internalises'' environmental and social impacts by assigning monetary values to the respective effects), by using accounting prices. Societal LCCs may also be characterized as ''socio-economic'' or ''welfare-economic'' assessments. Societal LCC is for socio-economic assessments and therefore includes budget costs and externality costs (Martinez-Sanchez et al. 2015). Environmental and Societal LCCs must include all of the phases of the system and thereby have system boundaries identical to the LCA.

The system boundaries of the LCC naturally depend on the study in question, but their definition should correspond closely with those of the LCA. Especially when the aim is combining the LCC with an LCA, the definition of object of analysis should be a joint procedure between the two method approaches. As the system boundaries need to be the same, and the logical boundaries for an environmental and economic analysis sometimes differ, this can be difficult. An economic analysis is usually based on economic systems, such as a municipality, a corporation, a state, or the like. These economic systems rarely follow environmental life cycles for products or functions: the economic chain is often cut off by economic borders that should be ignored in a logical LCA system, and vice versa. Therefore, it is important to realize this difficulty and define the object of analysis with both the environmental and economic systems in mind. Often the economic system studied thus becomes a hypothetical system, which more or less diverges from existing economic systems (Carlsson Reich 2005).

In order to match the economic calculations to the LCA calculations, using the same time frame becomes necessary. In order to be able to allocate costs accordingly, the use of standard economic tools is necessary, such as the time value of money (interest rate, discounting, present value), and annuity calculations (allocation of investments over time). To monetarise environmental effects such as emissions and resource use it is possible to use different weighting methods. As both LCCs use the same unit of account, they can easily be added together to a welfare economic tool. According to Carlsson Reich (2005) one of the purposes of weighting methods and therefore of an environmental LCC, is to reduce the number of decision variables into a manageable amount and to better communicate results from environmental studies.

Very few studies combine economic and environmental assessments and are carried out separately most often with different system boundaries and assumptions (Hunkeler et al. 2008, Swarr et al. 2011, Carlsson Reich, 2005). Few cases have discussed integration of LCC and LCA within a single assessment (Carlsson Reich 2005, Dahlbo et al. 2007). In addition to traditional LCC definition some studies see the life cycle costing (LCC) as a complement to the LCA results in the field of this project: Resurreccion et al. (2012) assessed LCC and LCA separately and combined the outcomes together, seeing them as complements of each other and as tools in decision making processesand the other two studies by Luo et al (2009) and Martinez-Sanchez et al. (2015) took this further by placing LCC in an environmental context. In addition, Martinez-Sanchez et al. (2015) developed a comprehensive cost model seeing the financial LCC as a parallel analysis tool to LCA: they both analyze the same problem, but from different aspects and financial LCC just adds another ‘‘impact category’’ to the LCA, namely the economic dimension. In that case they are used in parallel, no aggregation or weighting of environmental aspects is done.

There are still many challenges and obstacles when combining LCC with LCA and developing comprehensive method is still on progress. Martinez-Sanchez et al. 2015 discovered three context-specific challenges involved in economic assessments: 1) which type of costs should be assessed (for example private or social costs), 2) for whom should these costs be assessed (for example facility operators, households, public entities or entire systems) and 3) which cost calculation principles should be applied for the individual waste technologies included in a system. Critical outcomings from the literature observed that system boundaries were not always equivalent between economic and environmental parts of assessments, transfers were sometimes included in Societal LCC’s which should not be the case, and the internalization of environmental damages in Societal LCC’s was carried out with poor explanations. According to Martinez-Sanchez et al. (2015) the studies detected that economical and environmental life cycle outcomes have same trends. It was also demonstrated that while some life cycle phases were not critical for the economic assessment itself, a significant influence on environmental impacts could be observed. The results illustrated that unbalanced decisions for system cut-off (examining LCC and LCA outcomes separately) cannot be advised.

LCC of algae cultivation for bioenergy production

The study by Resurreccion et al. (2012) compared algae cultivation methods for bioenergy production (algae biomass was converted into biodiesel and methane-derived bioelectricity) by using a combined life cycle assessment (LCA) and life cycle costing (LCC) approach. The financial viability of the four model cultivation systems was assessed as a complement to the LCA results so LCC models were built atop corresponding LCA models for each system. In all cases, system boundaries were ‘‘cradle-to-wheel’’, incorporating all processes upstream of the delivered energy product (i.e., extraction of raw resources) and proceeding to consumer use in a passenger automobile. Model inputs were determined based on literature reports, first-principles engineering calculations, or personal communications with industry experts. All projects were assumed to have a 30-year useful life. For consistency and comparative purposes financial estimates were developed using same assumptions as those used for the LCA methods. LCC begins by identifying the startup costs, revenues and expenses. Salvage values at the end of the period were assumed to minimal and therefore ignored. Also Environmental remediation services (e.g., removal of N and P from wastewater effluents) were ignored since there was no present basis for estimating their market value.

The results showed that based on the environmental LCA, there are differences between systems. However, according to the LCC, all four systems are currently financially unattractive investments. Sensitivity analyses suggest that improvements in critical cultivation parameters, conversion parameters, and market factors could alter these results. The study also found out that the market forces, specifically the selling price of biodiesel and the discount rate, have the most pronounced impact on the profitability of algae biodiesel in all cultivation configurations. Other factors, e.g., the price of bioelectricity or the price of raw materials for building the algae cultivation facility, are important, but not as important as the price of biodiesel or the discount rate.

6.1.3. Social Life Cycle Assessment

Social aspects can be included in the life cycle assessment by using social Life Cycle Assessment (s-LCA), of which a basic framework and guidelines have been developed by UNEP/SETAC (2009 and 2013). S-LCA focuses on aspects that can directly affect stakeholders positively or negatively during the life cycle of a product (UNEP/SETAC 2009). The basis of s-LCA assessment is socially significant themes or attributes named subcategories. These are classified either by stakeholder categories or impact categories and assessed by the use of inventory indicators, measured by unit of measurement (or variable). More detailed information on subcategories is available in UNEP/SETAC (2013). Stakeholder categories are defined as clusters of stakeholders that are expected to have shared interests due to their similar relationship to the investigated product systems. Impact categories include human rights, working conditions, health and safety, cultural heritage, governance and socio-economic repercussions (UNEP/SETAC 2009). In each s-LCA study, appropriate indicators need to be selected depending on the particular context. Depending on the context of the study, also new stakeholder categories (e. g. NGOs, state) or subgroups (e. g. shareholders, suppliers) can be added.

A central challenge in s-LCA is that the social impacts are closely connected to the certain processes and companies and are not easily expressed per unit of process output (UNEP/SETAC 2009). However, the indicator values can be weighted by the share of each unit process of the life cycle using an activity variable and then aggregated. Activity variables (e. g. monetary value or worker hours) are measures of process activity or scale which can be related to the output in each process and therefore, to the functional unit.

For example, the Social Hotspots Database (SHDB 2015) can be used as a data source. It includes five social categories divided in 22 social themes (Fig. 7), which are described by more than 100 indicators altogether. The data is presented as the level of risk or opportunity of the occurrence of a social aspect on a four-level scale (low, medium, high and very high risk). These risk levels are presented at country and business sector level. These can be classified on a numerical scale by assigning e. g. a zero to the social issues with low risk etc.

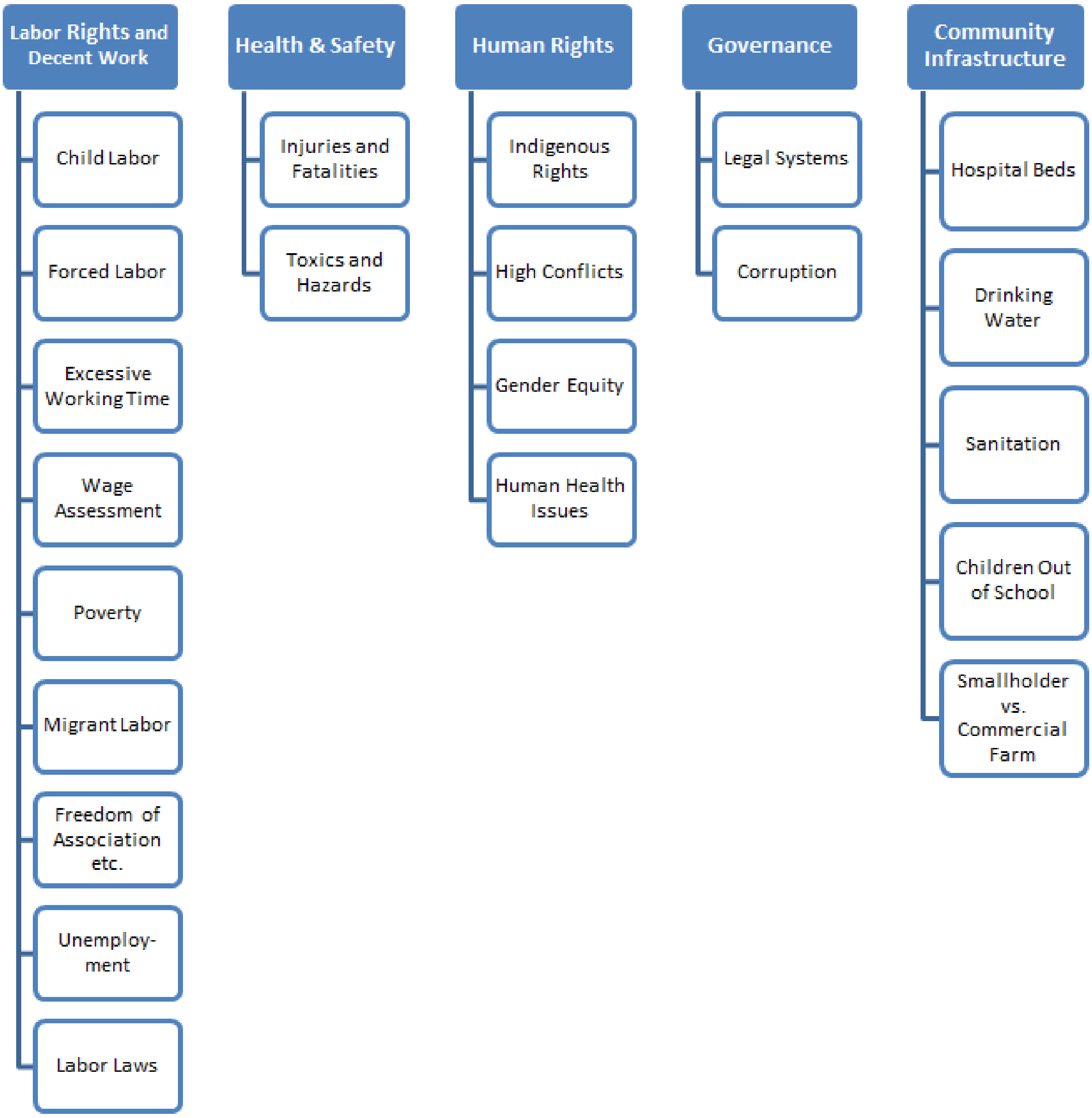

Figure 7. Social categories (at the top row) and social themes under each category covered by the Social Hotspot Database (SHDB 2015).

The methodology of s-LCA is still under development and only few real case studies are yet performed. There are, however, some studies also related to biorefineries. Blom and Solmar (2009), Manik et al. (2013), Macombe et al. (2013) and Ekener-Petersen et al. (2014) have conducted studies on biofuels and Martinez-Blanco et al. (2014) on fertilizers, including compost. Also, Padilla et al. 2013 have studied the effects of wastewater treatment and Vinyes et al. (2013) studied the collection systems of cooking oil waste, which has potential in the production of biodiesel.

All s-LCA studies applied to biorefineries included a large set of indicators, in some of them the number of indicators was reported to exceed forty. Also, the involvement of stakeholders in the choice of the stakeholder categories, subcategories and indicators as well as in data collection was emphasized in both the UNEP/SEATAC guidelines (2009) and many of the biorefinery studies reviewed (Blom & Solmar 2009, Manik et al. 2013, Padilla et al. 2013, Vinyes et al. 2013). Some studies used the SHDB as a data source (Martinez-Blanco et al. 2014) and Ekener-Petersen et al. 2014), Ekener-Petersen et al. (2014) as the only data source. Other literature data, statistics and company reports were also used, as well as interviewes of experts and business key persons. The data collection of Manik et al. (2013), Padilla et al. (2013) and Vinyes et al. (2013) was largely based on the involvement of a broad range of stakeholders. Macombe et al. (2013) did not perform an assessment, but they discuss mainly the availability of literature data, statistics and company reports.

When adapting s-LCA to Finnish biorefinery chains, we strongly recommend stakeholder involvement in the choice of relevant categories and subcategories as well as data collection. In the case of novel technologies, stakeholder interviews are often the only way to get data. The usability of e. g. the SHDB is limited if all parts of the studied production chains are located in one country. However, the SHBD could be used in this case in the identification of social hotspot issues, which could be then be focused on in more detail.

Social impacts of biofuels

Macombe et al. 2013 discuss how to assess social impacts in LCA in three different processes of biodiesel production (from palm oil, wood chips and algae). Their study was not linked to any specific country, region or company, although they presented hypothetical examples of production processes connected to Finland. They focused their analysis on well-being and health impacts on three levels: company, regional and state level. The groups considered are workers involved in the production chain, the population of the region(s) and the national population(s). The authors suggest tools and methods to assess these impacts and also identify knowledge gaps, but did not do the actual assessment of those impacts of the biodiesel production.

Ekener-Petersen et al. (2014) screened the potential social impacts of fossil fuels and biofuels used in vehicles. The biofuels investigated were ethanol from Brazilian sugarcane, French wheat, French maize and US maize, and biodiesel from Lithuanian rapeseed. The study included the life cycle stages cultivation, processing and transport. This means that the stakeholder category ‘consumer’ was excluded from the study. All the indicators included in the SHDB were screened. The risks identified were listed and aggregated by counting the number of high and very high risk indicators for each fuel. According to study, both fossil and biofuels displayed high or very high risks of negative social impacts. Therefore, applying social criteria only on biofuels may be unfairly benefiting fossil fuels.

7. Summary

This report gives a glance at biomass processing technologies in agricultural and food sector. There is growing interest and political mandates to utilise renewable resources for new products, partly to replace non-renewable material sources, including products from oil-based production to fertilizers. However, biomass availability is limited and therefore all production processes should be highly efficient. The goal should be having efficient and sustainable use of biomass for nonfood applications and improving the food chain efficiency. The main driver should be the environmental, economic, and social sustainability, covering the whole life cycle.

There are several possibilities to utilize the biomass resources, but deep knowledge of the synergies between different processes is still limited. In many cases, the technological processes give variable possibilities to first convert the biomass to high-value products and use the rest of the biomass to energy and nutrient production. Key questions are what the mass and energy balances are between different processes, and how much biomass is needed to make the process chain economically feasible. All the process chains need to be built case by case as what is feasible in one location, may not be so in another. Combining, for example, the fermentation or pyrolysis process with AD gives benefits from the energy utilization perspective (when another process can utilize the energy produced by another process) while on the other hand the investment for two different processes may be too high especially in small scale applications.

In all applications, nutrient recycling should be takein into account as many agricultural and food based biomasses have high concentration on nutrients. The need for recycled fertilizer products is increasing due to decrease in phosphorous resources and well as high energy utilization in nitrogen production. The increasing interest for organic farming increses also the need for organic fertilizers, which can be produced from agricultural and food industry by-products. The improved use of recycled nutrients is also part of the circular economy defined in European Circular Economy Strategy and promotes local, regional and national nutrient self-sufficiency.

Collaboration between industries, farmers and SME’s are needed for building an effective and economic value chain for processes. Biorefineries can bring new competence and job opportunities both in industrialised and developing countries, but the processes need to be designed in a sustainable way.

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