Pre-feasibility assessments for innovative bio-based value-chains in the South Baltic Region

June 2021

Pre-feasibility assessments on innovative agro-industrial value-chains and biomass-based production in the South Baltic Region

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Executive summary

The bioeconomy transition can be described as the next economic development shaping the low-carbon, resource efficient and circular economy, in which new biomass-based materials and products are introduced to substitute fossil-based materials and products.

As part of this transition, the BioBIGG project seeks to strengthen the innovation capacity of SMEs in the South Baltic Area (SBA) by documenting new possible products and/or improved production processes related to selected biomass-based feedstocks. The selection process is based on a common framework for the development of a sustainable and circular bioeconomy and is structured by a comprehensive screening of agro-industrial value chains, innovation opportunities and material flows embedded in the participating regions. The aim of this report is to introduce the selected bioeconomy concepts through 16 pre-feasibility studies, divided into four sectors: agriculture, forestry, agro-industrial and households. The concepts are envisioned as a point-of-departure for new collaborative efforts between SMEs, business organisations and academia within the SBA.

Please note that selected pre-feasibility assessments has been further developed in the reports: *Innovation programmes for bio-based value chains in the South Baltic Region* and *Business cases for bio-based value chains in the South Baltic Region*. These reports include suggestions on innovation potentials, roadmaps and business opportunities for the concepts and can be found on the BioBIGG homepage: https://biobigg.ruc.dk

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Agricultural sector

DIGITAL STRAW BALE MANAGEMENT IN DENMARK

COLOURBOX47342830

I. Authors note

This report (i.e., report 1) is part of three reports introducing a technological concept for an automated management of straw bales in large-scale supply chains.

Report 1 presents a pre-feasibility assessment of the technological concept. This entails an introduction to the technological concept based on best available technologies (see innovation program), followed by a preliminary cost-benefit analysis.

Report 2 presents a framework for an innovation program for the development of the technological concept from Technology Readiness Level 2 to TRL5. This entails a seed-money project and R&D-project.

Report 3 presents a potential business case for the commercialization of the technological concept in a supply chain. This entails value propositions on customer satisfaction and cost minimization effects related to the technology.

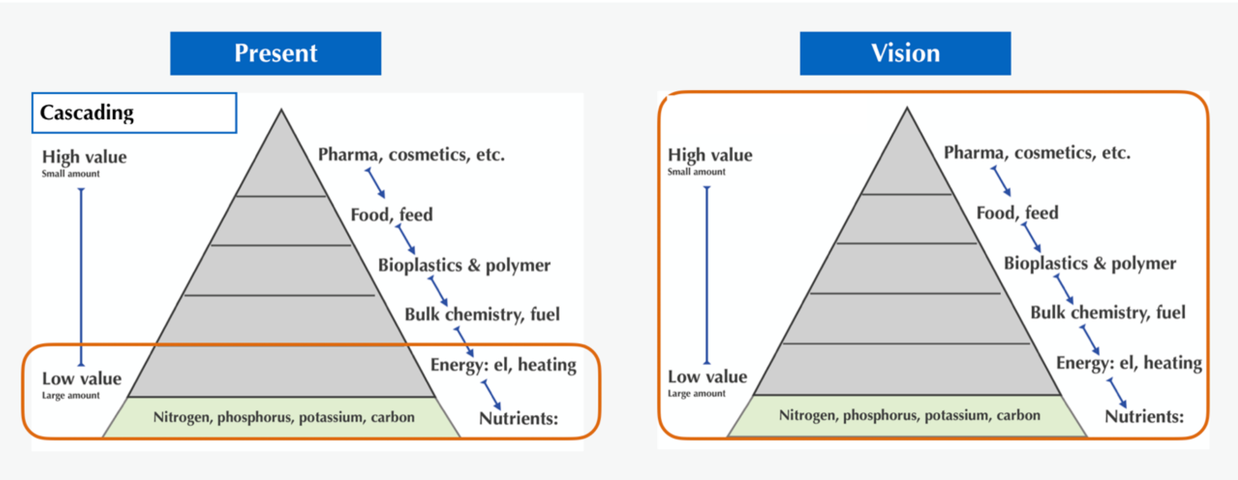
The reports have been written by Rasmus Nør Hansen, Roskilde University (Department of People and Technology) as part of the BioBIGG project under the Interreg South Baltic program 2014-2020.

1. Introduction

Resource-effective and multi-purpose utilization of low-cost agricultural by-products is expected to increase significantly over the coming decade. This is also referred to as the cascade-oriented and sustainable bioeconomy; i.e., by-products are allocated according to highest environmental and financial impact in a cascading manner, subsequently circulated on arable land for nutrient uptake (see figure 1).

Cereal straw constitutes a key driver for this development, as the lignocellulosic biomass is one of the main agricultural by-products in the South Baltic Region. However, the stability of a cascade-oriented supply market, presupposes an effective system for sorting and categorizing straw according to demand-side requirements. A maturity level rarely found within the management of agricultural by-products. The focus of this paper is thereby to present a data-driven digital concept for large-scale management of straw bales in accordance to material quality.

Figure 1: From a low value to a cascade-oriented market



1.1. The vision

From a technological perspective, the concept is envisioned as an automated supply management system for identifying and allocating bales in accordance to material properties. The main functions of the system are (1) to inform suppliers on bale sorting procedures, inventory and supply chain flow and (2) inform processing facilities on future amount and quality to be delivery. The primary target groups are (1) suppliers capable of delivering at least 5.000 tons of large square bales and (2) agro-industrial processing facilities utilizing at least 20.000 tons of large square bales pr. year. Large suppliers are expected to be more applicable for the concept, as they already have well-established supply chains. Or in other words; the machine capacity (balers and tractors) is expected to be equipped with technological components supporting the integration of the technological concept.

From an organizational perspective, the concept is envisioned as a support structure for a consortium of straw suppliers in Denmark, delivering large amounts of bales for multiple purposes. In the first part of the organizational development, the concept is expected to be developed as an external structure financed by license costs. However, the end-goal is to integrate the support structure into a formal collaboration between a consortium of suppliers and processing facilities. In this way, the technological concept is converted into an internalized bale management system for multiple value chains.

From a financial perspective, the concept is envisioned as a support structure for the development of a certification scheme for straw. Here, the main purpose is to brand consortium straw as a high-quality feedstock, delivered via transparent, effective and stable supply chains. This is expected to generate a competitive advantage over other feedstock suppliers, and thereby increasing demand, while also expanding the market potential of straw in DK and potentially also other biobased EU-markets. These aspects are discussed further in the business case.

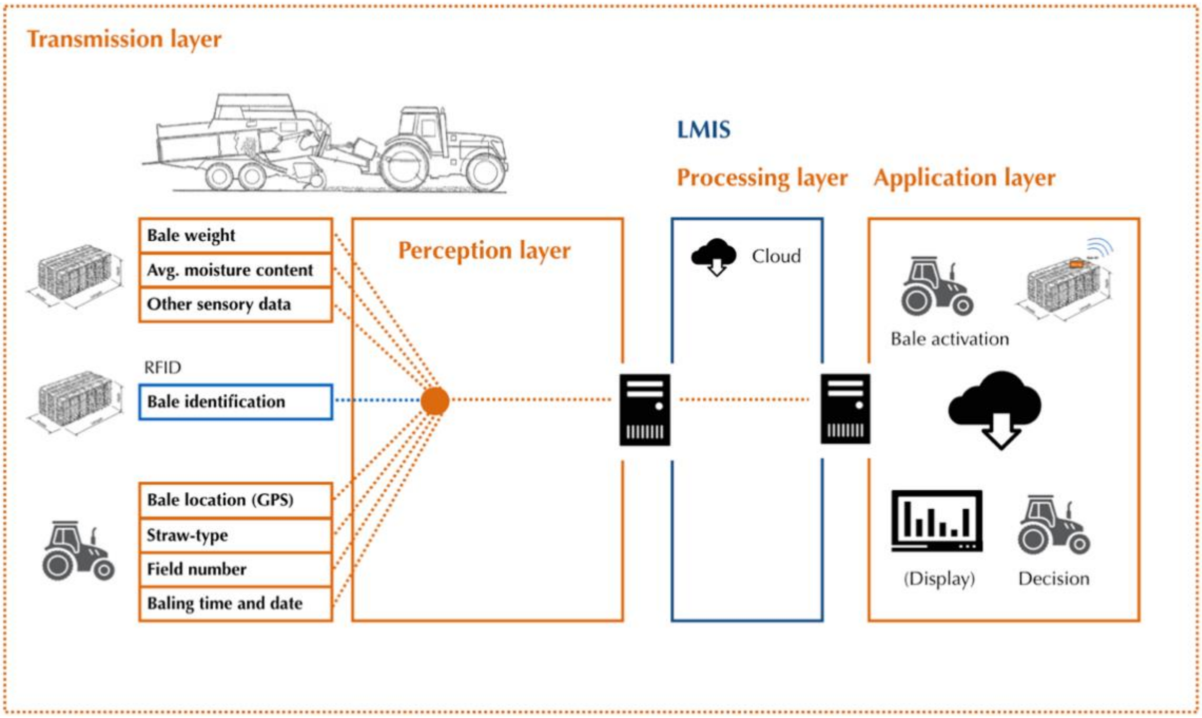
2. Technological concept

Systems for sorting and categorizing raw materials have been used to organize supply chains for thousands of years. According to Pelletier (2013) archeologists discovered a beer bottling and preservation site from around 3600 BC, leading to the conclusion that 'ancient Egyptians already had some kind of economic organization that could stock and distribute raw materials' (2013, p. 197).

Modern day supply chains essentially have the same core goals. According to Snow (2017) an effective supply chain can be measured by the ability to provide 'right data of the right quality, at the right time, in the hands of the right people, in the right place, to make the right decision and take the right action' (i.e., the 7 R's) (p. 26). In such an ideal state, data on supply and demand needs to be seamlessly integrated into the entire supply chain, via a digitalized Logistics Management Information System (LMIS). According to Snow (2017) LMIS can best be defined as the operational aspect of supply chain management, which 'collects, organizes, and reports data that enables people to make operational and strategic decisions and take informed action'.

This definition is the 'heart' of the technological concept, as the logistical success of a supply consortium is rooted in the effective management of data from multiple sources (i.e., suppliers). The technical concept draws heavily on Internet of Things (IoT), Chain of Custody (CoC) and physical identification technologies (RFID). According to Green et. al. (2020) IoT was introduced in 1999, but has no official definition. The term implies a network of 'things' interconnected and accessible via the internet. Things are digitally recorded properties of a physical object, such as a bale, which can be accessed (autonomously or manually) throughout the supply chain. An essential function in any supply chain.

Figure 2: The four layers of the LMIS (see description below)



The LMIS/technological concept can be divided into four processes: perception, transmission, processing and application. The perception layer collects data on bale properties. The transmission layer wirelessly transmits data. The processing layer processes data into useful services and the application layer communicates these services to selected users.

2.1. Perception layer

The perception layer includes all devices installed in a baler or tractor, measuring, gathering and identifying properties about a bale or related operations. Measurement procedures are expected to be executed by sensory devices installed in the baler or potentially also the loader for managing bales. Moisture content is determined by probes inserted into bales (installed in the pressing chamber) or by microwave technology (installed at the exit-point of the chamber). Bale weight is expected to be an integrated part of modern balers or else installed as a sensory device in loaders, converting hydraulic pressure into weight. The current usage of bale data is primarily displayed to the driver for 'on-the-spot' operations but is sometimes also recorded and manually transferred to an internal server at the farm by a USB-key.

The combined properties of a bale will be defined as a data-point. The concept is however not focusing on a single data-point (i.e., a single bale), but the interconnection between multiple data-points (i.e., the management of several bales in relation to each other). Basic properties can be sensory data (bale moisture content, bale weight, fuel consumption) and non-sensory data (bale location, field number, straw-type, baling time). One data-point is expected to consist of around 500 bits. The total data-points of 200.000 bales (100.000 tons) only consist of 6 MB, equivalent to the memory of a small USB flash drive.

Figure 3: Data-points

Bale-ID	Moisture	Bale weight	Baling time	Date	Field nr.	Straw type
Baler	Baler	Baler	Tractor	Tractor	Tractor	Tractor
123456	12%	520	10.12 AM	01/09/2021	1234	Winter wheat
123457	11%	524	10.20 AM	01/09/2021	1234	Winter wheat
123458	10%	500	10.30 AM	01/09/2021	1234	Winter wheat
123459	13%	497	10.40 AM	01/09/2021	1234	Winter wheat
123460	13%	550	10.50 AM	01/09/2021	1234	Winter wheat
123461	14%	500	11.00 AM	01/09/2021	1234	Winter wheat
123465	14%	530	12.00 PM	02/09/2021	1235	Barley
123466	21%	550	12.10 PM	02/09/2021	1235	Barley
123467	23%	534	12.20 PM	02/09/2021	1235	Barley
123485	24%	600	12.30 PM	02/09/2021	1235	Barley
123468	16%	563	12.35 PM	02/09/2021	1235	Barley
123469	18%	512	12.40 PM	02/09/2021	1235	Barley
123470	12%	497	1.40 PM	04/09/2021	1236	Oat
123471	10%	450	1.50 PM	04/09/2021	1236	Oat
123472	11%	480	2.00 PM	04/09/2021	1236	Oat
123473	8%	500	2.10 PM	04/09/2021	1236	Oat
123474	12%	510	2.20 PM	04/09/2021	1236	Oat
123475	8%	499	2.30 PM	04/09/2021	1236	Oat

A datapoint

2.1.1. Bale identification

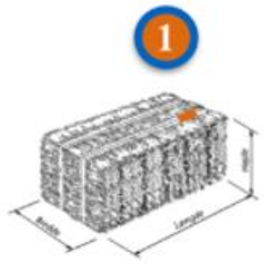
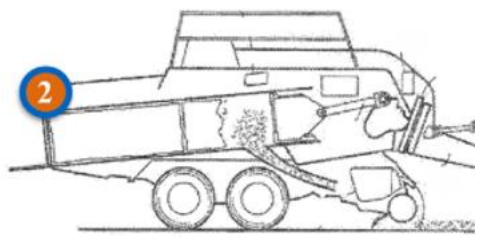
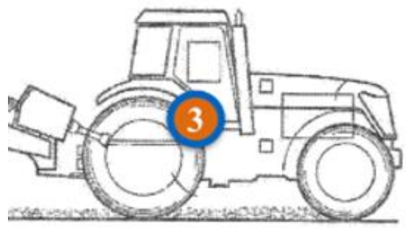
The digital and physical identification of bale properties is developed as an integrated part of the baling operation. This is executed via a RFID-system[1] conducting the following autonomous process; A small RFID-filament is attached to a bale via the bale binding material in the pressing chamber. On the RFID-filament a unique number is stored. This will be referred to as the Bale-ID[2]. When the bale exits the pressing chamber, the ID is transmitted to an antenna and sent to a telematic control unit (TCU) installed in the tractor. Bale properties are also sent (via a CAN-bus system) to the TCU. The TCU is the main hardware and software component used for identifying bales digitally (i.e., also referred to as a reader in a narrower sense).

The control unit creates a data-point by assign the ID to the properties of the bale, completing the digital identification process. This also means, that no data is stored on the filament (other than a Bale-ID), which ensures a high level of flexibility in the flow of information, as bale properties can be accessed, stored and changed by scanning the filament on the bale or by manually logging into the LMIS.

[1] Radio Frequency Identification refers to the process of identifying a physical object via radio waves by attaching a low-cost and small filament/tag/label (containing a microchip and antenna) to a physical object.

[2] The Bale-ID (also define as an EPC, Electronic Product Code) is stored on a microchip embedded into the RFID-filament. The memory bank is usually 94-bits, which corresponds to 12 letters, signs or numbers. The risk of two bales having the same bale-ID (at the same location) is thereby very low.

Table 1: Key technical requirements for hardware components and physical placement.

RFID filament (1):		
Type	Passive	
Data-functionality:	Read-Only	
EPC memory:	94-bits	
Radio frequency:	865.6 – 867.6 MHz[3]	
Antenna (2):		
Environment:	Outdoor	
Polarization:	Omnidirectional	
Telematic control unit (3):		
Type:	Fixed (In-vehicle)	
Power source:	Vehicle battery	

As the system evolves, the integration of external data into the LMIS also becomes possible via Machine Learning functions. This can be used for calculating more complex bale properties not directly measured by sensory devices in the baler. For example, the content of lignin in a bale, as a dependent variable of material composition (external data), bale weight (sensory data) and weather data (external data) or nutritional feed value, as a dependent variable of moisture content (sensory data), baling time and storage time (external data). Integrating external data with sensory data also indicates an important design principle: the concept is structured as an open and dynamic system for data inputs over time and in accordance to certain customer needs.

This design creates the ability to continuously quantify existing and new definitions of material bale quality (and indirectly the financial valuation of bales). The present paper will nevertheless only address the basic management concept, limited to measurements in the baler, tractor and, to some extent, external static data.

[3] ETSIs standard for Ultra High Frequency (UHF) for passive RFIDs is 865.6 – 867.6 MHz in Europe (GS1, 2021).

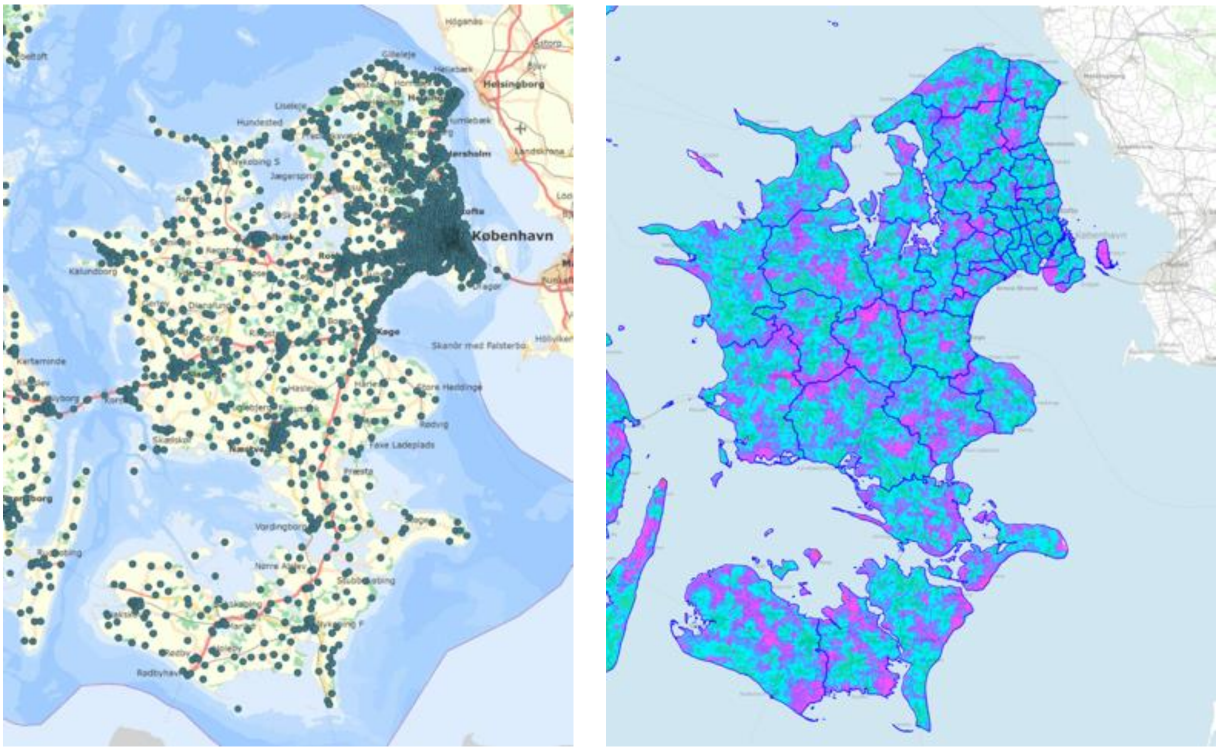
2.2. Transmission layer

The transmission layer refers to the wireless transfer of multiple data-points from the perception layer to the processing- and application layer via an internet protocol. The layer is thereby represented at several steps in the supply chain, wirelessly interconnecting the flow of data. This entails data transmission from tractors conducting baling operations, to tractors conducting logistical bale management procedures (i.e., on-field collection and intermediate inventory management) to relevant production data for processing facilities (i.e., customers).

Multiple transmission technologies are used within IoT-systems to transfer data to/from one layer to another, such as ZigBee, LoRa, WiFi, NB-IoT, 4G and LTE-M (Green et. al. 2020). The best available transmission technology depends on the application, cost and surrounding environment. Or in other words; how fast data needs to flow in order to deliver a demanded service. The time-period between baling straw (i.e., data collection) and executing logistical services (i.e., utilizing data) is anywhere between a couple of days, to a week, and sometimes even more. This means that the requirement for the transmission is relatively low. Latency issues for the concept is thereby expected to be minimal or non-existing.

The 4G mobile network is expected to be an applicable protocol for the concept, as it is well established in DK. There is almost full access to a 10 Mbit/s network (download) regardless of tractor location (see figure 4). The upload speed is not measured over total areas, but is also expected to be sufficient for the concept.

Figure 4: Transmission network in Region Zealand



Note: Installed masts (left), internet coverage of 10 Mbit/s download (right). Source: https://www.mastedatabasen.dk/viskort/PageMap.aspx

2.3. Processing layer

The processing layer refers to a centralized cloud-based system. The system stores, analyzes and processes data-points into useful information in the application layer. This is the back-end of the support structure, also referred to as the middleware platform. The processing layer is expected to be integrated into an established IoT infrastructure supporting farm-related services, as bundling services together reduces development costs.

Balers and tractors sometimes store proprietary data in different file formats (due to different manufacturing companies). This reduces machine-to-machine interoperability (i.e., M2M) between the layers and users, subsequently creating scalability issues for the concept. The first step is thereby to establish an integration unit, capable of converting data-points from multiple sources into the same file format. Here, the ADAPT-framework[4] is expected to be a key enabling technology, as the open-source software can convert different file-formats into a standard file-format, and back to specific machine formats. Several leading technology manufacturers within the agricultural sector have already committed to the framework[5].

2.3.1. Data-points to services

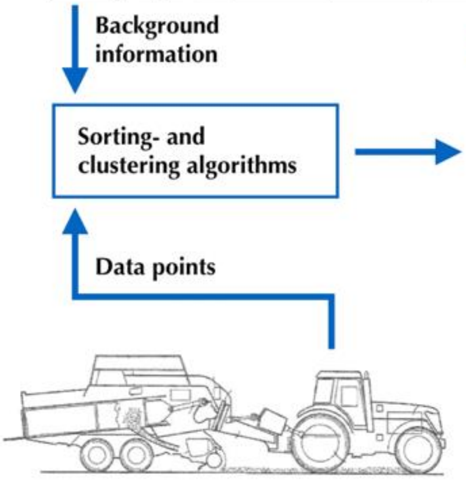
After pre-processing data-points into unified file-formats, the bale properties are stored on a centralized database and processed into useful services by a server. The analytics consists of algorithms grouping data-points by one or multiple selected properties. A functionality controlled by basic sorting- and clustering algorithms, successfully used within logistics management systems of bulk goods for years.

In figure 5, a fictive example of different material quality requirements, price ranges and feedstock flexibility are presented for five processing facilities. This represents the background information (or framework) used when programming the algorithm. Frameworks are defined by the individual processing facilities in collaboration with the consortium.

[4] The ADAPT framework was developed as an open-source software under a Horizon2020 project called IoF2020.
[5] AGCO Corporation, CLAAS, John Deere, Kuhn, Ag Leader, CNH Industrial, Hemisphere GNSS and Trimble Ag (Source: https://adaptframework.org/companies-supporting-adapt/).

Figure 5: Visualization of the color-based clustering process

	Processing facility 1	Processing facility 2	Processing facility 3	Processing facility 4	Processing facility 5
Delivery location:	GPS coordinates	GPS coordinates	GPS coordinates	GPS coordinates	GPS coordinates
Company name:	A	B	C	D	E
Product:	Energy	Biogas	Biogas	Bulk chemicals	Fibers
Process:	Thermal	Biological	Biological	Chemical, Biological	Mechanical
Price range:	0,078 - 0,082 €	0,067 - 0,070 €	0,065 - 0,070 €	0,094 - 0,12 €	0,12 - 0,13 €
Feedstock flexibility:	Low	Medium	High	Low	Low
PQR:	avg. moisture	avg. moisture	avg. moisture	avg. moisture	Straw type
Quality value:	10 - 12%	13 - 15%	19 - 23%	14 - 19%	Oat
SQR:	N/A	N/A	N/A	N/A	avg. moisture
Quality value:	N/A	N/A	N/A	N/A	0 - 11%
TQR:	N/A	N/A	N/A	N/A	N/A
Quality value:	N/A	N/A	N/A	N/A	N/A



Bale-ID	Moisture	Bale weight	Baling time	Date	Field nr.	Straw type
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123473	8%	500	2.10 PM	04/09/2021	1236	Oat
123475	8%	499	2.30 PM	04/09/2021	1236	Oat

Note: Price range is in € pr. kg straw. Feedstock flexibility is from low – high. Notice the purple color. For this processing facility, bales are first assigned to straw type (i.e., oat) and then moisture content

Within each framework, key requirements are integrated for sorting data-points into color-based groups (clusters). This will primarily be related to material properties of a bale. If several properties are selected (i.e., purple processing facility), the algorithm will function in a sequential manner: primary-, secondary and tertiary quality requirements (PQR, SQR, TQR). Colors represent the visual identity of each processing facility used in the application layer to communicate the sorting procedure of bales.

If multiple processing facilities has the same quality requirements, a clustering algorithm will prioritize highest contractual price, followed by lowest feedstock flexibility. The priority order will not only take into account base prices, but also expected price regulations upon delivery. Under poor weather conditions lowest feedstock flexibility can also be selected as the only prioritization (i.e., undermining price in favor of long-term supply security). Priority order of both parameters will dictate the timely collection/allocation of bales in the application layer: i.e., top priority bales are collected first, bottom priority bales are collected last.

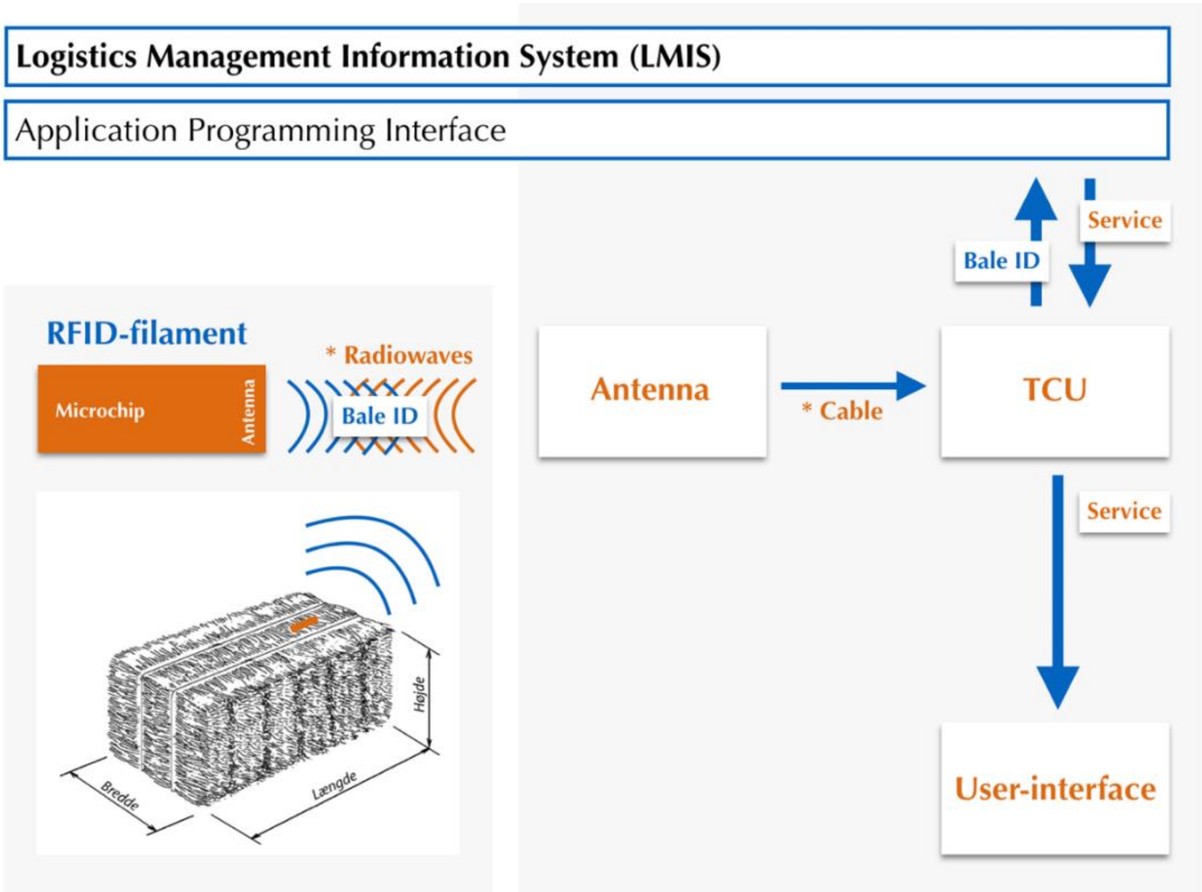
To summarize; clustering can be used as an autonomous method for integrating material quality, supply logistics and supply security into the financial valuation of bales. The number of quality requirements, restrictiveness of requirements and feedstock flexibility is reflected in the contractual price range; i.e., several restrictive material requirements and low feedstock flexibility would lead to higher bale prices and vice versa.

2.4. Application layer

The application layer refers to the autonomous communication of a service to a user. Services are sorting procedures for bale placement and inventory overview. The activation of a service to a bale can briefly be explained in the following way: A bale is picked up by a tractor/loader. An antenna, mounted on the loader, activates the RFID-filament and sends the bale-ID to the tractor. The ID is then transmitted to the processing layer, which in return, establishes and sends back a service related to the specific bale to the user.

This also means that services are the only function of the system visible for the users. All other aspects will be automated and managed by the support structure and bale identification technologies. The entire communication process is conducted by an Application Programming Interface (API). This is an intermediary software, sending a request to the processing layer, receiving a response and displaying the response to a user (see figure 6).

Figure 6: The activation of a RFID, communication of Bale-ID and Services



2.4.1. Sorting procedures (service 1)

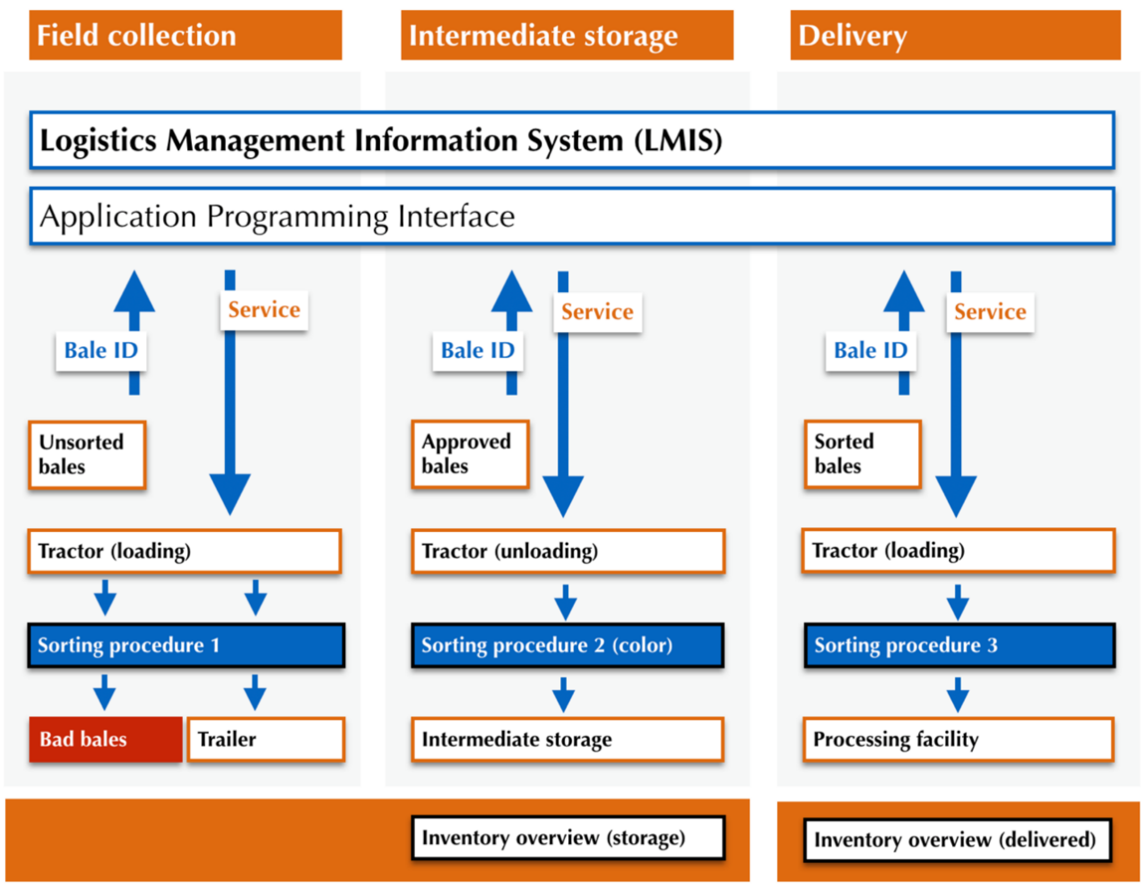
Sorting procedures enables supply chain personnel/users to make informed logistical decisions on bale-placement according to properties. The service is communicated as a color via a user-interface and is divided into three sorting procedures. These procedures are placed at strategic points in the supply chain and has the same criteria: i.e., to support the delivery of high-quality bales to multiple processing facilities according to multiple demand-side requirements.

The first sorting procedure is executed when bales are transferred from a field to a trailer. The purpose is not to allocate bales in approved quality categories (this is done in step 2 and 3), but to inform drivers about bales of substantial poor quality. The information is communicated to the driver by a red screen, symbolizing a bale should not be transferred to any contractual processing facilities (i.e., left on field for later pick-up or placed on trailer apart from other approved bales). The bale is thereby rejected on-field, instead of at the processing facility, effectively reducing sunk cost for bale management (see business case).

The second sorting procedure is executed when approved bales are transferred from a trailer to an intermediate storage. This is the main sorting process. A color is displayed to the driver upon bale pick-up within 5 seconds (i.e., near-real time). When the driver enters a storage facility, certain areas are divided into colors by signage. The matching color specifies the physical placement of the bale. Color signs should be visible and adaptable to variations in area-size, as bale-amount will vary over the years.

The third sorting procedure is executed when bales are delivered to a processing facility. A processing facility informs selected users about a delivery time and color via the software. If a driver accidentally picks up a wrong bale within the transfer period, the API will respond with a red screen followed by the bale color, securing correct transfer from storage to trailer (and internal re-allocations). The tractor or truck is informed about a delivery address and route by the software.

Figure 7: Sorting procedures and inventory overview



Over time, material quality of stored bales can potentially change. This will usually be related to moisture content, storage conditions and environmental conditions. Dry bales stored inside a well-ventilated facility on a cement floor, will be more or less stable over time. Whereas bales stored outside on the ground will be less stable over time. Moisture content over a certain level (> 20%) can also influence quality, as the moisture increases bale temperature and microbial activity resulting in the formation of mold.

Changes to material quality will generate misleading data-points in the processing layer. A certain level of inaccuracy is expected to be acceptable within all clusters upon delivery. However, substantial changes in material quality at intermediate storages, can be manually updated by accessing the RFID-filament on a single bale or multiple bales. The algorithm will then automatically re-allocate bales into other clusters. As the system evolves, bale updates can potentially be autonomously defined and re-arranged, by utilizing historical baling data and bale samples.

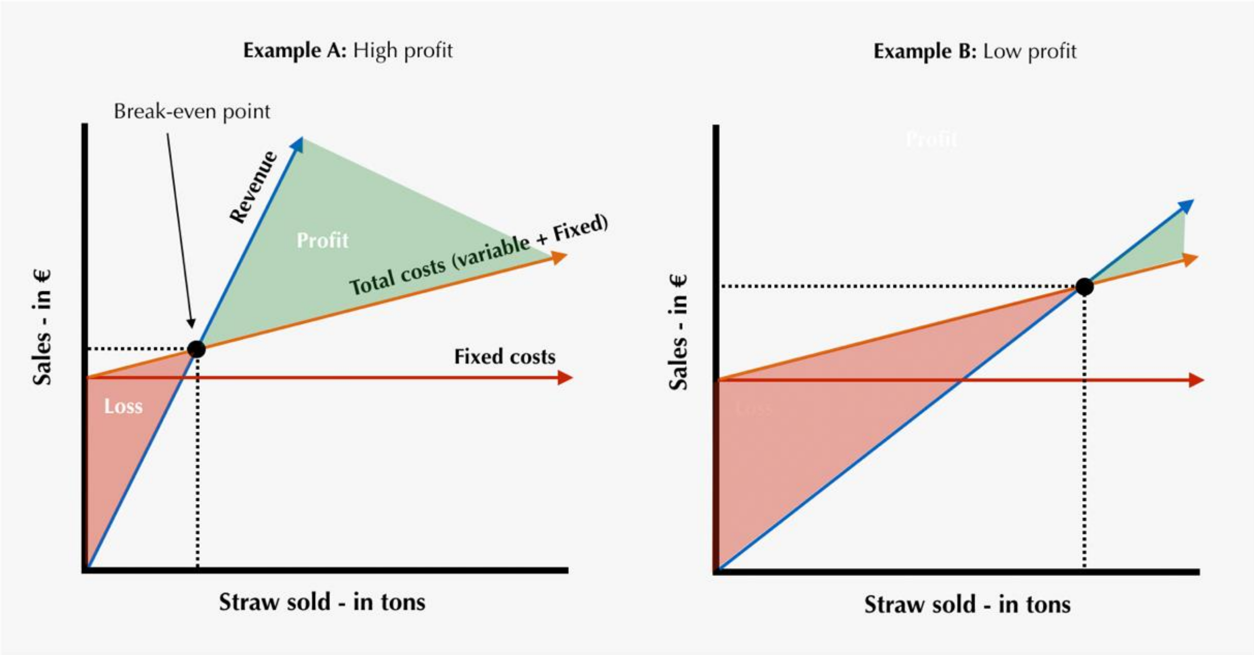
2.4.2. Inventory overview (Service 2)

As part of the sorting procedures, an inventory overview will be created and transmitted to the users (near-real time). This overview entails bales transferred to intermediate storages, existing reserves at intermediate storages and delivered bales. By subtracting stored amount from delivered amount reserves are calculated after the yearly delivery. In addition to this, reserves on a consortium-level can be defined as a data-driven supply security indicator for the entire value chain. Finally, it should also be mentioned, that RFID-filaments can be scanned by hand-held readers, giving the opportunity for processing facilities to adjust production inputs in accordance to individual bale properties. All of these aspects will be discussed further in the business case. The point here, is only to explain that the value of the LMIS should not only be defined by service 1, but also by the derived service(s) for establishing a cloud-based and data-driven inventory overview of bales throughout the supply chain.

3. Financial pre-feasibility of concept

In the following section, a break-even analysis will be used to determine how much straw a supplier needs to sell in order to cover fixed- and variable costs, related to the establishment and utilization of the LMIS. Or in other words; when total revenue equals total costs (i.e., break-even point, see figure 8). Such analysis is especially useful in early development stages, as it indicates the pre-feasibility of a concept. Development costs for the processing and application layer is assumed to be financed through an EU program for farm-based IoT. This will be further elaborated in the innovation program.

Figure 8: Overview of a break-even in relation to profit



Note: Example A is expected to be representative for the project concept, whereas example B is expected to be representative for the current contractual market for incineration (i.e., a marginal profit to suppliers). Please notice, that changes to fixed- and variable costs could also affect the break-even point.

The analysis will be conducted for a fictive supplier, delivering an annual amount of 5.000 tons over a 6-year contractual period (30.000 tons in total). The supplier utilizes 3 tractors and balers, installed with antennas and TCUs. All fixed costs related to the system is financed by a loan (interest rate of 2 %) with a payback period of 3 years. Life-expectancy of antennas and TCUs is assumed to be 6 years.

3.1. Variable costs

Variable costs refer to unit prices for RFID filaments attached to bales and bale handling costs. Market prices for RFID bale tags with an adhesive label are valuated at around 0,56 – 0,66 €/unit. Similar RFID tags without a label is priced at around 0,21 – 0,24 €/unit. RFID filaments are woven into the bale binding material (see innovation program for elaboration) and is thereby not directly comparable to labelled RFID bale-tags. However, the technical components and function of the RFID bale tag is comparable. A unit price of 0,70 € is thereby expected to be a realistic estimate. The filament price pr. ton would thereby be around 1,40 € (i.e., bale weight: 500 – 550 kg).

Bale Handling Cost (BHC) refers to costs for procuring straw (on-field), drying straw, baling, loading, unloading, intermediate storage and transport. The financial calculation will be divided into five categories. Each category representing a cost minimization related to bale handling, as the concept becomes more and more integrated into the supply chain (see table 2). These cost categories should only be viewed as conservative estimates, as it is difficult to quantify the financial effect of the concept before a trial period (i.e., TRL5-6). Current bale handling costs for straw to incineration is assumed to be around 67 € pr. ton.

Table 2: bale handling costs and potential reductions

Bale handling costs	**Reduction from present costs**
BHC1 (present cost)	
67 € pr. ton	0%
BHC2	
64 € pr. ton	5 %
BHC3	
62 € pr. ton	8 %
BHC4	
59 € pr. ton	12 %
BHC5	
56 € pr. ton	17 %

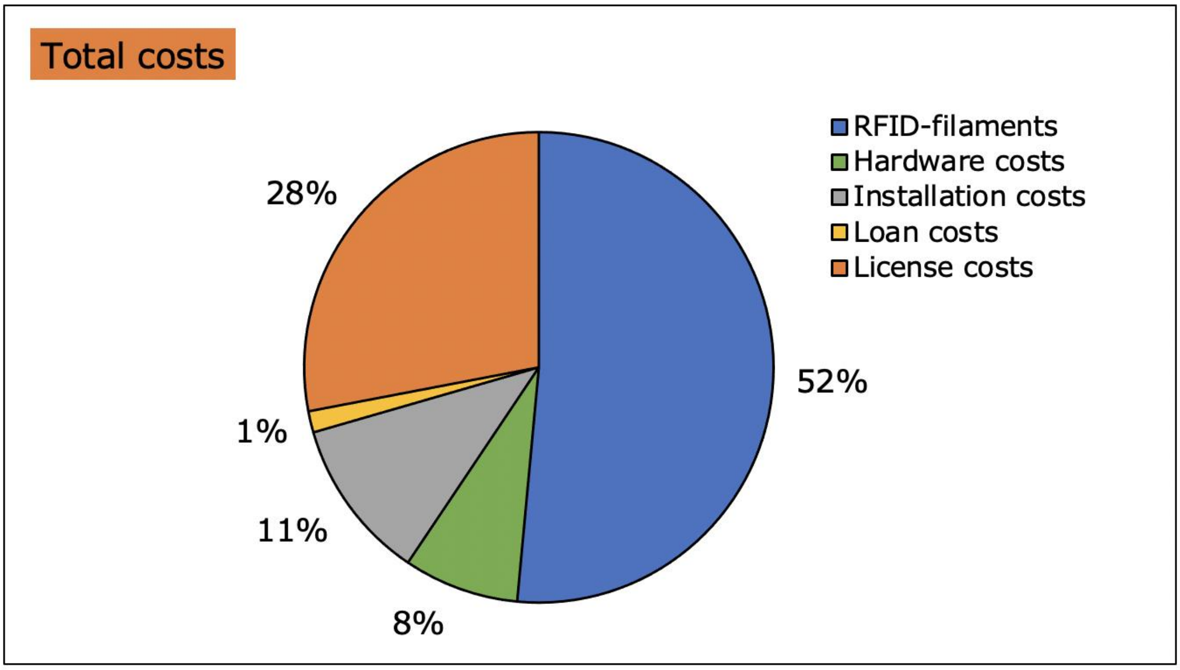
3.2. Fixed costs

Fixed costs refer to license fees for software services, antennas and TCUs installed in tractors and balers. License costs are defined pr. tractor[6], and needs to cover salary and profit to a service provider. The service provider manages data in the processing layer and the user-interface in the application layer. As the amount of data is small and services are relatively simple, costs are expected to be less than 1.269 € pr. tractor pr. year.

Prices for applicable outdoor antennas vary between 102 – 218 € pr. unit with an average price of 154 € pr. unit. Mounting brackets and cables for antennas is priced at around 30 € pr. unit and 50 € pr. unit. The total price for an antenna system on a baler (i.e., identification) or tractor (i.e., sorting) is thereby expected to be around 234 €. Installation costs are estimated to be 672 € pr. unit. A telematic systems is estimated to cost around 1.692 € pr. unit. Installation and configuration costs is expected to be 1.680 € pr. unit. Highest cost is expected to be related to RFID-filaments, followed by license fees. Costs related to hardware, installation and loan is relatively low (see figure 9), compared to the potential profit presented in the break-even analysis (see table 3)

[6] License costs could also be viewed as semi-variable costs (more straw, more tractors, more licenses). However, to keep the calculations simple, the total license costs for a certain period is estimated on the assumption that a machine station licenses all tractors regardless of amount.

Figure 9: Cost structure for the concept



Note: The percentage distribution of conceptual costs is based on the assumptions of a delivery of 30.000 tons of straw over 6 years.

3.3. Break-even analysis

A worst- and best-case scenario has been calculated for the break-even analysis. In the best-case scenario, all costs related to the concept (i.e., hardware, installation, licenses, loan and RFID-filaments) will be unchanged (see appendix 2a and 2b). In the worst-case scenario, all costs related to the concept will be assumed 100 % higher (see appendix 3a and 3b). The result of the analysis is presented in table 3.

Table 3: break-even analysis

	Break-even point	**Total profit**
[BHC 1]		
Best-case scenario	1.896 tons	587.711 €
Worst case scenario	4.056 tons	506.121 €
[BHC 2]		
Best-case scenario	1.656 tons	677.711 €
Worst case scenario	3.516 tons	596.121 €
[BHC 3]		
Best-case scenario	1.470 tons	767.711 €
Worst case scenario	3.102 tons	686.121 €
[BHC 4]		
Best-case scenario	1.368 tons	827.711 €
Worst case scenario	2.880 tons	746.121 €
[BHC 5]		
Best-case scenario	1.242 tons	917.711 €
Worst case scenario	2.598 tons	836.121 €

In all five cost categories and regardless of scenario, a profit can be generated when delivering a total amount of 30.000 tons (over 6 years). In the best-case scenario, the break-even point is 4,5 – 6,3 % of total delivery. In the worst-case scenario, the break-even point is 9,6 – 13,5 % of total delivery.

However, the financial pre-feasibility also needs to be compared to a base scenario (i.e., current situation) in order to evaluate the estimated additional profit related to the concept. The base scenario will represent a market price of 80 € pr. ton for incineration purposes, variable cost for bale handling at 67 € pr. ton. No costs are related to the concept, as it is assumed not implemented (see appendix 4a). In table 4 the additional profit generated over 6 years is presented (see appendix 5).

Table 4: Additional profit (total, and pr. ton)

	Total additional profit	**Pr. ton**
[BHC1]		
Best-case scenario	197.711 €	6,6 €/ton
Worst case scenario	116.121 €	3,9 €/ton
[BHC2]		
Best-case scenario	287.711 €	9,6 €/ton
Worst case scenario	206.121 €	6,9 €/ton
[BHC3]		
Best-case scenario	377.711 €	12,6 €/ton
Worst case scenario	296.121 €	9,9 €/ton
[BHC4]		
Best-case scenario	437.711 €	14,6 €/ton
Worst case scenario	356.121 €	11,9 €/ton
[BHC5]		
Best-case scenario	527.711 €	17,6 €/ton
Worst case scenario	446.121 €	14,9 €/ton

As already mentioned, BHC 1 represents the additional profit generated if no cost minimization occurs. The additional profit is thereby only related to the increase in revenue for selling straw to higher value markets instead of only to incineration purposes. BHC 2 – 5 represents the additional profit generated, if both cost minimization and increased revenue is realized.

The additional profit under BHC 3 – 5 is assumed sufficient for both scenarios. The most plausible scenario is expected to be the best-case scenario for BHC 3 (i.e., 12,6 €/ton) for two reasons. (1) The LMIS is expected to have a positive impact on costs related to intermediate bale management (i.e., personnel time, inventory overview, delivery logistics) and bale transport (i.e., route planning and execution), whereas a cost reduction of 5 €/ton (from 67 to 62 €) should be achievable. (2) Total conceptual costs are already assumed high in the best-case scenario, whereas the worst-case scenario is highly unlikely.

4. Conclusion

The utilization of straw for multiple purposes is expected to increase in the future. The present supply chain in Region Zealand thereby needs to be re-structured, in order to meet new demands. Or in other words; The integration of multiple demand-side requirements in supply logistics will be a structural pre-requisite for managing cascade-oriented supply chains effectively.

A technological concept for supply chain management has therefore been presented. The system is integrated into a support structure for a consortium of large-scale suppliers (i.e., > 5.000 tons), delivering high-quality certified straw bales for multi-purposes. The main idea entails a Logistics Information Management System (LMIS) autonomously creating an inventory of categorized bales in the supply chain, while also informing suppliers on placement of bales at strategic points in the supply chain (i.e., field collection, Intermediate storages and delivery).

Bale placement is conducted by the LMIS, as a colour-based sorting procedure. Services are autonomously sent to a driver (tractor/loader) informing him/her on where to allocate bales, via a colour sorting scheme defined in according to demand-side quality requirements. The system simultaneously (or near-real time) updates inventory overviews for a supplier, as the management of bales progresses through the supply chains.

Inventory overview of total delivery can also be accessed by selected processing facilities to assess future secured supply amount and quality. Creating a valuable opportunity for the facilities to adjust and optimize production processes to future feedstock data, while also increasing response time to potential supply shortages.

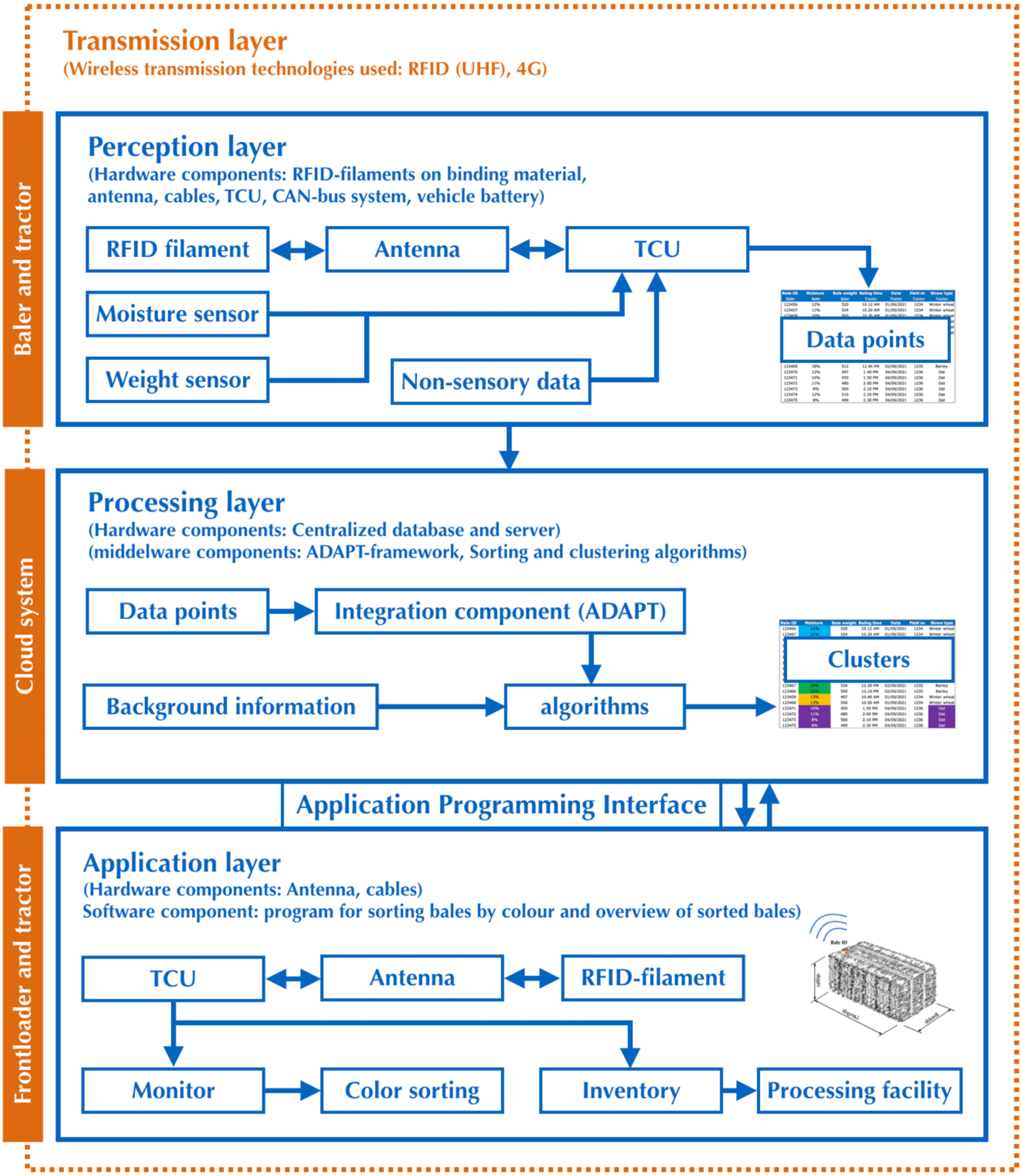
4.1. Technical description of the concept

A unique bale number is physically attached to a bale via a RFID-filament (woven into the bale binding material). The attachment procedure is conducted as an integrated part of the baling operation. This number is then digitally assigned to sensory and non-sensory bale properties via a TCU installed in the tractor and wirelessly transmitted to a cloud-based server (via a 4G network). The server utilizes clustering algorithms to process transmitted data-points into a pre-defined service related to inventory and bale-placement. Upon subsequent bale pick-up by a loader, the filament on the bale is activated by an antenna and TCU (installed in the loader/tractor). The activated filament sends the bale number to the TCU, and the TCU transmits the number to the cloud-based server via an API. Finally, the server/API transmits a service to the driver via a user-interface.

4.2. Financial pre-feasibility of the concept

The financial pre-feasibility of the concept was also evaluated. In a worst- and best-case scenario, the implementation- and running cost for the system is expected to generate an additional profit for suppliers (compared to present market conditions). The additional profit depends on the ability of the system to increase revenues related to contractual prices, while also reducing costs related to bale handling. This is elaborated in the business case. Under these assumptions, an additional profit of 12-13 €/ton is expected to be realizable for a supplier delivering an annual amount of 5.000 tons over 6 years. The highest conceptual costs are expected to be procurement of RFID-filaments (unit cost), followed by fees for accessing the LMIS (i.e., license cost). The latter cost is expected to be reduced as supplier memberships increases over time.

Appendix 1: Overview of the technological concept



Appendix 2a: Best-case scenario

The following analysis calculates the margin after variables costs are subtracted from revenues. The margin is used to cover hardware costs , installation costs, license costs and loan cost (see appendix 2b). The deliverance and contractual prices are estimates for further disc

Deliverance pr. year:

Facility:	Incineration	Biogas	Biofuels	Bulk Chemicals	Biocomposite
Amount - %	24%	37%	5%	17%	17%
Amount - ton	1.200 t	1.850 t	250 t	850 t	850 t
Price - pr. ton	80 €	67 €	87 €	107 €	134 €

Total deliverance: 100% 5.000 tons

Variable cost for RFID-filaments - € pr. ton:		***Notes:***
RFID costs	1,4 €/ton	[1]
Variable cost for bale handling - € pr. ton:		
BHC 1	67 €/ton	
BHC 2	64 €/ton	
BHC 3	61 €/ton	
BHC 4	59 €/ton	
BHC 5	56 €/ton	

Variable cost - total € pr. year						
	Incineration	**Biogas**	**Biofuels**	**B. Chemicals**	**Biocomposites**	**Total**
BHC 1	82.080 €	126.540 €	17.100 €	58.140 €	58.140 €	342.000 €
BHC 2	78.480 €	120.990 €	16.350 €	55.590 €	55.590 €	327.000 €
BHC 3	74.880 €	115.440 €	15.600 €	53.040 €	53.040 €	312.000 €
BHC 4	72.480 €	111.740 €	15.100 €	51.340 €	51.340 €	302.000 €
BHC 5	68.880 €	106.190 €	14.350 €	48.790 €	48.790 €	287.000 €
Revenues - total € pr. year						
All categorie	96.000 €	123.950 €	21.750 €	90.950 €	113.900	446.550 €
Contribution margin 1 - total €						
BHC 1	13.920 €	-2.590 €	4.650 €	32.810 €	55.760 €	104.550 €
BHC 2	17.520 €	2.960 €	5.400 €	35.360 €	58.310 €	119.550 €
BHC 3	21.120 €	8.510 €	6.150 €	37.910 €	60.860 €	134.550 €
BHC 4	23.520 €	12.210 €	6.650 €	39.610 €	62.560 €	144.550 €
BHC 5	27.120 €	17.760 €	7.400 €	42.160 €	65.110 €	159.550 €
Contribution margin 1 - € pr. ton						
BHC 1	12 €	-1 €	19 €	39 €	66 €	21 €
BHC 2	15 €	2 €	22 €	42 €	69 €	24 €
BHC 3	18 €	5 €	25 €	45 €	72 €	27 €
BHC 4	20 €	7 €	27 €	47 €	74 €	29 €
BHC 5	23 €	10 €	30 €	50 €	77 €	32 €

Notes:

[1]: The RFID-filament unit price is based on prices for the passive RFID bale-tag system from New Holland called CropID and 4 outdoor RFID-tag prices from AtlasRFIDstore resembling the technical functions of the conceptual RFID filament.

Appendix 2b: Best-case scenario

The following analysis investigates the final profit after fixed costs are subtracted from revenu es. Fixed costs refers to the procurement of antennas (incl. cables and mount), TCUs and exp ected installation costs, license costs. Additionally costs is related to the loan financing the fixed costs.

Hardware cost:				*Notes:*
Machinery used:				
Tractors:	3 units			[1]
Balers:	3 units			[1]
Hardware:				
Hardware lifetim	6 years	72 months		
Antennas	6 units	234 €/unit	1.404 €	[2]
TCU	3 units	1.692 €/unit	5.076 €	[3]
Total:			6.480 €	
Hardware installation cost:				
Hourly wage:		168 € pr. hour		[4]
Installation costs [Antenna]		24 Hours	4.032 €	
Installation costs [TCU]		30 Hours	5.040 €	
Total			9.072 €	
License cost:				
License cost pr. TCU pr. year:			1.269 €	[3]
License costs - total			22.842 €	
Loan cost (interest rate):				
Loan:			38.394 €	
Net interest rate:			2%	
Total interest rate cost:			1.195 €	
Monthly payback			1.100 €	
Payback period		3,0 years	36 months	
Loan free period:		3,0 years	36 months	
Total cost:				
Total costs:			39.589 €	

Contribution margin 2 [profit]			
Total:		**Pr. ton:**	**Break-even:**
BHC 1	**587.711 €**	**20 €/ton**	**1.896 Tons**
BHC 2	**677.711 €**	**23 €/ton**	**1.656 Tons**
BHC 3	**767.711 €**	**26 €/ton**	**1.470 Tons**
BHC 4	**827.711 €**	**28 €/ton**	**1.368 Tons**
BHC 5	**917.711 €**	**31 €/ton**	**1.242 Tons**

Notes:

[1]: The amount of tractors and balers is calculated based on the following assumption about the baling operation: baling capacity: 3,9 ha/h, yield: 4 t/ha, total baling time 14 h/day for 10 days.

[2]: The antenna price is based on the average market price of 14 outdoor antenna.
Source: AtlasRFIDstore and RFID4ustore.

[3]: The TCU and license cost is based on a price overview of telematic systems on farmprogress.com.
Source: https://www.farmprogress.com/precision-farming/telematics-20. Published 2010.

[4]: The hourly wage for installing the hardware is based on the price for hiring a mechanic with technical skills related to farm equipment.
source: https://www.maskinbladet.dk/artikel/59214-maskinforretning-vi-skal-betale-ekspertise. Published: 2018

Appendix 3a: Worst-case scenario

The following analysis calculates the residual margin after variables costs are subtracted from revenues. The residual margin is used for covering fixed costs, installation costs, license costs ar loan costs (see appendix 3b). The deliverance and contractual prices are estimated. The cost for RFID-filaments is assumed 100% higher than the expected market price (see appendix 2a).

Deliverance pr. year:

Facility:	Incineration	Biogas	Biofuels	Bulk Chemicals	Biocomposites
Amount - %	24%	37%	5%	17%	17%
Amount - ton	1.200 t	1.850 t	250 t	850 t	850 t
Price - pr. ton	80 €	67 €	87 €	107 €	134 €

Total deliverance: **100%** **5.000** **tons**

Variable costs for RFID-filaments - € pr. ton:

RFID costs	2,8 €/ton

Variable costs for bale handling - € pr. ton:

BHC 1	67 €/ton
BHC 2	64 €/ton
BHC 3	61 €/ton
BHC 4	59 €/ton
BHC 5	56 €/ton

Variable costs - total € pr. year

	Incineration	Biogas	Biofuels	B. Chemicals	Biocomposites	Total
BHC 1	83.760 €	129.130 €	17.450 €	59.330 €	59.330 €	349.000 €
BHC 2	80.160 €	123.580 €	16.700 €	56.780 €	56.780 €	334.000 €
BHC 3	76.560 €	118.030 €	15.950 €	54.230 €	54.230 €	319.000 €
BHC 4	74.160 €	114.330 €	15.450 €	52.530 €	52.530 €	309.000 €
BHC 5	70.560 €	108.780 €	14.700 €	49.980 €	49.980 €	294.000 €
Revenues - total € pr. year						
All categorie	96.000 €	123.950 €	21.750 €	90.950 €	113.900	446.550 €
Contribution margin 1 - total €						
BHC 1	12.240 €	-5.180 €	4.300 €	31.620 €	54.570 €	97.550 €
BHC 2	15.840 €	370 €	5.050 €	34.170 €	57.120 €	112.550 €
BHC 3	19.440 €	5.920 €	5.800 €	36.720 €	59.670 €	127.550 €
BHC 4	21.840 €	9.620 €	6.300 €	38.420 €	61.370 €	137.550 €
BHC 5	25.440 €	15.170 €	7.050 €	40.970 €	63.920 €	152.550 €
Contribution margin 1 - € pr. ton						
BHC 1	10 €	-3 €	17 €	37 €	64 €	20 €
BHC 2	13 €	0 €	20 €	40 €	67 €	23 €
BHC 3	16 €	3 €	23 €	43 €	70 €	26 €
BHC 4	18 €	5 €	25 €	45 €	72 €	28 €
BHC 5	21 €	8 €	28 €	48 €	75 €	31 €

*See appendix 2a for notes on RFID-filament prices

Appendix 3b: Worst-case scenario

The following analysis investigates the final profit after fixed costs are subtracted from revenues. Fixed costs refers to the procurement of antennas (incl. cables and mount), TCUs and expected installation costs, license costs. Additionally costs is related to the loan financing the fixed costs. All costs are assumed 100 % higher than estimated in appendix 2b.

Hardware costs:			
Machinery used:			
Tractors:	3 units		
Balers:	3 units		
Hardware:			
Hardware lifetime:	6 years	72 months	
Antennas	6 units	468 €/unit	2.808 €
TCU	3 units	3.384 €/unit	10.152 €
Total:			12.960 €
Hardware installation costs:			
Hourly wage:		336 € pr. hour	
Installation costs [Antenna]		24 Hours	8.064 €
Installation costs [TCU]		30 Hours	10.080 €
Total			18.144 €
License cost:			
License cost pr. TCU pr. year:			2.538 €
License costs - total			45.684 €
Loan cost (interest rate):			
Loan:			76.788 €
Net interest rate:			2%
Monthly payback			2.199 €
Interest rate cost:			2.391 €
Payback period		3,0 years	36 months
Loan free period:		3,0 years	36 months
Total cost:			
Total costs:			79.179 €

Contribution margin 2 [profit]			
Total:		**Pr. ton:**	**Break even:**
BHC 1	**506.121 €**	**17 €/ton**	**4.056 Tons**
BHC 2	**596.121 €**	**20 €/ton**	**3.516 Tons**
BHC 3	**686.121 €**	**23 €/ton**	**3.102 Tons**
BHC 4	**746.121 €**	**25 €/ton**	**2.880 Tons**
BHC 5	**836.121 €**	**28 €/ton**	**2.598 Tons**

*See appendix 2b for notes on costs.

Appendix 4a: Base scenario (1)

The following analysis calculates the residual margin after variables costs are subtracted from revenues. The contractual price and BHC is estimates, based on interviews with straw suppliers.

Deliverance pr. year:

Facility:	Incineration	Biogas	Biofuels	Bulk Chemicals	Biocomposite
Amount - %	100%	0%	0%	0%	0%
Amount - ton	5.000 t	0 t	0 t	0 t	0 t
Price - pr. ton	80 €	67 €	87 €	107 €	134 €

Total deliverance: **100%** **5.000** **tons**

Variable costs for RFID-filaments - € pr. ton:

RFID costs 0 €/ton

Variable costs for bale handling - € pr. ton:

BHC 67 €/ton

	Incineration	Biogas	Biofuels	B. Chemicals	Biocomposites	Total
Variable costs - total € pr. year						
	335.000 €	0 €	0 €	0 €	0 €	335.000 €
Revenues - total € pr. year						
	400.000 €	0 €	0 €	0 €	0	400.000 €
Contribution margin 1 - total €						
	65.000 €	0 €	0 €	0 €	0 €	65.000 €
Contribution margin 1 - € pr. ton						
	13 €	0 €	0 €	0 €	0 €	13 €

Appendix 4b: Base scenario (2)

The following analysis calculates the final profit for the base scenario assuming no costs relate to the concept as it is not implemented. Reflecting current market conditions.
The base scenario is used for calculating additional profit for the concept (see appendix 5).

Hardware costs:				***Notes:***
Machinery used:				
Tractors:	0 units			[8]
Balers:	0 units			[9]
Hardware:				
Hardware lifetime:	6 years	0 months		
Antennas	0 units	0 €/unit	0 €	[10]
TCU	0 units	0 €/unit	0 €	[11]
Total:			0 €	
Hardware installation costs:				
Hourly wage:		0 € pr. hour		[12]
Installation costs [Antenna]		0 Hours	0 €	
Installation costs [TCU]		0 Hours	0 €	
Total			0 €	
Loan conditions:				
Loan:			0 €	
Net interest rate:			0%	
Monthly payback			0 €	
Interest rate cost:			0 €	
Payback period		0,0 years	0 months	
Loan free period:		0,0 years	0 months	
License cost:				
License costs pr. year:			0 €	
License costs - total			0 €	
Total cost:				
Total costs:			0 €	
Contribution margin 2 [profit]				
Total:		**Pr. ton:**		
Profit	**390.000 €**	**13 €/ton**		

Appendix 5: Additional profit

The following analysis calculates the additional total profit generated by implementing the conc
compared to the total profit generated under current market conditions (see appendix 4a).

Base scenario					
Contribution margin 2 [profit]					
Profit	390.000 €				
Best-case scenario					
Contribution margin 2 [profit]		**Additional profit [*compared to base scenario]**			
BHC 1	587.711 €	**BHC 1**	**197.711**	**€**	**6,6 €/ton**
BHC 2	677.711 €	**BHC 2**	**287.711**	**€**	**9,6 €/ton**
BHC 3	767.711 €	**BHC 3**	**377.711**	**€**	**12,6 €/ton**
BHC 4	827.711 €	**BHC 4**	**437.711**	**€**	**14,6 €/ton**
BHC 5	917.711 €	**BHC 5**	**527.711**	**€**	**17,6 €/ton**
Worst-case scenario					
Contribution margin 2 [profit]		**Additional profit [*compared to base scenario]**			
BHC 1	506.121 €	**BHC 1**	**116.121**	**€**	**3,9 €/ton**
BHC 2	596.121 €	**BHC 2**	**206.121**	**€**	**6,9 €/ton**
BHC 3	686.121 €	**BHC 3**	**296.121**	**€**	**9,9 €/ton**
BHC 4	746.121 €	**BHC 4**	**356.121**	**€**	**11,9 €/ton**
BHC 5	836.121 €	**BHC 5**	**446.121**	**€**	**14,9 €/ton**

Bibliography

- Pelletier, J. (2013). *From Ancient to Modern Logistics: Evidence in Ancient Egypt & the Early Development of Marketing.* College of Business, University of South Florida, Tampa, Florida, USA.

- Snow, J. (2017). The *Supply Chain Manager's Handbook, A Practical Guide to the Management of Health Commodities.* Arlington, Va.: John Snow, Inc.

- Andres Villa-Henriksen, Gareth T.C. Edwards, Liisa A. Pesonen, Ole Green, Claus Aage Grøn Sørensen (2020). *Internet of Things in arable farming: Implementation, applications, challenges and potential*. Aarhus University, Department of Engineering, Denmark. Agro Intelligence, Denmark. Natural Resources Institute Finland (LUKE), Finland. Aarhus University, Department of Agroecology, Denmark.

- GS1. (2021). *Regulatory status for using RFID in the EPC Gen2 (860 to 960 MHz) band of the UHF spectrum.*

STRAW FROM CEREAL AS CO-PRODUCT FOR CONSTRUCTION MATERIALS AND ACTIVATED CARBON IN MECKLENBURG-VORPOMMERN

Pre-Feasibility-Study: Straw from Cereals as Co-Product for Construction materials and Activated Carbon in Mecklenburg-Vorpommern (MV)

Introduction

Properties of straw

Straw is an agricultural by-product consisting of the dry stalks of cereal plants after the grain and chaff have been removed. The threshed ears of grain usually remain on the stalk and are also part of the straw. Straw makes up about half of the yield of cereal crops.[1]

Straw utilization

Cereals are cultivated in MV on an area of 556,400 ha.[2] MV is, therefore, the most significant production land in East-Germany.[3] After cultivation, the cereals are harvested, which means cutting and mechanized separation of grains and straw. The grains are further processed: The central part is milled and the flour obtained is either marketed directly or further processed in the food industry.

Crop straw is a valuable by-product in the cultivation of cereals. It accumulates in large quantities and its production does not require additional land to that already taken up by cereals. During the classic grain harvest, the main part of the straw is left in the field for fertilization of the soil. A small part is used as bedding for livestock.

Since only harvesting costs and the nutrient replacement of the soil have to be taken into account when the straw is used, its utilization is potentially attractive from an economic perspective. The innovative potential lies in the better use of the by-product straw as a raw material or as fuel (see Fig. 1).

For this purpose, additional processing steps must be extended: The operating steps straw baling, loading, transport, unloading, and storage were previously only necessary for use as bedding. The effort was low and the transport of the straw bales could even be almost completely ignored, since it was mostly only necessary within the own agricultural enterprise. In total, an expansion of the processing steps (if additional straw from the field is to be processed) leads to a considerably increased amount of work and time.

[1] https://en.wikipedia.org/wiki/Straw
[2] Destatis (2019): Statistical annual 2019: Agricultural holdings and utilized agricultural area by crop
[3] BioBIGG (2019): Prade, T., Andrzejczyk, R., M. Booker Nielsen, B. Cuypers, P. Dąbrowski, A. Ekman Nilsson, T. Kjær, J. Lund, D. Mikielewicz, M. Mittenzwei, D. Schiller, J. Wajs and M. Westkämper Biomass and innovation potential of residues, by-products and other sustainable feedstock for biobased products in four South Baltic Area regions, Interreg project Bioeconomy in the South Baltic Area: Biomass- based Innovation and Green Growth - BioBIGG

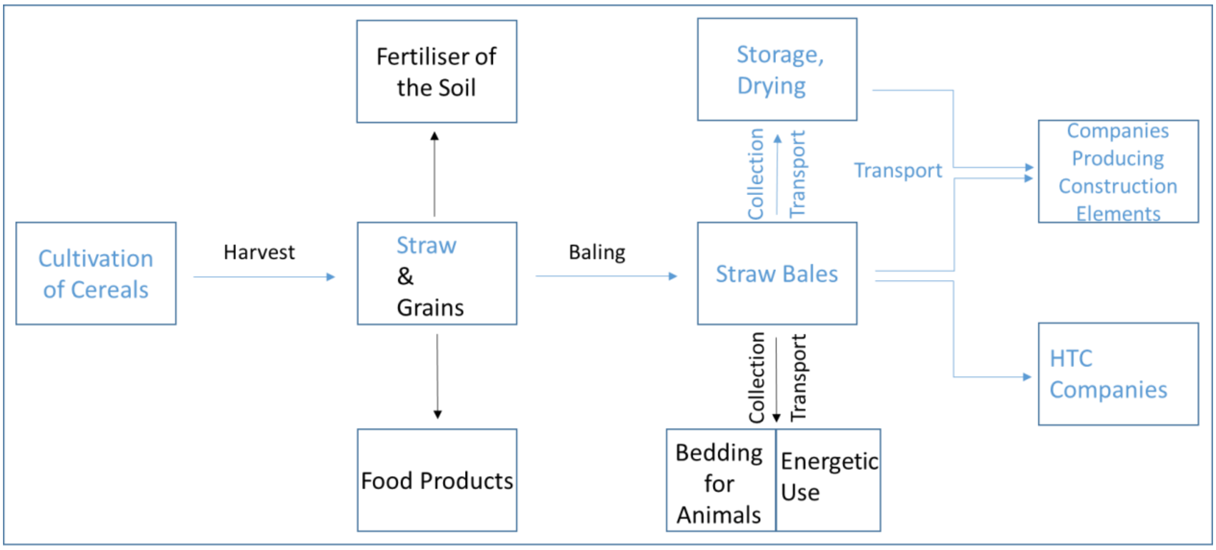


Fig. 1: Value chain of cereals (blue: new use of straw)

For material recycling, straw can be used as reinforcement or structural element in plasters and panels or insulation. It is also possible to expose straw to high temperatures and pressures to produce HTC (**H**ydro**T**hermal **C**arbonization) coal. These HTC carbons can be used as fuel or replace conventional wood-based activated carbons that are used to clean process fluids and gases[4].

Staw processing[5]

Straw bale formats:

In agriculture, straw is pressed into round or square bales to facilitate transport, storage, and further use. Straw bales are made using rectangular bales from agriculture. These are either produced on the field during harvesting or pressed at a later date. Dimensions up to a cross-section of 40 cm by 50 cm are considered small bales, and larger are considered large bales.

Straw bales can be used directly as structural elements in buildings. In many straw-bale construction methods, a wooden compartmentalized frame is erected and the compartments are then filled with straw bales. The precise dimensions of the compartments are determined based on the bale size used, so that the straw bales can be installed tightly and without gaps. To date, the most common construction methods use small bales with a width of approx. 48 cm and a height of approx. 36 cm depending on the type of baler. With balers, the width and height cannot usually be adjusted, but the length of the bale can be adjusted to a limited extent. Big bales are more efficient to install, but usually require the use of machinery and are a more material-intensive design.

Storage and transport of straw:

Straw must be transported and then stored in a dry place. It may only have short-term soil contact and must be protected from the rain. When stored under foils, these must be permanently rainproof as well as absorb UV radiation and any other stress. No condensate should drip onto the straw below the cover.

[4] DBFZ-Website: https://www.dbfz.de/projektseiten/hydrothermale-prozesse-htp/anwendungen-produkte/htc-kohle/

[5] Strohbaurichtlinie SBR-2014; Fachverband Strohballenbau Deutschland e.V.; 2014

Biomass potential: Calculation of the utilizable biomass

Biomass potentials are assessed from different points of view. In particular, a distinction is made between the theoretical potential and the technical-ecological potential[6]. The theoretical potential describes the biomass offered in principle, independent of technical or organizational obstacles, and indicates the maximum available biomass. The technical-ecological potential is the part of the theoretical potential that can be used under ecological and technical restrictions such as the mobilization of biomass, technical options for use, and ecological restrictions such as maintaining closed nutrient cycles or the protection of habitats.

Tab. 3: Biomass Residue Potentials in Germany[7] (FS = fresh substance, DS = dry substance)
*technical-ecological potential of the fresh substance is 15 million tons per year[8]

	Theoretical Potential		Technical-Ecological Potential		
	FS	DS		DS	Carbon
	[million t a^{-1}]		[%]	[million t a^{-1}]	
Agriculture	283.8	57.45	48	31.42	14.50
Cereal straw	*30.97*	*25.80*	*27*	*6.90**	*3.34*
Forestry	57.00	45.60	86	39.19	19.20
Food Industry	36.9	13.76	95	13.07	5.23
Municipality	48.7	43870	78	7.17	3.14
Sum	**426.40**	**126.01**		**90.85**	**42.07**

Table 3 shows that the highest potential of biomass residues lays in the agricultural sector. From 283.8 million tons of fresh biomass per year, nearly 31 million t (11%) can be generated from cereal straw; theoretically on an area of 6.2 million hectares in Germany. The technical-ecological potential is 6.9 million tons dry mass respectively 15 million tons fresh biomass in Germany. It takes into account the straw not harvestable (too short stalks; one third of the total amount) and the demand for animal husbandry (approximately 4.8 million t of the total fresh straw occurrence annually). The average cereal straw productivity per hectare is 4.8 t. [9,10]

In the region under consideration, straw could be harvested from almost 45,000 ha of cereal land and used for industrial purposes, without endangering the supply for animal-related use and the humus balance of arable soils. This amounts to about 15% of the region's cereal area.

[6] Umweltbundesamt (2016): Chancen und Risiken des Einsatzes von Biokohle und anderer „veränderter“ Biomasse als Bodenhilfsstoffe oder für die C-Sequestrierung in Böden, p. 48
[7] Adapted from Umweltbundesamt (2016): Chancen und Risiken des Einsatzes von Biokohle und anderer „veränderter“ Biomasse als Bodenhilfsstoffe oder für die C-Sequestrierung in Böden, p. 23 + 29
[8] Weiser, C. et al. (2014): Integrated assessment of sustainable cereal straw potential and different straw-based energy applications in Germany. In: Applied Energy Journal. 114
[9] Weiser, C. et al. (2014): Integrated assessment of sustainable cereal straw potential and different straw-based energy applications in Germany. In: Applied Energy Journal. 114
[10] BioBIGG (2019): Prade, T., Andrzejczyk, R., M. Booker Nielsen, B. Cuypers, P. Dąbrowski, A. Ekman Nilsson, T. Kjær, J. Lund, D. Mikielewicz, M. Mittenzwei, D. Schiller, J. Wajs and M. Westkämper Biomass and innovation potential of residues, by-products and other sustainable feedstock for biobased products in four South Baltic Area regions, Interreg project Bioeconomy in the South Baltic Area: Biomass- based Innovation and Green Growth - BioBIGG

If 5 tons are taken as a basis, the usable quantity is 216,000 tons of straw. The straw is usually offered in bales of 500 kg. Per ton (=2 bales) a price of about 70-80 € can be obtained at present, giving producers an annual turnover of around 16,2 million €.

Beyond the theoretical and technical straw potential, the sustainable straw potential also considers the humus balance of the soil as well as greenhouse gas emissions (Input of process energy and raw materials are mainly responsible for a significant amount of GHG emissions.).

To continue to use the grain areas without loss of biomass over the years, part of the straw must remain in the field so that the soil is not permanently deprived of nutrients. Only the remaining amount of straw that is not required for the safeguarding of animal husbandry and the maintaining of the soil fertility should be used for energy or material use. The evaluation of humus supply is based on the position of a VDLUFA (Verband deutscher landwirtschaftlicher Untersuchungs- und Forschungsanstalten; Association of German Agricultural Analytic and Research Institutes) working group[11].

The humus effectiveness of the carbon present in an organic material varies greatly. Low molecular carbon compounds are often subject to relatively rapid conversion and mineralization. The different types of fruit are very different in their behavior as humus eaters or multiplier. A change in the fruit type ratios also changes the potential of extractable straw mass in a region. For example, the expansion of maize cultivation is associated with a disproportionate reduction of the straw potential, as the maize as root crop is a significant humus eater. This variation in humus effectiveness in the biomass leads to significant fluctuations in the calculations.

Between 7.97 and 13.25 million t of straw can be classified as sustainable straw in Germany. MV is a federal state with a high amount of sustainable straw potential (see Tab.4).

Tab. 4: Sustainable straw potential in the federal states in Germany (teragramm a^{-1} = million t a^{-1})[12]

Federal states	Theoretical potential	Technical potential
Schleswig-Holstein	1908	1004
Hamburg	13	4
Lower-Saxony	4649	2392
Bremen	4	1
North Rhine Westphalia	3014	1611
Hesse	1508	741
Rhineland-Palatinate	990	464
Baden-Wuerttemberg	2116	887
Bavaria	4707	1890
Saarland	96	35
Berlin	3	1
Brandenburg	1807	844
Mecklenburg-Western Pomerania	2839	1575
Saxony	1701	900
Saxony-Anhalt	2689	1572
Thuringia	1787	978
Germany	29,832	14,897

[11] Verband Deutscher Landwirtschaftlicher Untersuchungs-und Forschungsanstalten (2014): Humusbilanzierung - Eine Methode zur Analyse und Bewertung der Humusversorgung von Ackerland

[12] Adapted from Weiser, C. et al. (2014): Integrated assessment of sustainable cereal straw potential and different straw-based energy applications in Germany. In: Applied Energy Journal. 114, page 758

Calculation of the straw price

Cereal harvesting is integrated into the company's land management, so this would not cause any special requirements or produce costs until then. Only the expansion of the additional processing steps (baling, loading, transport, unloading, and storage), must be taken into account when calculating the straw price.

Tab. 1: Costs for straw production[13]

	€/t straw		
	from	to	Practice operation
Pressing, loading, transport	22	58	38
Storage	4	24	6
Sum I	**26**	**82**	**44**
Nutrient removal	16	24	20
Sum II	**42**	**106**	**64**

In table 1, the cost of straw production is calculated without (Sum I) and with (Sum II) consideration of nutrient loss. However, it should be noted that with the removal of the by-product cereal straw, potential humus replacement is removed in that area. Taking this into account, the total straw costs are between 42 and 106€/t, depending on the utilization of the straw processing technology.

In MV, the market prices per ton of straw have fluctuated between just under 50 € and almost 140 € since 2009. On average, straw costs around 75€/t. The price for the big bale of straw was 81.19 €/t for July 2016 and 104.54 €/t for June 2019. In MV in 2016, the producer prices for big bales are 100 Euro per ton.[14] Overall, it is clear that the sale of straw is generally economically viable. Only under very unfavorable conditions (high processing costs, low market price), no profit can be achieved.

Straw for construction materials

There are many favorable properties which promote straw as an excellent insulation alternative (see Tab. 2).

The straw of the domestic cereals wheat, rye, spelt, triticale (breeders cross between wheat and rye), and barley can all be used for construction purposes. Whilst wheat and rye appear particularly suitable, oat straw is considered unsuitable for use in construction.[15]

[13] Adapted from FNR (2015): Heizen mit Stroh - Wertschöpfung für Landwirtschaft und Kommunen
[14] https://markt.agrarheute.com/futtermittel-3/stroh-19, 07.10.2020
[15] Fachverband Strohballenbau Deutschland e.V.; Strohbaurichtlinie SBR-2014; 2014

Tab. 2: Evaluation of the characteristics/features of straw with regard to insulation[16]

characteristic/feature	**effect in practice**	**disadvantage**
good vapour diffusion properties	regulates indoor humidity	
good insulating properties	protection against heat and cold	high insulation thickness required (at least 28 cm)
good sound insulation	lowers the noise level	
natural condition	harmless processing; disposal without difficulty; CO_2-fixation	
very good environmental balance		
long lifetime with adequate protection	sustainable	protection against weather and moisture necessary
regional availability	short transportation routes	
low price		
normal degree of inflammabilty	fire protection class B2	

Building with straw contains however also some disadvantages:

- In case of fire the house often suffers a total loss.
- Wood and straw bale houses are classified with the real estate evaluation as less valuable compared with massif houses.
- Straw is not suitable as core insulation of masonry.
- In terms of licensing law, it is almost impossible to build load-bearing with straw in Germany. Using straw as infilling constructions is legally possible.
- Clay plastered walls are sensitive to mechanical damage.
- There is an increased risk of fire in the production phase, when loose straw occurs.
- Experts for planning and execution are not yet available throughout the country.
- The logistics of the straw supply is connected with higher communication expenditure than with other building materials.

Straw bales can either be used directly in a wooden wall construction or further processed for manufacturing panels. These panels can then be incorporated into furniture or house walls.

Insulating materials must be recognized as building products following state building regulations as they perform essential tasks of a building component. In the sense of the state building regulations, straw is an unregulated building product, as there are no recognized rules of technology for it. Straw is either, like many other thermal insulation materials, marked with specific properties following general building approval, with Ü[17] or CE[18] mark and used in accordance with the scope of this

[16] https://www.energieheld.de/daemmung/daemmstoffe/stroh
[17] Ü: Usability of a building product in Germany
[18]CE: Products that can be freely traded in the European Union (EU)

approval, or the use of straw is approved with the corresponding justifications by approval in individual cases.

Straw in buildings

Loose straw is known for its ability to bind clay and concrete. A mixture of clay and straw, known as cob, can be used directly as a building material. Germany is famous for its old half-timbered houses.

Straw can be used not only as a binding material, but also directly as a basic element in buildings. For this purpose, the pressed bales of straw are usually fitted into a timber frame. In this case, the straw serves as an infilling construction und insulating material, whereas the timber frame bears the pressure load. The walls are then plastered or cladded. Another possibility of insulating with straw is blow-in straw, which can be used like cellulose: Via a long tube, specially prepared ISO straw fibers are blown through a nozzle into the respective component using air and then compressed.[19]

When baled, straw has moderate insulation characteristics. Physically, the thermal conductivity in the direction of the stalks is higher, which results in a worse thermal insulation value when the heat flow is in this direction. For this reason, bales of straw are usually used standing upright or standing flat. For Germany the rated value of thermal conductivity to be used for calculations is: $\lambda = 0.049 W/(m \cdot K)$ according to ETA-17/0247 Construction Straw.[20]

Although Germany has a professional association for straw bale construction with 160 members (some of them are craftsmen)[21], there are no special companies dealing with this kind of technique in MV. There are carpenters, engineers or architects who have experience with straw bale houses and can assist in building.[22] Although building with straw has a long tradition, it is still an innovation in Germany. The method is in the early phase of market introduction and has so far been used by few innovative building owners.[23]

Market[24]

Building with straw requires special knowledge and skills of the craftsmen. Mainly hand tools are used, so that larger investments by the carpentry companies are not necessary. The mostly small businesses can normally only build one or two houses per year. Therefore, larger timber construction companies are needed for an effective market introduction of straw-insulated buildings. Since there has been a great demand for construction services for a longer period of time, there is not much interest in new innovations on the part of craftsmen's companies. This will only change if the environmental impact of construction would be assessed and incentives (support programs) would be created accordingly.

The demand for straw bale houses in Germany is currently very low: in 2017 one out of 2,381 residential buildings was built as a straw bale house. The price of conventional compared with straw bale houses is similar. But the latter ones are met with more (wrong) skepticism, especially because of durability, sensitivity against moisture as well as animal and mould infestation.

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[19] Technischer Folder ISO-Stroh (https://www.isostroh.com)
[20] Fachverband Strohballenhaus Deutschland (2019): STROHBAURICHTLINIE SBR-2019
[21] https://fasba.de/
[22] Rex, M. / Stroase; personal communication (2020)
[23] Kaesberg, W., Kaesberg, B.; Interreg North-West Europe Up Straw (2019): Marktstudie zur Durchdringung des Deutschen Baumarktes mit strohgedämmten Gebäuden
[24] Kaesberg, W., Kaesberg, B.; Interreg North-West Europe Up Straw (2019): Marktstudie zur Durchdringung des Deutschen Baumarktes mit strohgedämmten Gebäuden

Overall, both supply and demand are very low. However, since straw bale houses are a much more environmentally friendly alternative to traditional house building, an increase in attractiveness would be very desirable both for the companies involved and for the customers.

Environment

For production. straw-insulated buildings require only about half of the non-renewable primary energy (PENRT [kWh]) compared to conventional solid construction. The difference between the two construction methods in the field of the greenhouse potential is approx. 97 t CO_2 equivalent.[25]

Straw in construction elements

Straw panels are made from cereal straw without glue by pressing under high pressure and temperature. The only binding agent is straw lignin. The straw plates are then coated with paper cardboard on all sides. The boards are significantly thicker than plasterboard, but due to the high stiffness and a length of up to 3.20 m it is possible to create self-supporting walls without substructure.[26]

Currently, there are two plants in the project region processing straw. Both companies work closely together – one develops straw panels and other products, the other one produces construction material from the panels:

Strohlos Produktentwicklung GmbH[27] from Waren develops custom-made products from various straw types, fibers, and chaff. Size, density, structure, and texture are tailored and developed to the individual needs of the customer. The aim of product development is the replacement of petroleum-based and wood products with products made from fast-growing renewable raw materials - mostly annual plants.

The Strohplattenwerk Müritz GmbH then carries out the production of panels, construction elements and formed parts[28].

The use of straw as a construction material is already at TRL-level 9: The economic proof of the concept is already realized in a few companies, but there is a much higher capacity for processing straw. There are other companies in MV and the surrounding regions that are interested in or at least have the capacity to utilize straw as raw material.

One company, MRG Blauton Friedland[29], participated as a project partner in the "VIP - Vorpommern Initiative for Paludiculture"[30], led by the Botanical Institute at the University of Greifswald and undertook experiments with the incorporation of reed fibers in their product “Friedländer Blauton (blue tone)” in order to produce clay plasters. It has signaled interest in the processing of straw to expand their product range.

Other plants in the surroundings of the project region are Bioformtex[31], Hanffaser Uckermark eG[32] and Holzwerke Bullinger GmbH & Co. KG[33].

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25 Fachagentur Nachwachsende Rohstoffe e. V. (2017): Strohgedämmte Gebäude
26 https://www.oekologisch-bauen.info/news/trockenbau/trockenbauplatten-eine-uebersicht-160.html
27 http://www.strohlos.com/
28 http://www.strohplattenwerk-mueritz.de/
29 http://www.mrg-blautonwerk.de/
30 https://www.moorwissen.de/de/paludikultur/projekte/vip/index.php
31 https://bioformtex.de/
32 https://www.hanffaser.de/
33 https://www.bullinger.de/

The Holzwerke Bullinger GmbH & Co. KG from Werder near Neuruppin is one of the largest European manufacturers of glulam (glued-laminated) and structural timber with about 100 employees at the company's headquarters in Werder and a further 33 employees at Xaver Bullinger GmbH&Co.KG in Abtsgmünd (Baden-Württemberg). Currently, Bullinger only uses wood. There are plans to build a site for the processing of bulrushes (*Typha*) in Vorpommern to process *Typha* for oriented strand boards (OSB panels). Bullinger Holzwerke would, therefore, also be able to process straw for construction and insulation.

Straw for activated carbon

Hydrothermal carbonization (HTC) is a chemical process for the conversion of organic compounds to structured carbons with hot and pressurized water. Beneath gaseous and liquid products, also solid char can be produced, depending on temperature and pressure during processing.[34,35] (see Fig. 2). Feedstock can be wet biomass, including straw: Since HTC is carried out in an aqueous medium, the biomass with high water content especially suitable for the procedure[36]. The product can be used to manufacture a wide variety of products, like nanostructured carbons, carbon catalysts, brown coal substitutes, liquid biofuels, soil conditioners, carbon material for liquid contaminant adsorption, synthesis gas, and humus from biomass with the release of energy[37,38].

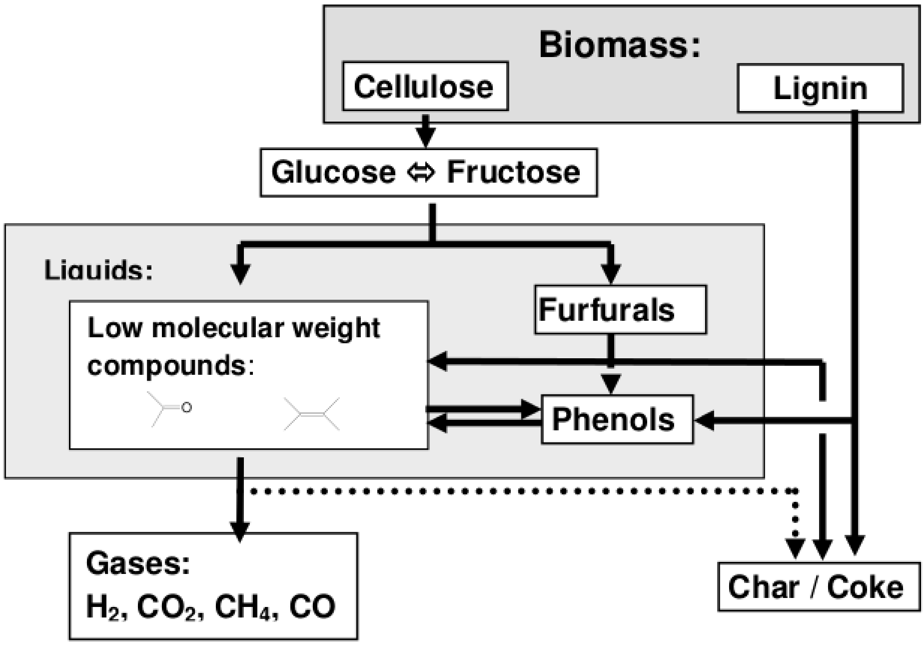

Fig. 2: Simplified reaction sequence of HTC[39]

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[34] Sharma, R. et al. (2020): A Comprehensive Review on Hydrothermal Carbonization of Biomass and its Applications; Chemistry Africa 3, 1-19

[35] Houkmann, S.K. et al. (2011): Hydrothermal Carbonization (HTC) of Lignocellulosic Biomass; Energy Fuels 25, 1802–1810

[36] Buttmann, M. (2011): Klimafreundliche Kohle durch Hydrothermale Karbonisierung von Biomasse; Chemie Ingenieur Technik 83, No. 11, 1890–1896

[37] https://en.wikipedia.org/wiki/Hydrothermal_carbonization

[38] Reza, M.T. (2015): Hydrothermal carbonization (HTC) of wheat straw: Influence of feedwater pH prepared by acetic acid and potassium hydroxide; Bioresource Technology 182, 336–344

[39] Kruse, A., Funke, A., Titirici, M. M. (2013): Hydrothermal conversion of biomass to fuels and energetic materials. Current Opinion in Chemical Biology, 17 (3), 515-521

From a technical perspective, hydrothermal processes are considered for large-scale applications as matured (TRL level 9). Plants with similar technical requirements were designed with a production capacity of several million tons per year at the beginning of the 20th century for the hydrothermal drying of lignite[40] and treatment of peat[41]. It is questionable, however, whether such plants can be economically viable under the current and future framework conditions.[42]

Motivation

To achieve the climate protection goals of the Paris Agreement by reducing the greenhouse gas emissions by 1,5-2° C, the CO_2 emission rate must be drastically reduced in the next few years. This requires different solutions in a variety of fields.

Hydrothermal carbonization of biomass is one solution. [43] One advantage of the method is the effectiveness in the use of biomass, because each part of the plant material can be used. No waste is generated and so the fixed CO_2 remains in the product instead of being released into the atmosphere. If for instance biodiesel is produced from oil plants, only the energy contained in the fruit can be used. Processing the entire plant for fuel production can increase the energy yield by a factor of three to five with the same cultivation area[44]. Hydrothermal carbonization makes it possible to use almost all of the carbon contained in the biomass for fuel generation.

Opportunities and risks[45]

The process, which technically imitates the brown coal formation (German "Inkohlung" - "to coal process") taking place in nature within 50,000 to 50 million years within a few hours, was investigated by Friedrich Bergius and first described in 1913[46]. Besides the short duration of the process, the thermochemical treatment has further advantages: The carbon from the straw is stabilized in the biochar. Carbon dioxide losses can thus be reduced. Since the central part of the carbon remains trapped in the biochar, greenhouse gas emissions could be reduced considerably (see also chapter “motivation”). The high process temperatures of thermochemical conversion can also destroy pathogens and potential organic pollutants. For energetic use of biomass, usually complex drying steps of the biomass are necessary. This drying steps are not necessary with the HTC method, since wet starting materials can also be used. Furthermore, due to the substantial reduction of mass through carbonization, the transport of organic carbon in the form of biochar over long distances becomes more economical than the transport of the original biomass.

However, the thermochemical treatment of biomass can also pose considerable risks. A redirection of organic material flows away from humus reproduction in soils would be a potential risk. This could be the case if large amounts of straw are removed from a particular area to produce biochar, but the

[40] Fohl, J., Lugscheider, W., Wallner, F. (1987): Entfernen von Wasser aus der Braunkohle – Teil 2 – Thermische Entwässerungsverfahren. Braunkohle, 39 (4), 78-87

[41] Mensinger, M. C. (1980): Wet carbonization of peat: state-of-the-art review. Peat as an Energy Alternative: Symposium Proceedings Chicago, Ill. IGT, 249-280

[42] Umweltbundesamt (2016): Chancen und Risiken des Einsatzes von Biokohle und anderer „veränderter“ Biomasse als Bodenhilfsstoffe oder für die C-Sequestrierung in Böden

[43] Titirici, M.-M., Thomas, A. Antonietti, M.: Back in the black: hydrothermal carbonization of plant material as an efficient chemical process to treat the CO_2 problem?; New Journal of Chemistry 6; 2007

[44] https://en.wikipedia.org/wiki/Hydrothermal_carbonization

[45] Umweltbundesamt (2016): Chancen und Risiken des Einsatzes von Biokohle und anderer „veränderter“ Biomasse als Bodenhilfsstoffe oder für die C-Sequestrierung in Böden

[46] Friedrich Carl Rudolf Bergius: Anwendung hoher Drucke bei chemischen Vorgängen und die Nachbildung des Entstehungsprozesses der Steinkohle. W. Knapp, Halle a.S. 1913

missing organic material at this point is not compensated by the introduction of biochar or other organic material. To date, the HTC process has not yet been fully developed. Differences in the starting material, the reaction time, but also different pressures and temperatures lead to a different product composition. Further risks are associated with the concentration of the harmful substances of the straw in the biochar - the long-term effects in the soil have not yet been clarified.

Appropriate process management and problems in the collection, transportation, and storage of accumulated biomass are still unresolved. These processes also require energy, which should be less than is released by hydrothermal carbonization.

Profitability[47]

Besides the abovementioned costs of the processed raw material (on average, around 75€/t), costs of processing biomass to biochar, output costs, and, if applicable, disposal costs for by-products determine the final price of the biochar.

Transport costs are often decisive for the economic profitability of the use of biochar.[48] The transport costs depend on the available biomass and the conversion company (the more extensive the conversion company, the further it has to go to deliver the raw materials). Eberhard et al[49] calculated, based on an industrial plant for the production of HTC coal from biomass with a plant capacity of 45,000 tons of fresh mass per year, transport costs of the biomass amounting from 360,000 to 470,000 €, which corresponds to costs of 8 to 11 € per ton of fresh mass. For the transport of the resulting 22,950 tons of HTC coal to the destination 50 km away, the authors estimate 267,375 €, which is 11.65 € per ton of HTC coal (6 € purchased for one ton of dry raw material).

The production costs vary considerably depending on the production process. The abovementioned author[50] estimates that the costs of an HTC system depend on the plant size taking into account investment-dependent costs, personnel costs, and energy costs calculated. With an annual processing capacity of 45,000 tons of fresh mass, it is 0.14 € kg^{-1} HTC coal (26.50 € t^{-1} raw material).

Market[51]

There is a high demand for HTC coal. It can be used in energetic as well as material use in numerous applications

- Improvement of soil functions (e.g. nutrient and water balance, soil reaction, sorption of contaminants, productivity)
- Energy
- Production of nanomaterials (e.g. for medical purposes)

[47] Umweltbundesamt (2016): Chancen und Risiken des Einsatzes von Biokohle und anderer „veränderter“ Biomasse als Bodenhilfsstoffe oder für die C-Sequestrierung in Böden

[48] Roberts, K.G. et al. (2010): Life Cycle Assessment of Biochar Systems: Estimating the Energetic, Economic, and Climate Change Potential. Environmental Science & Technology, 44 (2), 827-833

[49] Eberhard, G. (2011): Rentabilität der Hydrothermalen Karbonisierung unter besonderer Berücksichtigung von Transportkosten. Berichte über Landwirtschaft - Zeitschrift für Agrarpolitik und Landwirtschaft, 89, 400-425

[50] Eberhard, G. (2011): Rentabilität der Hydrothermalen Karbonisierung unter besonderer Berücksichtigung von Transportkosten. Berichte über Landwirtschaft - Zeitschrift für Agrarpolitik und Landwirtschaft, 89, 400-425

[51]Umweltbundesamt (2016): Chancen und Risiken des Einsatzes von Biokohle und anderer „veränderter“ Biomasse als Bodenhilfsstoffe oder für die C-Sequestrierung in Böden; Umweltforschungsplan des Bundesministeriums für Umwelt, Naturschutz, Bau und Reaktorsicherheit; 2016

- catalytic converters (e.g. for the chemical industry)
- component in batteries and fuel cells
- component of electrochemical capacitors
- raw material for the production of carbon fibers and plastics
- cosmetics (soap, skin cream, therapeutic bath additive)
- dyestuffs (food dyestuffs, industrial dyestuffs)
- textiles (fabric additive and thermal insulation for functional underwear)
- plant protection
- pelleting of seeds
- binders for dry toilet
- insulation material and wall coating for house construction
- production of synthetic gas for power generation in combined heat and power plants (CHP plants, for the production of biomethane for feeding into the natural gas grid, for the production of bio-gasoline and as a raw material for solid fuel cells.[52]

Looking at the 550 biogas plants in MV, it becomes apparent that they have biochar filters to clean the gases produced and are thus an exciting target group as customers for bio-coal.

Current application intentions

In Relzow near Anklam (MV), the hydrothermal carbonization plant AVA Green Chemistry Development GmbH[53] (now: HTCycle[54]) started operation in November 2017 ("Innovation Park Vorpommern"). According to the company, the HTC plant in Relzow represents a "new stage in the field of hydrothermal carbonization[55]. AVA is also the first company in the world to establish an HTC plant on an industrial level in 2010.

GreenCarbon GmbH[56] (Uelitz, Mecklenburg-Western Pomerania) has built one of the most innovative pyrolysis plants to produce vegetable coal in Uelitz, approx. 15 km south of Schwerin (MV). On 15,000 square meters, approx. fifteen thousand tons of biomass of most different kinds and origin are processed to 3,000 tons of carbon. GreenCarbon develops and produces organic coal of various qualities. The focus here is on producing biochar for the agricultural sector and the manufacture of technical coals for industrial applications. Also, charcoal is produced for the barbecue coal and activated carbon industry.

Conclusion and Summary

MV is equipped with a big area of arable land, and much cereal is produced. It makes sense to enlarge the value chain of straw for material use rather than leaving the straw on the fields. There are many possibilities to process the raw product into different high-value final products. All in this report described straw processing procedures are possible and already realized in a few companies. **The challenge is not to find new applications for the straw, not to calculate the net return (there are already success stories), but to encourage more companies to change their concepts: If more companies include straw products in their product portfolio and process the straw in the described way, almost all available straw, which can be used sustainably, might be processed.** The companies

[52] http://www.bv-htc.de/was_ist_htc.php
[53] http://duene-greifswald.de/doc/rrr2013/talks/HTC.pdf
[54] https://htcycle.ag
[55] Jeitz, P.; Deiss, O.: Neue Wege in der Klärschlammaufbereitung; Aqua & Gas 4, 42-45; 2012
[56] http://www.greencarbon-gmbh.de

can implement the new concept by contracting additional straw suppliers and by expanding and optimizing their production chain with straw as (additional) starting material. By expanding their product portfolio, the customer pool can also be expanded. Increasing the market for straw bales will also increase the incentive for farmers to process the straw into bales and sell them.

For further implementation of the new utilization into the manufacturing process, the following steps have to be initiated:

- convincing the farmers to harvest the unused straw instead of leaving it on the fields
- bringing farmers together for collaboration and sharing expensive machines (e.g. straw press)
- finding regional purchaser (convincing CEO's of wood or plastic processing plants to use straw as sustainable raw material)
- finding companies that manufacture construction material and are interested in materials from straw
- finding plants that manufacture activated carbon and convince them to use straw as raw material
- looking for solutions for the high transportation costs of straw (e.g. founding of small regional subcontractors for the first processing procedures)
- make contact chains: farmer to producer of construction raw material to processor of construction raw material to consumer
- research on standardized quality: Cereal straw has annual and seasonal changes in the chemical composition. It must be possible on the one hand to reduce the differences of straw composition and on the other hand manage a variable material with standardized processes and products.

Forestry and biomass-related sectors

MATERIAL USE OF ALNUS GLUTINOSA FROM PALUDICULTURE AS CONSTRUCTION MATERIAL IN MECKLENBURG VORPOMMERN

COLOURBOX44507557

Pre-Feasibility-Study: Material use of *Alnus glutinosa* from Paludiculture as Construction Material in Mecklenburg Vorpommern (MV)

Germany is a wood importing country and the demand for wood in MV can by far not be covered. The increase in processing capacities from 350,000 m³ (1998) to now 3.6 million m³ has led to the fact that the state's forest holdings cannot supply the trees even if the utilisation potential is fully exploited. In addition, due to the development of various sub-markets for classic timber assortments, an estimated 30% of the felling of the total forest is not processed in MV (supply to neighbouring federal states as well as export abroad). Thus, it can be assumed that in the future trunk and industrial timber processing will continue to be dependent on imports, not only in MV.

Most of the raw wood used for material purposes (76 percent) is processed in sawmills. The residue is almost completely recycled by the wood-based material and cell/ wood pulp industry. In addition, there is an intensive cross-linking of the raw and residual material flows of the different economic sectors. For example, a large part of the sawmill by-products is further processed in the wood-based panel and pulp industry. Overall, numerous residual materials and by-products are energetically utilized (especially the low value timber waste from thinning), which means that the proportion of wood used for energy purposes is a good 50 percent.

But how can we deal with the situation that the wood market makes a non-sustainable import of wood necessary? One possible answer is to strengthen local wood capacity by harvesting and marketing of alder from wet peatlands. It would increase capacity utilization in the wood industry and partly reduce the import of wood.

Mecklenburg-Western Pomerania (or Vorpommern) is a predestinated region for this purpose. The Northeast-German part of Pomerania, is stretching from the Recknitz River to the Oder/Odra Delta. The region is rich in peatlands as well as fens[1]. Fens cover an area of about 820,000 ha in Northern Germany alone. 300,000 ha of which are in Mecklenburg-Western Pomerania[2].

Cultivation of biomass (in the current case wood) on wet and rewetted peatlands, defined as paludiculture, conserves the peat soil and minimizes drainage, which has negative impact on the environment. It particularly reduces greenhouse gas emissions from drained peat soils, contributes to the conservation of rare species and habitats and additionally, it can serve as a raw product for the production of sustainable construction material.

At the moment, biomass from peatlands is hardly processed as construction material. Reasons are:

- Usage of traditional material is already implemented in the processing process in agricultural companies
- Accessibility for seeding and harvesting peatland plants are complex and expensive
- Other machines might be necessary
- Good knowledge of the plant properties during growing and their physical properties are necessary
- Biotope protection laws

[1] Peatland– bogs are also called rainwater fed peatland because they are fed solely with rain water as well as fens, which are always in contact with the mineral groundwater and dependent on the surface inflow from the surrounding landscape.
[2] http://www.wrrl-info.de/docs/wrrl_steckbrief_alnus.pdf

Material use of biomass from paludiculture[3]

Biomass from paludiculture is suitable for a wide variety of material use. Due to conditioning the properties of the biomass can be changed in a targeted manner and can be provided as a raw material for a broad product range. We speak of material recycling when the use of the raw material properties is the purpose. Compared to the energetic use or the use in animal-bound processes (e.g. animal feeding or pasturing), the material recycling of biomass from paludiculture can achieve higher added value by elongation of the value chain: High value wood can be processed to high value products (e.g. furniture), after use converted to lower value products (e.g. insulating material) and at the end used for energy production.

There are many traditional recycling possibilities such as roof reed, paper, braiding material or innovative building materials. The recycling possibilities are determined by the specific properties of the raw materials. The quality depends on the water and nutrient supply, the management of the species composition and the genetic constitution of the plant populations.

Demands of peatland plants on soil

In order to get a maximum amount of biomass of cultivated plants on peatlands the water content in the soil and the right harvest time play a crucial role.

The water content of the soil differs from peatland to peatland and further, the plants have different requirements to the humidity of the soil.

According to the table below, peatland is characterized by water levels 2+ to 6+.

Water level	**long-term median of the water level under floor**
6+ lower eulitoral	Ww: +150 bis +10 cm; Ws: +140 bis +0 cm
5+ wet (upper eulitoral)	Ww: +10 bis -5 cm; Ws: +0 bis -10 cm
4+ semi-wet (very humid)	Ww: -5 bis -15 cm; Ws: -10 bis -20 cm
3+ humid	Ww: -15 bis -35 cm; Ws: -20 bis -45 cm
2+ moderately humid	Ww: -35 bis -70 cm; Ws: -45 bis -85 cm
2- moderately dry	WD: < 60 l/m²
3- dry	WD: 60 – 100 l/m²
4- very dry	WD: 100 – 140 l/m²
5- arid	WD: > 140 l/m²
Ww: long-term median of the water level in the wet season (winter) Ws: : long-term median water level in the dry season (summer) WD: water deficiency +: humid locations –: dry locations	

source: Couwenberg et al. 2008, modified[4]

[3] Wiedow, D.: Burgstaler,J.; Paludikultur – Bewirtschaffung nasser Moore Klimaschutz – Biodiversität – regionale Wertschöpfung; Wichtmann, W. et. al, Hrsg.; 2016

[4] Couwenberg, J. et. al: Endbericht – „Entwicklung von Grundsätzen für eine Bewertung von Niedermooren hinsichtlich ihrer Klimarelevanz"; 2008

In this report we highlight the use of *Alnus glutinosa*[5] wood for the use as valuable construction material.

Properties of *alder* tree


[6]

The alder stands in Mecklenburg-Western Pomerania on approx. 40,000 ha and is the second most common deciduous tree in the country (7% of the total forest). Usually, the trees grow on soil with a moderately humidity. In Mecklenburg-Western Pomerania 53% of the alder are growing on marshy or wet fens[7].

Therefore, the alder is very well adapted to wet soils. The lenticels at the stem base ensure a sufficient oxygen supply to the roots even when the groundwater level is high. The alder has a rather high nutrient requirement, but has the ability to improve the nitrogen supply in symbiosis with bacteria living at its roots. It provides the best growth performance on humid to moderately humid sites with a good nutrient supply. Satisfactory growth can still be expected under semi-wet conditions (4+ = water level 0-20 cm under floor). Sites with persistently very high groundwater levels (4+/5+) are no longer suitable for the economic cultivation of alder. The preferred range includes the water level "semi-wet" (4+). This corresponds largely to the forest moisture level "swampy". Long-lasting and high flooding is unfavorable for alder growth.

For using the biomass from alder as construction material a high-grade wood from high forest is recommended. 4-6 uses within 60-80 years with a total growth capacity of approx. 600-800 m³ per hectare can be calculated.

Properties of *the alder* wood[8]

There are many possible applications for strong alder wood, which makes the alder a very popular tree species. The wood is light and easy to harvest, knife and peel. Therefore, it's fully suitable for veneering. By pickling it, it can be refined and used to imitate tropical woods. It's particularly suitable

[5] *Alnus glutinosa* = alder. In the following report term „alder“ will be used.
[6] CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=449910
[7] Ministry of Agriculture, Environment and Consumer Protection MV: Grundlagen und Empfehlungen für eine nachhaltige Bewirtschaftung der Roterle in Mecklenburg-Vorppommern; 2012
[8] Barthelmes, A. et al.; Alnus-Leitfaden: Erlenaufforstung auf wiedervernässten Niedermooren; 2005

for imitating mahogany and ebony and can be used instead of cherry and walnut. With a worldwide increasing demand for raw wood and at the same time the need to decrease the harvest of tropical woods, promising marketing perspectives for alder woods are opening up. Due to its excellent durability under water, it's also used in hydraulic engineering.

However, the marketing opportunities are not only determined by the good technical properties. Similarly important is the continuity of supply. Only if timber customers can rely on a consistently high supply of timber, significant processing capacities can be established. The current niche product alder wood could be used more frequently in the future through the increased cultivation of the tree species.

Usage of machines for management of peatlands[9]

Wet peatland sites have special demands on management, especially with regard to passability. A soil-protecting, and thus permanent use of the peatlands is only possible with adapted technology, i.e. with low soil pressure, appropriate harvesting methods and the consideration of criteria of gentle logistics (e.g. avoidance of multiple traffic). If possible, conventional machines should be used, because this is the cheapest alternative. Wood therefore should be harvested preferably in winter, when the soil is frozen. But this is not a reliable option: In MV there are often winter season without ongoing frost periods, hence special technologies are necessary.

If it is possible to drive over the area, a combined working method with horses and a light caterpillar tractor could be used after motor-manual logging. The wood advanced by horse can then be picked up by the caterpillar forwarder using a load crane and moved further. If there is no possibility of trafficability, the cable crane technology proven in mountainous areas is an ideal solution.

Rope-crane technology[10]

mobile rope-crane of type VALENTINI V 1000

Environmentally-friendly production of alder value wood on rewetted peatland sites can be done with soil-preserving wood return process by means of rope crane on non-trafficable wet sites. The

[9] https://www.moorwissen.de/de/paludikultur/hintergrund/moorstandorte/niedermoor.php
[10] Röhe, P. &J. Schröder (2010): Grundlagen und Empfehlungen für eine nachhaltige Bewirtschaftung der Roterle in Mecklenburg-Vor-pommern, Schwerin, p. 49

proven rope crane technology proved to be suitable and very soil-friendly. However, it's very cost-intensive.

The comparatively high process costs make a broader application of rope crane technology on wet sites difficult. The costs are on average at least three to five times higher than with conventional tractors on trafficable sites. Under the current economic conditions, timber harvesting costs would in many cases exceed revenues from the use of alder. This applies in particular to qualitatively unsatisfactory alder stocks with a low proportion of valuable wood and high industrial wood proportions. Only from average revenue of about € 50.00 per m³ across all assortments the complete cost recovery for the timber harvesting process presented here can be achieved under comparable site and structural conditions.

Preconditions for material use of *the alder tree* from paludiculture

DBU[11] Projekt „Alnus“[12]

Most of the following data are results of the project "Renaturierung von Niedermooren durch Schwarzerlenbestockung" ("Renaturation of fen by black alder stocking"). During the project period (2002-2005) a test area of 10 ha in the Trebeltal[13] was reforested. The growing plants were monitored constantly (generation of data for statistical analyses) and different working methods were tested.

Economy[14]

In the case of paludiculture the economic efficiency of a production method for agricultural businesses results from the revenues that can be generated and the attributable costs of production processes. In addition, the eligible direct payments and/or subsidies are relevant, too.

The economic efficiency of the absorption of biomass from wet peatlands depends in particular on two factors: the biomass yields that can be achieved and the power of the technology that can be used. On "drier" sites (e.g. water stage 4+) equipment of the conventional grassland management machinery can be used. Wet locations (water stage 5+/6+), on the other hand, require a special technology. If sufficiently large areas are cultivated, it's more likely that the costs are covered in a shorter period of time.

Expected revenues[15]

The economic success of alder farming depends to a large extent on the quality of the wood. High prices can only be achieved with high quality earth trunks (the lowest trunk sections). Revenues for weak wood assortments and trunk wood of poor quality, on the other hand, are low. In addition, there are higher costs for the difficult timber harvest on wet sites (see above and table below).

Alder infested with nuclear rot at an advanced age has a negative effect on quality. Especially old trees are susceptible for being infected with the pathogen *Phytophtora erythroseptica*. The pathogen infiltrates the roots if the soil conditions are too dry. In the advanced stage of infestation, the trunk wood is massively devalued. Therefore, the thinning strategy must be directed towards rapid growth

[11] DBU: Deutsche Bundesstiftung Umwelt
[12] https://www.dbu.de/ab/DBU-Abschlussbericht-AZ-19599.pdf
[13] 50 km east of Rostock, Germany.
[14] Kowatsch et.al (2008)
[15] Barthelmes, A. et al.; Alnus-Leitfaden: Erlenaufforstung auf wiedervernässten Niedermooren; 2005

of the tree thickness. The revenue framework is to be outlined on the basis of a simple model calculation. Only the revenues for the lower trunk piece of the valuable trees are taken into account. (assumption: 120 scm/ha in the closing stock). It becomes clear that the profit is strongly influenced by the quality shares. After deduction of the timber harvesting costs (overall 30 € per solid cubic meter), the average annual value performance can amount up to 300 EUR/ha in favorable cases. The rapid growth of the alder contributes significantly to this good result.

The aim should be to grow a high proportion of the best quality wood. The cutting maturity of the continuance should be reached within 60-70 years.

		Version 1: normal plant origin and silvicultural care, growing location			Version 2: good plant origin, best silvicultural care, very growing location		
wood assortments	€/scm	%	scm/ha	revenues/ha [€]	%	scm/ha	revenues/ha [€]
veneers	300	**10**	12	3.600	**50**	60	18.000
saw log	100	**70**	84	8.400	**40**	48	4.800
low quality, e.g. palette	40	**20**	24	960	**10**	12	400
total		100	120	**12.960**	100	120	**23.200**

scm: solid cubic meter

The conditions described above make it clear that the alder timber industry can only be successful on well-grown locations (version 2).

Remuneration for ecological services

An economically viable production of alder wood would be possible with the current timber prices and if the current instruments of promotion on good-growing locations are possible. However, the current grassland subsidy has the effect that the conventional forms of agricultural use, such as extensive green land use, is being held. From short-term economic calculations the introduction of an environmentally compatible form of use is made more difficult or will be even completely prevented. A higher incentive will only be created if additional ecological services (climate impact, species protection, etc.) will be honored.

In comparison with other climate protection measures, the CO_2 avoidance costs are very low. A reward for these ecological services must therefore be recommended from an economic point of view.

Impact of management on greenhouse gas emissions [16]

Drainage and agricultural use of peatlands lead to large losses of carbon and nitrogen[17]. These substances are released as carbon dioxide (CO_2) and nitrous oxide (N_2O). Carbon is also bound in the wood of the growing alder forest. This results in an additional temporary environmental relief of 3,000 to 8,000 kg $CO_{2\text{-eq}}$ per ha and year (in solid wood Ø >7cm)[18].

[16] Schröder, C. et. Al.: Schwarz-Erle (Alnus glutinosa) als Wertholzbaum; 2015
[17] Landeswaldprogramm Mecklenburg-Vorpommern (2016); Ein gesellschaftspolitischer Dialog zum Umgang mit dem Wald
[18] Schäfer, A. & Joosten, H. (Hrsg.) (2005): Erlenaufforstung auf wiedervernässten Niedermooren: ALNUS-Leitfaden. Institut für Dauerhaft Umweltgerechte Entwicklung der Naturräume der Erde (DUENE) e.V., Greifswald.), page 24

A fen management system with year-round water levels close to or equal to the field level (0-20 cm below ground level) ensures water saturation of the peat body, whereby oxygen-dependent decomposition processes and thus peat degradation are reduced. At the same time, the release of carbon dioxide and nitrous oxide is reduced. Under these conditions peat is largely preserved.

The creation of alder forests on rewetted peatland soils would result in an environmental relief of about 30,000 - 80,000 kg $CO_{2\text{-eq}}$ per year in total for the area in Brudersdorf.

Environmental release[19]

For peatland and climate protection, naturally wet peatland sites can be assessed as favorable. For the production of the value timber it is generally an unsuitable area.

But investigations have shown that even semi-wet sites with water-levels just below the floor have a slightly positive carbon balance of the soil or at least make it possible to preserve the peat body to a large extent. Good climate impact can be achieved if CO_2 storage in wood or even the replacement of fossil fuels (through additional energetic use) are taken into account. The afforestation associated with rewetting results in an increase of environmental relief. Afforestation of drier locations, on the other hand, does not relieve the environment, not even in comparison to the initial condition with drained fen grassland.

As a result, rewetted nutrient-rich peatland with semi-moist sites can be recommended as a preferred area for the environmentally compatible production of alder wood.

In addition, alder forests also contribute to habitat protection: they provide valuable habitats for endangered plant and animal species.

Market

There is a large variety of products that can be processed from wood: houses (walls, floors, ceilings), bridges, furniture, paper, toys, to name but a few.

After harvest, alder wood from peatlands can be processed according to wood from classical farmed trees. No special industry is needed. The wood is an add-on to the already established wood industry. It is possible either to enhance the wood processing (to generate more wooden products instead of plastic and other oil-based materials) or to replace tropical wood by alder wood by reduction of the import of tropical wood.

The price for high grade wood is varying depending of the demand of the customers. The demand of natural wood and their products in general can fluctuate and also the popularity of alder wood and their products in comparison to other wood species can vary. There is hardly any possibility to respond to the fluctuating market price because the median production time of high value wood is 60 years and therefore too long to extrapolate the present situation to the situation in 60 years. Nevertheless natural sustainable resources have a promising future and we are optimistic that also the following generations have a strong demand on high value wood.

The results of value wood auctions in recent years confirm the increased interest in alder. Thus veneer stems could be marketed predominantly at a high price level. For top qualities, revenues close to the level of high grade hardwoods in the range of 500 €/m³ up to more than 1,000 €/m³ were often achieved. In addition to proven valuable woods, saw timber of good to normal quality

[19] Schäfer, A., Schröder, J.; DBU Abschlussbericht zum Projekt „Renaturierung von Niedermooren durch Schwarzerlenbestockung; 2006

was also in high demand, primarily for solid wood furniture and interior fittings. The average revenues here were around 60 to 80 €/m³ for mixed assortments of quality classes B/C and in some cases well over 100€/m³ for pure B qualities.

POSSIBILITIES FOR AN INTEGRATED WOOD PELLET PRODUCTION

COLOURBOX9818068

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Project acronym BioBIGG

Work package Work package 5: Implementation of innovative agro-industrial value-chains and biomass-based production in SME's

Deliverable: Deliverable 5.2:Pre-feasibility and innovation programmes for innovative value chains

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Abbreviation

DEPI	Deutsches Pellet Institut (German Pellet Institut)
DEPV	Deutscher Energieholz- und Pellet-Verband (German Energy Wood and Pellet Association)
DESTATIS	Federal Statistical Office
EUWID	Europäischer Wirtschaftsdienst (European Economic Service)
TRL	Technology Readiness Level

1. Introduction

A sustainable lifestyle also includes sustainable consumption. This can be achieved if production, sales and consumption remain in the region. Hence, this study examines the different possibilities available to pellet manufacturers to produce and distribute their pellet products locally and regionally, and details the requirements necessary for a successful implementation. An autonomous pellet production as well as a vertically integrated pellet production into an already existing sawmill will be investigated. Furthermore, the study wants to provide information to sawmills about the integration of pellet production. Currently, there is very little information publicly available. The report aims to support the decision making progress for SMEs and by extension help to promote a regional bioeconomy. It is relevant to Mecklenburg West Pomerania (MV), as the sheer size of the Wismar Pellets company may already deter others from entering the market. Yet, as an integrated production process, this can be accomplished.

1.1 Wood Pellets

Wood pellets are a solid biofuel, which is made by compressing wooden particles under high pressure. Most commonly, they are made from sawdust, wooden shavings, and other chemically untreated side-products of wood-processing businesses and industries. While it is, mainly pressure and the wood's lignin that holds the pellets together, up to 2% of biological adhesives may be added. For this purpose maize starch or other starches are used. The diameter of these pellets ranges between 6 and 25 mm, while they may be up to 50 mm in length. Similar biofuels exceeding these measurements are classified as wooden briquettes (as specified by ISO 17225-3).
Internationally, wood pellets are defined and normed by ISO 17225-1 and ISO 17225-2. The latter introduces further specifications for non-industrial use, such as water-content, ash-content, mechanical strength, heating value, bulk density, and content of undesired elements (e.g.: nitrogen, sulphur, heavy metals, etc.). These requirements also serve as a quality standard.

The heating value of wood pellets is about 4.9 kWh/kg (LWF 2017). This means that 2 kg of wood pellets are on par with the heating value of about one litre of heating oil or 1.1 m3 of natural gas (ibid.). Around 3-5 tons of wooden pellets supply heat for one year in a modern family home (LWF 2017). Besides household consumption, wood pellets can also be used on a larger scale in biomass heating and electrical power plants.
In 2018, global wood pellet production continued its upward trend and grew to about 35 million tons (EPC 2018).[1] The four largest producers are in order: USA, Canada, Germany and Sweden (Thrän et al. 2017). Together they produce more than half of the global wood pellet output. Germany is responsible for about 7% of global production and accounts for about 6% of global consumption on its national market. At the same time, current production capacities in Germany would allow for an increase in production of 50% (EPC 2018; DEPI 2019; ITA 2016).

1.2 Limitations on Available Data

Sources of relevant market data on wood pellets are limited. Data on absolute prices, production, and consumption figures originate from the "Deutsches Pellet Institut" (DEPI). The DEPI is a research facility of the "Deutscher Energieholz- und Pellet-Verband" (DEPV). The DEPV mainly is an association of wood pellet producers, traders, and heating-system producers, but also smaller stakeholders, like barbecue producers. As all of the DEPI members have a direct interest in

[1] https://epc.bioenergyeurope.org/about-pellets/pellets-statistics/world-pellet-map/

positive market signals, special attention has to be paid to how the DEPI presents their data. Differences between the reported production capacity and the actual production figures were observed. Despite this clear relationship, the DEPI's data is disseminated by other renowned information outlets like the "Europäischer Wirtschaftsdienst" (EUWID) and the newspaper "Holz-Zentralblatt". Additionally, the DEPI is also cited in research on biomass trade in Germany funded and published by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Tempel 2010).

Concerning the production and consumption of wood pellets only, a few other studies could be found. For example, Mantau (2012a) determined wood-pellet consumption in private households for four sample years from 2000-2010. In another study, Mantau et al. (2012) determined wood pellet consumption of wood pellets in non-household biomass plants below 1 MW. The problem is that these studies do not encompass the entire wood pellet production and consumption and only have data for a few reference years. Besides, these studies are part of a larger research project called "Standorte der Holzwirtschaft – Holzrohstoffmonitoring", which in turn is sponsored in part by the DEPV (ibid.). The connection between DEPV and DEPI has already been mentioned. Therefore these studies only offer complementary information, but no real alternative to the information provided by DEPI.

Concerning price developments, data from DEPI can be cross-checked with data from the Federal Statistical Office (DESTATIS) to some extent. The difference here is that DEPI offers consumer prices, while DESTATIS offers relative price indexes for producer prices. DESTATIS also summarises wood pellets and briquettes into one product group. Yet the vast majority of goods produced within this group are wood pellets (Mantau 2012a). Hence, the influence of wood briquettes on overall price trends as an extremely similar commodity appears negligible.

2. Project Technology Concept

The technology for pellet production has been implemented and proven over the past years. Therefore, the Technology Readiness Level (TRL) can be defined as Level 9. This study examines the different possibilities available to pellet manufacturers in order to produce and distribute their pellet products locally and regionally. That includes the possibility of an autonomous pellet producer that receives its feedstock from many small sawmills as well as a vertical integrated pellet production into an already existing sawmill. The latter can also be evaluated with a TRL of 9, because it already exists and is successfully implemented. However, almost no publicly accessible information is available, which is a hurdle for replication. The prerequisites for a long-lasting success need to be carefully evaluated, especially with a view on a local distribution.

3. Definition of Project Concept

Wood pellets do not only have a very low energy consumption during the production process but also have a very low carbon footprint.[2] The carbon footprint of wooden pellets is more than 90 % lower than the proportion of CO_2 footprint per kWh of heat from fuel oil and around 70 % lower than the one for natural gas. However, due to long transport routes, the CO_2 footprint of the pellets increases enormously. Therefore, local and regional distribution is the most sustainable solution. The pellet production can further benefit from the waste heat of block-type thermal

[2] DEPI. Pelletproduktion. Energiebilanz der Brennstoffherstellung. URL: https://depi.de/de/pelletproduktion. [2020/11/12]

power stations or biogas plants, which can be used for the drying process. [3] The energy in general is important for the pelleting and drying process and makes a great share of the production costs (Hirsmark 2002). Therefore, the integration of existing heat and energy sources is of great economic and sustainable benefit.

In general, there are two possibilities for a regional/local pellet production. One of them is the integration of a pellet production into the operation of sawmills. This seems to be the economically safer route, since not only energy but also transport costs can be saved. The raw material is also already available. Furthermore, waste is turned into added-value products, whereby the business does not solely depend on pellets as their single product. Regarding risk management, diversification decreases the possible risks of corporate failure. Small sawmills could also purchase a pellet press if this does not lead to large extra hiring of employees. Since the transport costs of sawdust are much higher than the transport costs of pellets, sawdust has much more volume, the purchase of a pellet or briquette press would only be worthwhile if the total cost could be reduced in the long term. In Germany, the economic viability of stand-alone production facilities appeared to be a problem in the past years.[4] Many corporations went insolvent with mismanagement being the most common reason. The most infamous case regarding this aspect was the foreclosure of 'German Pellets'.[5, 6] This does not mean that stand-alone plants are not a possibility. A local pellet company could obtain sawdust from several small sawmills within a maximum surrounding of 30 km. The waste heat from a nearby biogas plant or other available heat sources can be used for the drying process. A region where there are several big buildings such as schools, apartment buildings and office buildings with a central heating and combustion plant running on wood pellets is lucrative as well. In general, pellet production is only feasible with a production capacity of at least 15,000 t/a. This number can vary and depends on the criteria mentioned in the next paragraph. For some pellet producers this number needs to be higher with a minimum production capacity of 20,000 t/a or even 25,000 t/a to make pellet production worthwhile. For a smaller quantity of feedstock, briquetting makes more sense.[7] The feedstock used for the pellets and briquettes production is untreated sawdust and wood chips.

When setting up small pellet companies that want to operate in the regional and local market, key framework conditions for an economic production must be considered beforehand such as consistent feedstock availability, reliable customers, short transport routes, use of existing energy sources as well as existing competition in the area. For this study, a few pellet companies in Germany were interviewed, who have made a name for themselves in their region and give great importance on sustainable production and an overall small CO_2 footprint.

[3] Holtmeyer. Sägewerk, Pellets, Energie. URL: http://holtmeyer.net/portfolio-item/pellets/. [2020/10/28]
[4] Stefan Friedrich. Pellethersteller und Pelletproduktion – LWF-Wissen 70. In LWF- Bayerische Landesanstalt für Wald und Forstwirtschaft. URL: https://www.lwf.bayern.de/forsttechnik-holz/biomassenutzung/033334/index.php. [2020/11/10]
[5] Wirtschaft in Sachsen. Vom Vorzeigebetrieb zum Insolvenzkandidaten. Landkreis Görlitz. 2018/12/13. URL: https://www.wirtschaft-in-sachsen.de/news/vom-vorzeigebetrieb-zum-insolvenzkandidaten-gid-2884?_region=landkreis-goerlitz. [2020/11/10]
[6] Dörnfelder, A., Hussla, G., Schneider, K: German Pellets. Der Insolvenzantrag ist da. [2016/02/10]. URL: https://www.handelsblatt.com/finanzen/maerkte/anleihen/german-pellets-der-insolvenzantrag-ist-da/12943452.html?ticket=ST-10689539-MWqc49btHBngnsocYcDL-ap5. [2020/11/10]
[7] E-Mail enquiry with representatives of pellet producers in Germany. [2020/10/27]

The determination of the location is a crucial component, as it is linked to the availability of raw materials and, if possible, energy costs can be reduced considerably if the company is located near a biogas plant or other heat sources (combined heat and power plant, etc.). The different environmental regulations stated by the Emission Protection Act and certain storage requirements are other decisive factors together with personnel costs. If a pellet production is integrated into an existing sawmill, which was recommended by the respondents, the personnel costs can be kept low for small operations. Entering the market is often difficult for smaller companies, as they have to compete with larger companies with years of experience. Partnerships with a distributor increase the chances of success. In conclusion, it is highly recommended to leave the business planning to external experts.[8] The experts do not only advise on the selection of the right production machines, which is appropriate for the individual production capacity, but also support the product when it enters the market. The experts establish contacts with the right distributors, which is of great importance.

4. Regional Market Situation

This study examines the possibilities of a regional pellet facility with a focus on the integration of a pellet production into an already existing sawmill. Due to the limited availability of public information in Germany, this report aims to support the decision making progress for SMEs. Large pellet manufacturers such as Wismar Pellets in Mecklenburg- Western Pomerania (https://www.wismar-pellets.de/, plant capacity currently 256,000 tons wood pellets per year) are squeezing small companies and may already deter others from entering the market. With the integrated pellet production process, small pellet producers are given a chance to succeed on local and regional level.

4.1 Market Size

The overall consumption of heating energy is rather stable since 2008. It fluctuates around 5 000 PJ (UBA 2020). At the same time, renewable energies are on the rise, increasing their market share from 4.4% in 2000 to 14.2% in 2012 (ibid.). Since then, the share of renewable heating energy has been stagnating too (ibid.). Wood pellets only make up a small part of this market.

Even when assuming that all consumed wood pellets were transferred into heat energy (1 kg = 4.9 KWh) without losses, the overall share of wood pellets in the renewable energies commutes between 5–7% (2009-2018). As a share of the total market for heat energy, this would always be well below 1%. DEPI (2020a) gives more realistic estimates at least 20% below these theoretical values. This places the market share in renewable energies for the heating energy consumption of wood pellets between 4–5% for the past five years. Hence, wood pellets still have to be considered a small market.

Within the sector of renewable energies, wood pellets compete with other wood products for energy use. Mantau (2012a) has shown that nearly ¾ of the total volume of firewood used in private households are split logs. Wood energy products (wood pellets and briquettes) only made up 8% of this total volume. Whilst wood logs offer the possibility of autonomous feedstock supply, their boilers are under pressure with a view to complying with emission regulations. This is easier for pellet heating systems, as they use a standardised fuel quality and operate on a more continuous basis. In a similar order of magnitude, wood energy products made up 10% of the total

[8] E-Mail enquiry with representatives of pellet producers in Germany. [2020/10/27].

volume of wood used in biomass plants with an output below 1 MW. Further projections from 2011 to 2015 predicted these shares to remain stable. In the first half of 2020, Germany recorded an increase of 150% over the previous year in newly installed pellet heating systems. At the end of August, applications for support for the installation of new biomass heating systems were 250% higher than in the previous year.[9] The overall growth of wood consumption puts these shares into perspective though and suggests growth in absolute figures.

4.2 Producers

According to DEPI (2020b), the majority of the production of wood pellets in Germany in 2018 was certified by 'ENplus'. Currently, there are 40 certified producers. Of these producers, 19 are members of the DEPV. Although these producers make up most of the wood pellet production in Germany, it is still an incomplete list.

Estimates place the number of production facilities at around 70 (ITA 2016). The facilities are either stand-alone or connected to sawmills. Some companies have adapted over time and integrated pellet production into their sawmills to reduce their dependence on the construction industry. With an annual cutting volume of 100,000 fm, it is a pellet production of around 30,000 t/a possible. The pellets are then sold loose or packed depending on the economic benefit of a packaging machine.[10] However, this is not worthwhile with an annual cutting rate of 50,000 fm.[11] Usually, the operation could continue through changes in ownership. The most infamous and recent case was that of 'German Pellets'. Its plants now operate under new ownership though (Hussla 2016; Dörnfelder & Hussla 2016). This process seems to be rather common and part of a

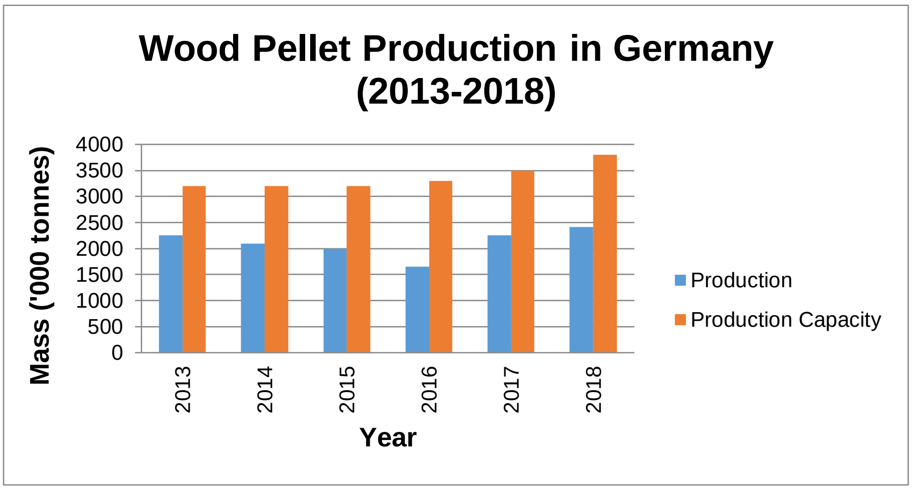

Figure 1: Wood pellet production and production capacities in Germany between 2013-2018. (Source: DEPI 2020b)

consolidation process, so that overall capacity and production does not seem to be affected too

[9] EUWID. Neue Energie. Erneuerbare-Energieeffizienz-Systemtransformation. DEPV übt scharfe Kritik an Bioenergy Europe-Umfrage. Edition 41.2020, 07.10.2020 | Jahrgang 13. p. 5. [2020/11/16]

[10] Nösler, Martina: Spagat zwischen schnell und flexible. Sägewerk des Jahres 2020, in: Holkurier.com, (2019/12/18), URL: https://www.holzkurier.com/schnittholz/2019/12/spagat_zwischen_schnellundflexibel.html. [2020/11/12]

[11] E-Mail enquiry with sawmills in Germany. [2020/11/06]

strongly (Friedrich 2010). Between 2013 and 2016, production volumes have been decreasing. Since then, production has drastically increased to 2.415 Mt again (about 24%, DEPI (2020b)).

Figure 1 shows this development of wood pellet production and production capacity. Although it may seem like the degree of capacity utilisation is very low, it has to be noted that Mitterlehner et al. (2010) have determined an average annual capacity utilisation of wood pellet production facilities of 68%. This would correspond to the current ratio of production capacity to actual production. Vacations and technical revisions were given as the main reasons for this low capacity utilisation. As a result, there is never a full utilization of the machines. Therefore, the pellet presses often run in two shifts. In the case of full utilization, it could happen that additional raw material has to be purchased. These are the reasons why only a macroeconomic data collection is possible and yet an increasing trend in the production of pellets is noticeable, albeit slightly. Whether storage capacity or poor sales had any influence on this could not be determined. Even if there is already overcapacity on the market, there is still potential for regional marketing of the pellet products. The resulting overproduction can be exported if necessary.

Döring & Mantau (2012) found that production capacities of integrated pellet presses in sawmills ranged from 200 t/year to 100,000 t/year. Larger production facilities, like in Wismar, have a production capacity of about 256.000 t/year. It has to be mentioned though that this seems to be the only production facility in this order of magnitude. Older studies have shown that about 2/3 of the producers are small scale producers with production capacities below 30,000 t/year, while medium-scale producers (up to 70,000 t/year) and large scale producers (more than 70,000 t/year) share the remaining third in equal parts (Hiegl & Janssen 2009). Although this distribution is based on data from 2008, there are no signs indicating a general departure from these ratios.

Compared to annual operating costs, initial investment costs are relatively low. A plant with an annual production of 40.000 tons requires an investment of about 3.7 million € (Obernberger & Thek 2010). The annual costs for production amount to about 5.5 million €, which results in a specific cost of about 136 €/t (ibid.). Costs will certainly be lower if existing infrastructure and resources can be used; for example, in a sawmill using side-products. The biggest cost factors in production are raw material costs (43%) and drying (35%), which is responsible for 93% of total energy consumption (ibid.).

4.3 Consumers

Similar to production, national consumption has also increased by a multitude since 2006. Since then it was consistently well below national production until 2016 when it surpassed national production for the first time in 10 years. In 2017 though, production values started to recover drastically so that the status quo was re-established (Tempel 2010; DEPI 2020b).

Figure 2 shows that during the same period Germany was constantly shifting away from its role as a wood pellet net exporter. This is mainly due to an increasing amount of imports reaching the German market (DEPI 2020c). Gross exports oscillate around 700,000 t/year since 2010 (ibid.). After a slump in 2016 and 2017, exports have fully recovered in 2018. The main foreign consumers of German wood pellets are Italy, France and Austria (DEPI 2020d). They import around 2/3 of Germany's exports. German exports mainly compete with U.S. American and Canadian exports – the two other largest wood pellet producers worldwide. Both, the U.S.A. and Canada are further expanding their wood pellet production (FAO 2015; 2016; Goetzl 2015).

Whether Germany will be able to uphold its role as an exporting nation of wood pellets depends on an end to the minor downward trend of production numbers, matching the domestic growth in consumption again.

The main domestic consumers of wood pellets are private households and small biomass heating plants. As wood pellets are used for heating, their use is hinged on the installation of adequate boilers. These are usually long-term investments for the above-mentioned consumers, so that they are unlikely to switch back to other heating systems. This causes demand to be relatively inelastic. An exception to this are owners of fireplace inserts, as they may have another primary or complementary heating system installed in their home, which relies on a different fuel.

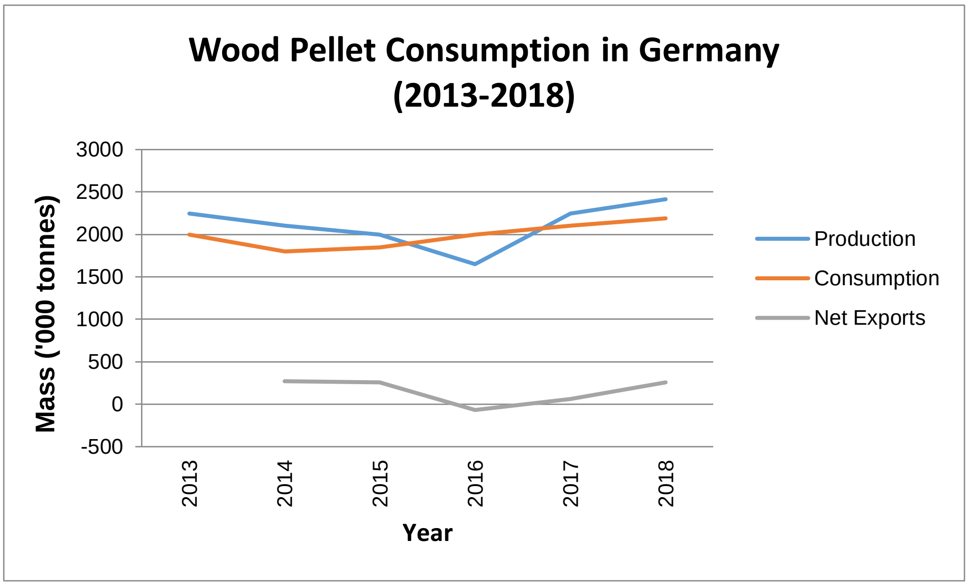

Figure 2: Wood pellet consumption, production and net exports in Germany from 2013-2018. (Sources: DEPI 2020b; DEPI 2020c)

Over the past 9 years, wood pellet furnaces have increased in a regular pattern from a total of about 200,000 in 2009 to about 464,000 in 2018 (DEPI 2020e). Most of these are fireplace inserts (38%) and boilers with an output below 50 kW (59%). These two categories were also responsible for most of the growth over the past years. Boilers with an output of more than 50 kW only make up 3% of wood pellet furnaces. Considering heat energy output the picture is reversed and fireplace inserts are outclassed by boilers (DEPI 2020a). Targeted data on the exact pellet consumption per federal state and region is not available in Germany or if so, they are not publicly accessible.

4.4 Prices

Since 2009, prices for wood pellets have risen constantly, reaching an all-time high in 2013. Since then price levels dropped back to their lowest point since 2010 in 2016. Since then, they have been recuperating. Figure 3 shows that prices increased significantly since 2009 (see Figure 3).

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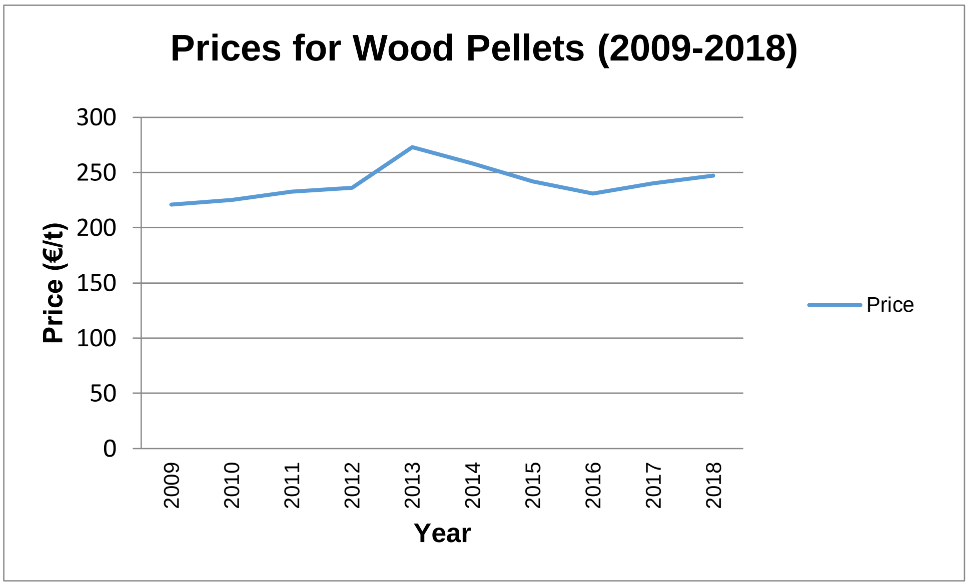

Figure 3: Average annual prices for wood pellets from 2009 to 2018. Prices are given in €/t for the purchase of 6 t ENplus A1certified wood pellets including VAT. (Sources: DEPI 2020f)

The steep increase in prices from 2012 – 2013 may be explained in part by a sudden rise in sawdust prices – the key resource for wood pellets (Schwärzer & Partner 2015). As they dropped, again in 2014 prices for wood pellets dropped as well. The accumulation of large stockpiles in the EU during that year seems to have prevented prices to drop accordingly though (Phillips 2016). During the previous and the current year, these stocks have been and will likely be reduced again (ibid.). This may contribute to the continued drop in price levels. According to the DEPV, average prices for 3, 6 and 26 t are charged throughout Germany. Regional prices are charged for the regions North/East, Central and Southern Germany (DEPV 2019e).

4.5 Resource costs

Besides energy, costs for drying, resource costs remain the highest cost factor in wood pellet production. Their overall share in production is around 43% (Obernberger & Thek 2010). For one ton of wood pellets between 6 lcm to 8 lcm of sawdust are needed. Although the use of industrial round timber has increased over the past years in the production of wood pellets, sawmill side-products (i.e. sawdust) still make up around 90% of wooden resources used in production (Mantau 2012a). What also has to be noted is the high volatility of the sawdust price. Historically this is common for price developments of sawdust (Obernberger & Thek 2010). The strongest competitors for sawdust are the wood-based panels industry and increased direct use of side-products as fuels by sawmills (Mantau 2012a; Döring & Mantau 2012a; Mantau 2012b).

Aside from sawdust, starch is also used as a raw material in wood pellet production. Its use can incur costs of up to 5% of total production costs (Pichler 2009). Yet the supply situation does not seem to be as competitive as it is with sawdust. Main consumers of industrial starch are paper and cardboard producers. The cultivation area for the production of industrial starch is actually being reduced since the paper industry is shrinking (BMELV 2010; BMEL 2015).

4.6 Relevant Policies

Resource mobilisation will be one of the future challenges for the market, as the demand for wood pellets rises and competition for resources increases. About half of the German forests are privately owned. The average forest property is less than 5 ha in size. Hence, most German states provide funding for the establishment and maintenance of forest enterprise cooperatives ('Forstbetriebsgemeinschaften'). In addition to this, some German states pay a premium for each m^3 sold to private forest owners (e.g. Saxony-Anhalt).

Counteracting the measures for resource mobilisation are targets for environmental conservation. The national strategy on biodiversity foresees a total area of 5% of the total forest area in Germany to be left for natural succession (BMUB 2007). This means halting timber production on these areas. Federal and state-owned forests are responsible for reaching this goal.

From a silvicultural perspective, there will also be changes in tree species composition of future German forests. Most states have developed best-practice guidelines that promote the increased cultivation of hardwoods. This will pose a challenge towards the sawmill and wood-based panels industries, which primarily use softwoods. As the demand for adhesives may increase. However, adhesives used for either softwood or hardwood should not be used interchangeably. The future changes that this will cause within these industries are difficult to gauge. In case of a lowering production in these industries, the domestic supply of sawdust will decrease. This will mean that pellet producers will have to find other sources of resource procurement (e.g. direct use of industrial round timber). This results in a negative impact on overall resource sustainability, which harms the product reputation and leads to increasing costs.

For wood pellet producers the transformation of German forests poses a lower direct risk. Production processes do not have to be adapted until a share of 10% of hardwood is used (Dörschel 2015). Beyond this point, production processes can be easily adapted (ibid.). A precise prediction until when the pellet production needs adaptation is not possible right now. The reason for this is the increasing use of starch as an adhesive in the future, which leads to a slight increase in production costs. It would be easy to pass these costs on to the consumer if conditions change for al producers within a certain region.

More developments that are significant to current are German policies on the use of renewable energies. The 'Gesetz zur Förderung Erneuerbarer Energien im Wärmebereich' of 2009 (EEWärmeG, Law for the Advancement of Renewable Energies in Heating) sets the goal of increasing the share of renewable energies in the heating sector up to 14% by 2020 (DEPI 2020g). Renewable energies encompass biomass, geothermal energy, and solar energy. The law makes the use of renewable energies mandatory in new constructions with a floor space exceeding 50 m^2. When using wood as biomass for heating the law specifies that it have to provide at least 50% of the total demand for heat energy of the building. This energy demand is determined according to the 'Verordnung über energiesparenden Wärmeschutz und energiesparende Anlagentechnik bei Gebäuden' (EnEV, Act on Energy-Saving Heat Insulation and Installations). In support of these new obligations, market incentive programs based on the EEWärmeG were introduced (ibid.). These programmes provide subsidies for the installation and financing of biomass heating systems in new buildings. Furthermore, they also subsidise the modernisation of heating systems in existing buildings. Wood pellet boilers fully classify for financial support through the EEWärmeG and its market incentive programs, making them more affordable for consumers. This causes the initial investment costs for wood pellet boilers to be more competitive to the generally cheaper investment costs for oil and gas heating systems (Bentele 2016).

Complementary to these policies are cheap credit opportunities from the 'Kreditanstalt für Wiederaufbau' (KfW), a state-owned national development bank. The bank also offers similar credit opportunities for the installation of oil and gas heating systems though (ibid.). This is criticised by the DEPV as counter-productive towards the overall policy (ibid.).

5. Conclusion

The German pellet market has seen a slight increase over the years and forecast shows that consistent behaviour is expected for the coming years. Since reliable market data for the production of pellets in Germany is limited, this study has summarized the important components. The production of wooden pellets is by far nothing new and presents a low-carbon alternative in the heating sector. However, regionally active pellet manufacturers are by far more sustainable and necessary when building a sustainable bioeconomy. This approach, however, is linked to several factors whereby the choice of location is of main importance for the construction of a regional pellet company due to its dependency of surrounding sawmills, existing energy sources and potential customers. Detailed consideration is needed whether a stand-alone or an integrated pellet production is more sustainable and economically efficient for the region.

References

Bentele M, 2016. Pelletbranche verspürt noch keinen Aufschwung. Holz-Zentralblatt, 51-52/2016, 1241.

BMEL (Bundesministerium für Ernährung und Landwirtschaft), 2015. Agrarpolitischer Bericht der Bundesregierung 2015. BMEL, accessed on 20.11.2020, https://www.bmel.de/SharedDocs/Downloads/DE/Broschueren/Agrarbericht2015.pdf?__blob=publicationFile&v=2

BMELV (Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz), 2010. Die deutsche Landwirtschaft Leistungen in Daten und Fakten. BMELV, accessed on 20.11.2020, https://www.bmel-statistik.de/fileadmin/daten/DFB-0020002-2009.pdf

BMUB (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit), 2007. Nationale Strategie zur biologischen Vielfalt – Kabinettsbeschluss vom 7. November 2007. BMUB, accessed on: 20.11.2020, https://www.bfn.de/fileadmin/BfN/biologischevielfalt/Dokumente/broschuere_biolog_vielfalt_strategie_bf.pdf

DEPI, 2020a. Wärmebereitstellung aus Pelletfeuerungen in Deutschland. DEPI, accessed on: 20.11.2020, https://depi.de/p/Pelletfeuerungen-und-Warmebereitstellung-in-Deutschland-ekThA6s8uQVRGMNNJmMotk

DEPI, 2020b. Pelletproduktion und –verbrauch in Deutschland. DEPI, accessed on: 20.11.2020, https://depi.de/p/Pelletproduktion-und-verbrauch-in-Deutschland-Anteil-ENplus-5eJAc88yiMU8j4BUh6SmPM

DEPI, 2020c. Entwicklung des deutschen Pelletaußenhandels. DEPI, accessed on: 20.11.2020, https://depi.de/p/Entwicklung-des-deutschen-Pelletaussenhandels-rksNevua2qgDKnRHVqHZS3

DEPI, 2020d. Pelletaußenhandel Deutschland: Ein- und Ausfuhrländer. DEPI, accessed on: 20.11.2020, https://depi.de/p/Pelletaussenhandel-Deutschland-Ein-und-Ausfuhrlander-4M3rvt8erMxVBAver5orJN

DEPI, 2020e. Pelletfeuerungen in Deutschland. DEPI, accessed on: 20.11.2020, https://depi.de/p/Pelletfeuerungen-in-Deutschland-aqzgTdFJwz77hk1Vrr3kHy

DEPI, 2020f. Jahresdurchschnittspreise von Holzpellets. DEPI, accessed on: 20.11.2020, https://depi.de/p/Jahresdurchschnittspreise-von-Holzpellets-72amWcMZ2VXLvqNYjn9viw

DEPI, 2020g. Förderfibel Heizen mit Holzpellets. DEPI, accessed on: 20.11.2020, https://depi.de/p/Broschure-Forderfibel-qkHFYruRQVE1HYuqZgtEcj

Döring P, Mantau U, 2012. Standorte der Holzwirtschaft, Holzrohstoffmonitoring, Sägeindustrie – Einschnitt und Sägenebenprodukte 2010. Universität Hamburg, Zentrum Holzwirtschaft. Arbeitsbereich: Ökonomie der Holz- und Forstwirtschaft. Hamburg, 50 p.

Dörnfelder A, Hussla G, 2016. Insolventer Brennstoff-Hersteller wird einzeln verkauft. Handelsblatt, accessed on: 20.11.2020, http://www.handelsblatt.com/unternehmen/ industrie/german-pellets-insolventer-brennstoff-hersteller-wird-einzeln-verkauft/13533182.html

Dörschel J, 2015. Der deutsche und europäische Pelletmarkt – Aktuelles und Trends. DEPV, accessed on: 20.11.2020, https://www.forumue.de/wp-content/uploads/2016/03/5_Doerschel_Pelletmarkt_1302_2015.pdf

EUWID. Neue Energie. Erneuerbare-Energieeffizienz-Systemtransformation (2020). DEPV übt scharfe Kritik an Bioenergy Europe-Umfrage. Edition 41.2020, 07.10.2020 | Jahrgang 13. p. 5.

FAO (Food and Agricultural Organization of the United Nations), 2015. Forest products statistics – 2014 Global Forest Products Facts and Figures. FAO, accessed on: 20.11.2020, http://www.fao.org/forestry/44134-01f63334f207ac6e086bfe48fe7c7e986.pdf

FAO, 2016. Forest products statistics – 2015 Global Forest Products Facts and Figures. FAO, accessed on: 20.11.2020, http://www.fao.org/3/a-i6669e.pdf

Friedrich S, 2010. Pellethersteller und Pelletproduktion. LWF Wissen, 70, 33-36.

Goetzl A, 2015. Developments in the global trade of wood pellets. U.S. International Trade Commission, Office of Industries, accessed on: 20.11.2020, https://www.usitc.gov/publications/332/wood_pellets_id-039_final.pdf

Granath J, 2015. The Global wood pellet market. Ekman & Co, accessed on: 20.11.2020, http://www.pelletheat.org/assets/docs/2015_Conference/speaker_presentations/2015_pfi_conf_presentation_granath_monday_900.pdf

Hussla G, 2016. Gründerfamilie kauft insolvente Werke in Sachsen. Handelsblatt, accessed on: 20.11.2020, http://www.handelsblatt.com/unternehmen/mittelstand/german-pellets-gruenderfamilie-kauft-insolvente-werke-in-sachsen/19166036.html

Hiegl W, Janssen R, 2009. Pellet market country report GERMANY. WIP Renewable Energies, accessed on 20.11.2020, https://ec.europa.eu/energy/intelligent/projects/en/projects/pelletslas#results

Hirsmark, Jakob (2002). Densified Biomass Fuels in Sweden: Country report for the EU/INDEBIF project. Swedish University of Agricultural Sciences, Department of Forest Management and Products, Uppsala. Examensarbeten nr 38, 2002.

ITA (International Trade Administration), 2016. 2016 Top Markets Report Renewable Fuels – Country Case Study: European Union. ITA, accessed on: 20.11.2020, https://legacy.trade.gov/topmarkets/pdf/Renewable_Fuels_European_Union.pdf

LWF (Bayerische Landesanstalt für Wald und Forstwirtschaft), 2017. Holzpellets. LWF, acccessed on: 20.11.2020, http://www.lwf.bayern.de/forsttechnik-holz/holzverwendung/051517/

Mantau U., 2012a. Holzrohstoffbilanz Deutschland – Entwicklung und Szenarien des Holzaufkommens und der Holzverwendung von 1987 bis 2015. Universität Hamburg, Zentrum Holzwirtschaft. Arbeitsbereich Ökonomie der Holz- und Forstwirtschaft, Hamburg, 65 p.

Mantau U, 2012b. Standorte der Holzwirtschaft, Holzrohstoffmonitoring, Holzwerkstoffindustrie – Kapazitätsentwicklung und Holzrohstoffnutzung im Jahr 2010. Universität Hamburg, Zentrum Holzwirtschaft. Arbeitsbereich Ökonomie der Holz- und Forstwirtschaft, Hamburg, 25 p.

Mantau U, Möller B, Jochem D, 2012. Holzrohstoffmonitoring Die energetische Nutzung von Holz in Biomasseanlagen unter 1 MW in Nichthaushalten im Jahr 2010. Universität Hamburg, Zentrum Holzwirtschaft. Arbeitsbereich Ökonomie der Holz- und Forstwirtschaft, Hamburg, 32 p.

Mitterlehner J, Griesmayr S, Majneri C, Haslinger W, 2010. Optimierung der Pelletsmarktversorgung – Endbericht. Klima- und Energiefonds, accessed on 20.11.2020, https://www.klimafonds.gv.at/wp-content/uploads/sites/6/BGR32009KB07EZ2F44368FSOpt-Pelletsmarkt.pdf

Nösler, Martina: Spagat zwischen schnell und flexible. Sägewerk des Jahres 2020, in: Holkurier.com, 2019/12/18), accessed on 12.11.2020, https://www.holzkurier.com/schnittholz/2019/12/spagat_zwischen_schnellundflexibel.html.

Obernberger I, Thek G (eds.), 2010. The Pellet Handbook. London, 549 p.

Phillips S, 2016. GAIN Report - EU Biofuels Annual 2016. USDA Foreign Agricultural Service, accessed on: 20.11.2020, https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=Biofuels%20Annual_The%20Hague_EU-28_6-29-2016.pdf

Pichler W, 2009. Holzpellets – der Stärke auf der Spur. Holzforschung Austria, 01/2009, 10-11.

Schwärzer & Partner, 2015. DeSH Bankenforum – Forum für Banken und Finanzpartner der Sägeindustrie. Schwärzer & Partner, accessed on: 20.11.2020, https://docplayer.org/60572038-Bankenforum-forum-fuer-banken-und-finanzierungspartner-der-saegeindustrie-16-maerz-2015.html

Tempel S, 2010. Study on Biomass Trade in Germany. BMUB, accessed on: 20.11.2020, https://silo.tips/download/study-on-biomass-trade-in-germany

Thrän D, Peetz D, Schubach K, 2017. Global Wood Industry and Trade Study 2017. IEA Bioenergy Task 40. June 2017.

UBA (Umwelt Bundesamt), 2020. Energieverbrauch für fossile und erneuerbare Wärme. UBA, accessed on: 20.11.2020, http://www.umweltbundesamt.de/energieverbrauch-fuer-waerme#textpart-1

Agro-industrial sector

LEAF PROTEIN CONCENTRATE PRODUCTION FROM INTERMEDIATE CROPS

PRE-FEASIBILITY STUDY OF LEAF PROTEIN CONCENTRATE PRODUCTION FROM INTERMEDIATE CROPS

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Summary

The current trend towards increasing the content of plant based protein in diets has been recognized in North America, Western Europe and also other parts of the world. In the course of developing products to address this trend, new plant protein-based products are entering the market and contributing to an increase in the total volume of plant protein products used in the food industry.

This pre-feasibility study investigates the production of protein concentrates from various crops grown as intermediate crops (IC). ICs are currently grown in Sweden as catch or cover crops in order to decrease nutrient leakage after harvest of a main crop or as a measure to prevent erosion or weed problems when the field usually would be bare soil. ICs are usually incorporated into the soil before the next main crop is established. Instead, we propose aboveground IC biomass can be harvested and plant proteins extracted.

The study concept aims at harvesting intermediate crop aboveground biomass and use it as feedstock for plant protein extraction. Protein can be extracted as white protein aimed as a food additive and a secondary green protein fraction containing cell debris and chlorophyll-related components. The green protein and the fibre pulp are evaluated as animal feed.

Results of the assessment show that green biomass from intermediate crops has large potential as a raw material in plant protein recovery for the production of protein-rich food and feed products. The white protein fraction contains essential amino acids and is suitable as a food ingredient or additive. The green protein and total recoverable protein fractions with essential amino acids and a likely efficient digestibility in mono-gastric and ruminant animals, can fulfil demand of locally produced protein-rich feed and thereby reduce the need for imported protein-rich feed products.

In the economic assessment for recovery of protein concentrates from green biomass, crop nitrogen content affects the protein yield and therefore is an important factor for high profitability. Furthermore, the low DM content observed for some ICs affects transportation and processing costs negatively. The wide span of production costs indicates the need for further studies to lower the variability and corresponding risk for production, e.g. by optimizing biomass production of IC regarding the above-mentioned production factors.

Technology readiness is generally high (TRL 6-9) for the feedstock supply steps, however, the protein extraction process and product preparation, needs to be adapted and verified to produce fractions with high protein yields and quality. Concrete scaling tests are currently being performed on the investigated crops outside the scope of the BioBIGG project. These tests will allow a more detailed and concise economic feasibility assessment.

1. Introduction

The current trend towards increasing the content of plant based protein in diets has been recognized in North America, Western Europe and also other parts of the world (Court 2018, Sutton, Larsen et al. 2018, GN 2019). This trend is driven by the consumers´ desire to reduce the share of meat in their diet for various reasons, such as animal welfare, health concerns, weight management or environmental concerns. In the course of developing products to address this trend, new plant protein-based products are entering the market and contributing to an increase in the total volume of plant protein products used in the food industry. To fulfil an increasing demand and to exploit the economic possibilities of supplying it, this pre-feasibility study investigates the requirements and prerequisites of commercial use of novel sources of plant protein from green leaves for food and feed applications.

1.1 Project concept

This pre-feasibility study investigates the production of protein concentrates from various crops grown as intermediate crops (IC). ICs are currently grown in Sweden as catch or cover crops in order to decrease nutrient leakage after harvest of a main crop or as a measure to prevent erosion or weed problems when the field usually would be bare soil. Also, greening measures defined by the common agricultural policy in the European Union include the cultivation of ICs. These ICs are grown on fields designated as ecological focus areas (EFA). ICs are usually incorporated into the soil before the next main crop is established. Instead, we propose aboveground IC biomass can be harvested and plant proteins extracted.

A potential production process involves separation of proteins in the leaves and stems from the fibre pulp, a cellulosic residue that can be used as ligno-cellulosic feedstock for biofuel production (Bals and Dale 2011) or as animal feed, depending on the source. Use of intermediate crops as feedstock for biofuel production could help to avoid indirect land use change (ILUC) effects and the food-vs-fuel debate.

The project concept aims at harvesting intermediate crop aboveground biomass and use it as feedstock for plant protein extraction. Protein can be extracted as white protein aimed as a food additive and a secondary green protein fraction containing cell debris and chlorophyll-related components. The green protein and the fibre pulp are evaluated as animal feed.

1.1.1 Motivation

Intermediate crops provide additional ecosystem services such as provision of nectar to pollinators from flowering ICs, plant nutrient release after soil incorporation (green manure) to the next main crop and contribution to soil organic carbon (SOC) and therefore to soil fertility.

However, advantages with soil incorporation of ICs before the next main crop are limited. Even if the IC can accumulate a substantial amount of nitrogen, on average around only 50% of that nitrogen may be made available to the following main crop (Aronsson, Hansen et al. 2016). Contribution of the aboveground biomass to SOC is limited as well, while the roots contribute about three times as much per mass unit. For these reasons, harvest of the IC is likely to still result in a considerable SOC contribution as well as reducing the amount of plant nutrients lost to leakage, while yielding a valuable feedstock for plant protein production.

1.1.2 Crop choice and field experiment

At least 24 crops are currently approved on ecological focus areas, by the Swedish Board of Agriculture (SBA 2019). For crops on EFA, a mix of at least two crops is required and catch crops additionally include ley crops with a maximum legume share of 15% (SBA 2019).
For this study, four crops grown as summer intermediate crops were chosen: buckwheat (*Fagopyrum esculentum*), phacelia (*Phacelia tanacetifolia*), industrial hemp (*Cannabis sativa*) and oilseed radish (*Raphanus sativus* var. *oleiferus*) for their ability to produce high biomass yields per hectare. The crops were established in the end of July and harvested in the autumn (September, October, November). Field experiments and sample analyses were carried out during 2017. The Field Research Station of the Rural Economy and Agricultural Society in Skåne, Kristianstad, carried out all field operations in Norra Åsum, Kristianstad, southern Sweden. IC were sown on a field (55° 58' 9.33"N; 14° 9' 25.97"E) with sandy soil in a randomized block design, with and without fertilization of the IC. The four ICs were grown as sole crops with 40 kg N/ha fertilization. Biomass yields, dry matter content and nitrogen content are presented in Appendix Table A1.

1.1.3 Protein potential

Total protein potential was estimated by determining the biomass nitrogen content and multiplying it with the biomass dry matter yield and a protein factor[1]. The nitrogen content in the harvested biomass ranged between 0.8 and 2.3% of the dry matter (DM), corresponding to a protein content of 0.8-4.4% wet weight, which is typical e.g. for leafy vegetables (Figure 1). Buckwheat and hemp reached a nitrogen content of 1.7 and 1.8 %, respectively. Phacelia and oilseed radish reached approx. 30% higher nitrogen content with 2.3% for both. The resulting protein potential for the chosen ICs varied between 128-794 kg per hectare. Buckwheat and phacelia reached protein potentials of 342 and 338 kg/ha, respectively. Hemp and oilseed radish produced nearly double that total protein potential with 794 and 734 kg/ha, respectively.
In 2015, one third of the area under the greening measure obligation implemented by the European Commission were cultivated with catch crops, i.e. ICs, which amounted to 2.65 million hectares (EC 2017). In Sweden, about 70,000 hectares with catch crops were cultivated in 2018 (Asplund and Svensson 2018). The Swedish Board of agriculture has a goal (for environmental reasons) to increase the cultivation area to 138,000 hectares. Earlier studies have presented an area of 194,000 hectares of potential ICs cultivation area in Sweden (Prade, Björnsson et al. 2017). Biomass from IC crops has been shown to have a substantial potential as feedstock for the bioeconomy (BioBIGG 2019, Prade, Andrzejczyk et al. 2019). Assuming an average protein potential of 500 kg/ha and a 10-21% fraction of recoverable protein (compare Figure 2. Material flow diagram for the use of intermediate crop biomass for production of green and white protein as well as fibre pulp and brown liquor. Percentages denote the content of protein in the fractions in relation to the total biomass protein content. Note that a mechanical disruption step of the IC biomass before feed-in to the juicer as well as a drying step of the final protein concentrates is required and has been considered in the analysis but is left out here.), a rough estimate of the protein potential yields 9,700-20,400 tonnes of food grade white protein produced from intermediate crops in Sweden alone (Muneer, Person Hovmalm et al. 2020). Scaled to the EU, based on the current IC cultivation area, this potential grows to 133,000-278,000 tonnes of food grade white protein produced

[1] We applied a protein factor of 5.6 Mariotti et al.: Mariotti, F., D. Tomé and P. P. Mirand (2008). "Converting Nitrogen into Protein—Beyond 6.25 and Jones' Factors." Critical Reviews in Food Science and Nutrition **48**(2): 177-184..

from intermediate crops. This corresponds to 1.5-3.1 % of the EU28 annual protein consumption[2], with potential to increase if intermediate crop cultivation areas increase.

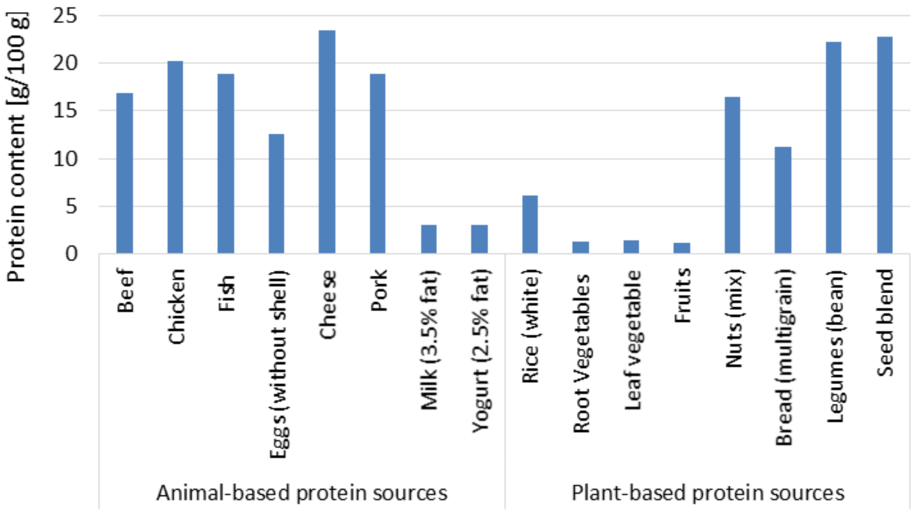

Figure 1. Average protein content in a selection of raw foods (EC 2019).

1.2 Production process and products

1.2.1 Process outline

In the extraction of protein from plant material, several products at different product quality levels are possible. Two different production pathways were investigated with respect to potential product recovery rates, product uses and market demands. The pathways include (A) production of green and white protein (Figure 2. Material flow diagram for the use of intermediate crop biomass for production of green and white protein as well as fibre pulp and brown liquor. Percentages denote the content of protein in the fractions in relation to the total biomass protein content. Note that a mechanical disruption step of the IC biomass before feed-in to the juicer as well as a drying step of the final protein concentrates is required and has been considered in the analysis but is left out here.) or (B) total recoverable protein production (Figure 3). Both processes result also in a fibre pulp and a brown liquor fraction.

[2] Calculated assuming the daily average recommended protein consumption of 0.83 g/kg body weight/day (EC, 2019) and an average body weight of 60 kg for women and 70 kg for men, using Eurostat population data for 2016. EC. (2019). "Dietary Protein." Retrieved 26 Jul 2019, from https://ec.europa.eu/jrc/en/health-knowledge-gateway/promotion-prevention/nutrition/protein.

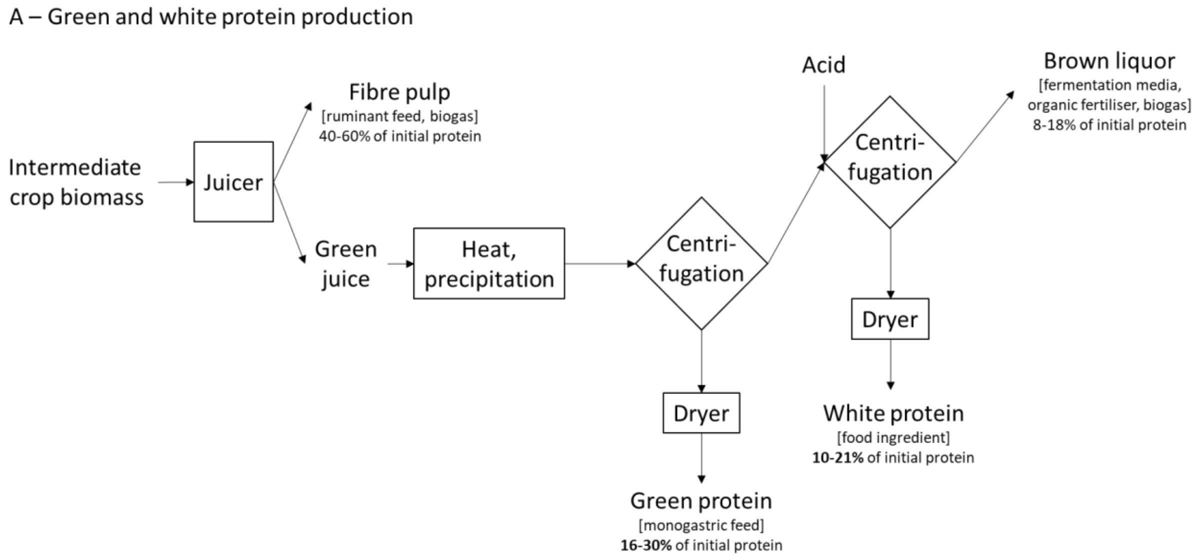

Figure 2. Material flow diagram for the use of intermediate crop biomass for production of green and white protein as well as fibre pulp and brown liquor. Percentages denote the content of protein in the fractions in relation to the total biomass protein content. Note that a mechanical disruption step of the IC biomass before feed-in to the juicer as well as a drying step of the final protein concentrates is required and has been considered in the analysis but is left out here.

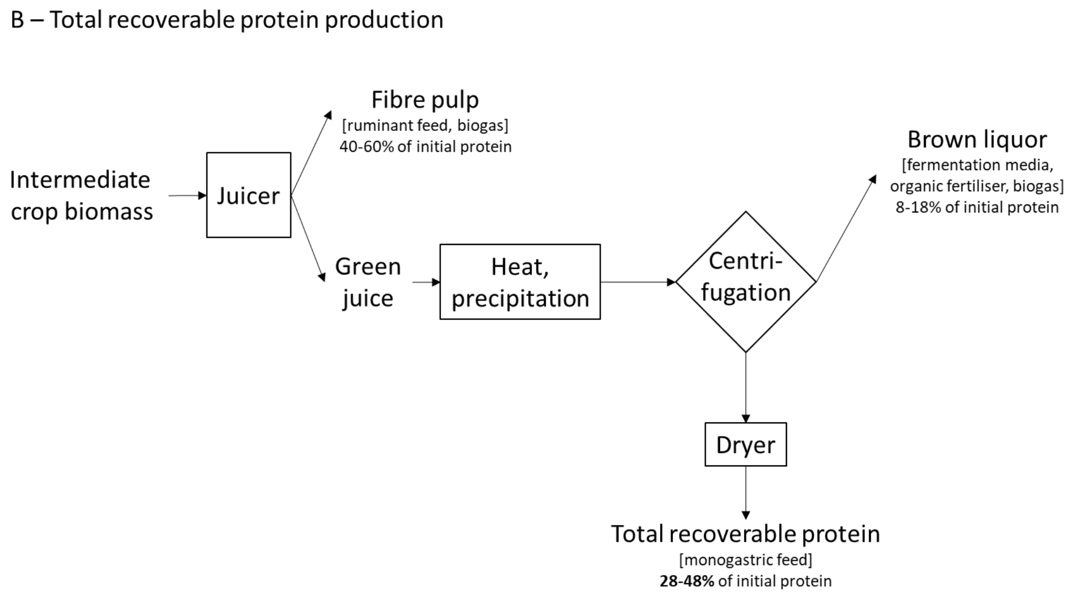

Figure 3. Material flow diagram for the use of intermediate crop biomass for total recoverable protein production. Percentages denote the content of protein in the fractions in relation to the total biomass protein content. Note that a mechanical disruption step of the IC biomass before feed-in to the juicer as well as a drying step of the final protein concentrates is required and has been considered in the analysis but is left out here.

For the protein production pathways A and B the following steps are carried out:

- Transfer of the harvested crop to the processing plant within 4 hours to avoid degradation and microbial growth.
- Loading to a feeding and conveying system that transports the biomass into washing and dewatering at constant feeding rate.
- Washing to reduce microbial contamination and remove soil particles.
- Screw-dewatering to disrupt the plant structure and separate the material into fibre pulp and green juice fraction.

For the protein production pathway B, the total protein content of the green juice is precipitated by heat treatment at 80 °C.
For pathway A, the following additional steps are performed:

- Coagulation of coarse particles and green chloroplast proteins into a green solid fraction by a mild heat treatment (50-60 °C)
- Separation of the green protein fraction by means of a decanter centrifuge
- Adjustment of pH to 4.0-4.5 to precipitate the white protein fraction
- Separation of the white protein fraction from the brown liquor by means of a disc centrifuge

1.2.2 Products

Proteins are the main product of both processes. Protein is present in concentrated form in different fractions. Protein fractions, i.e. fraction with a high protein content, need to be dried, resulting in a fine powder with a moisture content of 4-8% resulting in a long shelf life. White protein concentrate is aimed to be an ingredient in the food industry for human consumption. DM protein yields depend strongly on the conditions for protein precipitation, typically ranging between 0-30%. Harsh protein precipitating conditions (lower pH) tend to increase protein recovery although these conditions may negatively affect protein functionality. In this study, maximized precipitation was assumed, resulting in a protein content of 29%. An additional purification step was also assumed, that increased protein content to 85% in the final product (Edwards, Miller et al. 1975, Tenorio, Gieteling et al. 2016). Because of the harsh precipitation conditions assumed, only the nutritional value was considered in the techno-economic assessment. The product is considered an off-white powder with a protein profile suitable for human consumption.
The green protein fractions obtained from pathways A and B are prepared similarly as powder, but are intended for use as feed or feed ingredient. Similar to the white protein product, the protein content was assumed to be 29 % in the final product (Tenorio, Gieteling et al. 2016). The product is a green powder suitable for use as animal feed for both mono-gastric animals and ruminants.
The fiber pulp fraction has moisture content of 30% and is suitable for ensiling, a fast, in-expensive and mature solution for conserving the biomass as feed. Similar to e.g. ley grass silages, the product can be used as feed for ruminants, e.g. cattle or sheep. The protein content is approx. 3.3% wet basis or 10.8% dry basis, which is similar to that of whole-crop barley silage (Magnusson 2017). A protein profile suitable for use as animal feed for ruminants was assumed. Storage as dried powder, would be possible as well, where drum drying and conveyor drying would be the simplest method and in each case the main energy consumption would be for water evaporation. For instance, a similar approach is used in the production of wheatgrass powder for human consumption. However, to remove the liquid mechanically (dewatering) would lose some nutrients. With much of the nutrients left behind, it is unclear if a dewatered product is still interesting. After dewatering, the solids will be much easier to dry, as the structure will be opened, speeding the process, but the main energy is for water evaporation. These additional costs probably require that a dried product be sold as a premium product such as a healthy food additive.
Brown liquor is a residue product containing soluble components with potential use as biogas substrate. However, due to the low DM content (approx. 10%) transport cost are expected to be high. Potential operations to increase DM content need to be balanced against product value. Since this by-product can become a cost or revenue, depending on the transport distance, revenues have not been included in the economic assessment.

2. Project technology concept

2.1 Technology readiness of concept

The technology readiness of the presented concept was assessed in a preliminary and simplified manner in order to present a starting point. Actual TRL levels need to be assessed in close cooperation with participating business partners once an innovation program is to be implemented.

2.1.1 Feedstock supply

Technology of the feedstock supply for the suggested production process is comparable with technology used for harvest of feed materials or biogas substrate. These applied technologies include standard agricultural machinery for crop cultivation (TRL 9), harvest technology (TRL 6) and transport logistics (TRL 6), Figure 4.

2.1.2 Cultivation of ICs

Machinery for cultivation of intermediate crops include tractors and tractor appliances already broadly used in crop and intermediate crop cultivation. Operations for the cultivation of ICs include ploughing, seedbed preparation, harrowing and seeding of ICs as well as fertilizer spreading which are identical or very similar to operations used in food or feed crop production.

2.1.3 Harvest and transportation

Harvesting of fresh green biomass is not common in agriculture. Usually, even green biomass (e.g. ley crops) are field-dried in order to reduce water content and thereby reduce transportation costs. Crop biomass intended for protein extractions needs to be processed within few hours after cutting the plants to avoid cell processes that lead to deterioration of proteins as well as to avoid microbiological contamination. The lower TRLs for the harvest and transport logistics consider the considerably large differences in crop morphology, water content at harvest and field conditions and the resulting demand for adjusted and optimized machinery and harvesting logistics. TRL-levels higher than 6 for the harvest and logistical part are possible with available technology for e.g. ley grass harvest, which may have to be adjusted to transport of relatively wet biomass.

2.1.4 Processing

Several plant-based protein products are available commercially on the market, both such sold as food grade and as feed grade material. Despite the availability of these soya-, wheat-, pea- or rice-based proteins, the technology readiness level (TRL) of the presented processes is currently considered to be low, TRL 3-4, mainly due to the uncertainties regarding product extraction and recovery rates and the resulting need to adjust the extraction processes to the feedstock composition (Figure 4). Details on the process design are given in the economic assessment below.

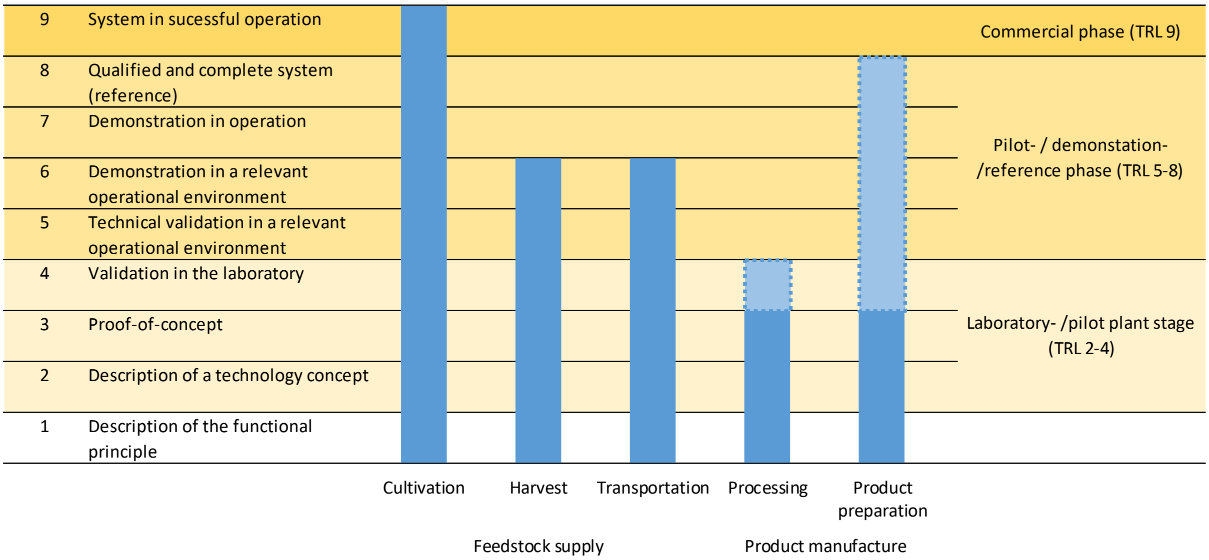

Figure 4. Technology readiness levels (TRLs) as preliminary assessed for the production steps of the concept.

Biomass for protein extraction needs to be processed within 4 hours after harvest in order to avoid protein deterioration and contamination. We assume a facility processing IC biomass in September to November. This facility needs to process other crops and biomass feedstock during the rest of the year (e.g. green rye in May to June, sugarbeet leaves in September and October) in order to become economically feasible.

2.1.5 Product preparation

For both pathways, once the wet protein-rich fractions are obtained via precipitation and centrifugation, they require drying to stabilise the product and avoid microbial deterioration. The necessary unit operations are standard operations, which need to be adjusted to the specific process, but the technology applied is mature and readily available with a TRL of 7-8. However, among other important steps, testing for anti-nutritional compounds must be carried out as well as taste and taste acceptance verified which reduces the overall TRL to 3 for this step.

2.2 Requirements and properties

2.2.1 Food grade production

In order to meet food grade standards, following existing processing facility rules and guidelines will be required. As the products resemble leafy greens, equipment such as conveyors and washers for those products are readily available but may need to be adapted for specific crops (TRL 8). The separation of juice and fibres resembles the production of fruit juices or other dewatering processes where food grade equipment is mature and readily available (TRL 9). Protein recovery does not differ significantly from some existing food grade plant protein production using commercial equipment such as heat exchangers, pumps, piping, centrifuges etc. (TRL 9).

2.2.2 Nutritional value and anti-nutritional compounds

A general challenge for plant proteins isolated from a single crop remains their "incomplete" essential amino acid content in respect to human nutritional demand. One way to receive a more complete nutritional amino acid content is to combine protein sources. However, these combination proteins tend to include ingredients with lower quality scores, which can affect the sales price of the ingredients and potential returns to producers and growers (Sutton, Larsen et al. 2018).

In order to gain an overview of the nutritional and anti-nutritional compounds present in ICs we briefly discuss the nutritional profile of each IC:

Similar to buckwheat seeds, the aerial parts of buckwheat also contain high amounts of phenolic compounds (Kreft, Janeš et al. 2013). The buckwheat leaves have been reported to also contain high amounts of rutin (Holasova, Fiedlerova et al. 2002), which is a phenolic compound with high antioxidant activity that is reported to have a positive impact on the human immune system and to decrease the risk of various cancers (Zhang, Zhou et al. 2012). Besides a variety of polyphenols, fagopyrins could be present in green aerial parts of flowering buckwheat (Tavčar Benković, Žigon et al. 2014). Fagopyrins are known to cause light sensitivity in humans with large consumption of green parts of buckwheat(Tavčar Benković, Žigon et al. 2014). There is a strong tendency that these compounds end up in the green protein fraction, as the solubility of fagopyrins and their coagulation temperature of around 60 °C is similar to chlorophyll-related components (Kreft, Janeš et al. 2013, Tavčar Benković, Žigon et al. 2014).

Radish is a vegetable that is reported to contain high amounts of bioactive compounds in their taproots and which is consumed as food for its health benefits (Blažević and Mastelić 2009, Goyeneche, Roura et al. 2015). Goyeneche et al. (2015) reported that red radish leaves contain high amount of minerals, polyphenols and ascorbic acid as compared to roots. During extraction of leaf proteins, these minerals and bioactive compounds could end up in various proteins fractions, increasing their value.

Hemp leaves consist of ca. 24 % of crude proteins, 19 % of crude fibers, 11 % of ash and other bioactive compounds. Leaf protein extracts of hemp have been shown to have an amino acid profile containing nine of the ten essential amino acids (Audu, Ofojekwu et al. 2014), which is comparable to those of egg white and soya bean. Hemp leaves contain a number of phytochemicals: cannabinoids (e.g. cannabidiol (CBD), cannabinol (CBN) and tetrahydrocannabinol (THC)) and non-cannabinoids (flavones, alkaloids, terpenes and steroids) (Audu, Ofojekwu et al. 2014, Khan, Wang et al. 2015, Pandohee, Holland et al. 2015). Industrial hemp varieties used in the field experiment in this study tend to have very low amounts of these compounds. When hemp leaf protein extracts are used for food and feed purposes, there is a low probability that these chemicals will cause negative health impacts in both humans and animals.

Sprouted phacelia seeds have been shown to contain polyphenols (Kruk, Baranowska et al. 2019, Pająk, Socha et al. 2019), with a higher amount of phenolic compounds and higher antioxidant activity compared to the seed (Pająk, Socha et al. 2019). Therefore, green biomass from phacelia could be a valuable resource for protein extraction but also for other valuable bioactive compounds beneficial for human consumption.

Chlorophyll degradation products can form during protein extraction processes, which may be undesirable for human consumption. Chopping and cooking of green biomass leads to the release of enzymes and acids, which start to degrade chlorophyll protein complexes (Heaton and Marangoni 1996). For coagulation of proteins, often high temperature is applied which may facilitate the conversion of chlorophyll into chlorophyllide. With a subsequent acid treatment for protein precipitation, the chlorophyllide can be converted into pheophorbide (Holden 1974, Heaton and Marangoni 1996), which is directly related to chlorophyllase enzyme activity in the leaves. Crops with higher chlorophyllase activity tends to produce higher amounts of pheophorbides that are believed to cause photosensitization effects seen in albino rats (Lohrey, Tapper et al. 1974).

3. Market situation

3.1.1 Existing market

The current trend towards diets with an increasing content of plant-based protein is driving the demand for plant based protein products. A desire to reduce the share of meat in the diet for various reasons such as animal welfare, health concerns, weight management or environmental concerns is part of the motivation for this development. This increasing demand is met by a limited, but quickly developing market and supply of plant-based protein. Besides soya-based proteins that have been part of Asian diets for a long time, very few plant-based proteins have been made available commercially in large quantity. These include proteins extracted mainly from pea, wheat and rice[3]. The market value of plant-based protein is predicted to grow from 4.16 billion US$ in 2017 with a geometric progression rate of 7.5% until 2025 (GN 2019). For example, the Canadian government plans to invest 150 million CAD in the plant-based sector, reflecting the increasing demand where 43% of Canadians are trying to eat more plant-based food (Court 2018).
The choice between the two pathways presented here is a cost optimisation problem. Costs for additional steps (secondary precipitation, purification) to extract the white protein fraction need to be covered by a higher product sales price. This is potentially possible, but likely requires marketing as high-value product, not as a bulk food additive (Table 1).

[3] Own analysis based on the commercial products offered at Alibaba.com

Table 1. Overview over product value, market size and market readiness for application of the different fractions obtained din the protein extraction process.

Product	Application	Product value	Market size	Market readiness
White protein (A)	a) Food additive b) High-value product (health food, cosmetics)	$-$$ $$- $$$	XXX XX	XX XXX
Green protein; total recoverable green protein	Feed for monogastric animals	$	XX	XXX
Fibre pulp	Feed for ruminant animals	$	XX	XXX

4. Feasibility of concept

4.1 Economic feasibility

A cost-benefit analysis of the use of IC for the valorisation of protein for food and feed applications was conducted. Calculations were carried out as a step-by-step assessment that included all necessary machinery operations in the field, transport, storage and processing in a simulated protein extraction plant. Results of this type of pre-feasibility study usually have an error margin of up to ±30% (Bals and Dale 2011).

Experimental results of field and laboratory studies were modified to reflect the technical potential of the crops, i.e. biomass yields were assumed to be 90 % of hand-harvested yields. Additional data used in the assessment of the IC production is presented in Appendix Tables A2 and A3. Cost of mineral nitrogen fertiliser was assumed to be 1.0 €/kg (SBA, 2017). Assumptions for the storage of fibre pulp are given in Appendix Table A4. A conversion factor of 1 SEK=0.09433 EUR = 0.10545 USD was applied.

4.1.1 Field and transport operations

A 200 kW tractor was used for all field operations. Two false seedbeds were prepared, seven and fourteen days after harvest of the preceding crop using a one-pass multi seedbed cultivator with an effective field capacity of 2.9 ha/h. The intermediate crop was then sown and fertilized with mineral nitrogen in one pass by using a combi seed drill (4 m working width) with an effective field capacity of 2.0 ha/h. Harvest of the intermediate crop was assumed to be carried out in one pass, using a tractor-draw mowing and self-loading forage container wagon with a maximum capacity of 13 tons biomass or 40 m^3. A maximum harvesting speed of 15 km/h was assumed for biomass yields per hectare lower than approx. 15 tons wet weight, or approx. 2.25 tons DM per hectare. The harvested biomass was transported by the tractor on field roads (1.0 km away at an average speed of 25 km/h) to a place where the container was switched to an empty one. The harvest capacity was between 1.0 and 1.5 hectares per hour, depending on the level of biomass yield per hectare. Three full containers, at a time, approx. 40 tons of biomass were transported by a container trailer truck to the protein plant (30 km away at an average speed of 60 km/h).

At the protein plant, the biomass was fed into the reception tank of the protein plant, using a 12 ton front loader. Transport density was estimated based on a dry matter (DM) density of 85 kg DM/m^3 (Pettersson, Sundberg et al. 2009) and the corresponding DM content. The costs of machinery operation were estimated according to cost per hour and the amount of time used for different field operations using standard cost recommendations (Maskinkalkylgruppen 2019).

4.1.2 Protein extraction

For the economic assessment, two protein production pathways were evaluated in this study, namely (A) the production of both green and white protein (Figure 2. Material flow diagram for the use of intermediate crop biomass for production of green and white protein as well as fibre pulp and brown liquor. Percentages denote the content of protein in the fractions in relation to the total biomass protein content. Note that a mechanical disruption step of the IC biomass before feed-in to the juicer as well as a drying step of the final protein concentrates is required and has been considered in the analysis but is left out here.) and (B) the production of total recoverable green protein (Figure 3). The protein production pathway A to obtain green and white protein fractions, assumed ranges of 16-30% and 10-21% of the total initial protein content in the plant biomass, respectively. The process includes the following procedures (Figure 2. Material flow diagram for the use of intermediate crop biomass for production of green and white protein as well as fibre pulp and brown liquor. Percentages denote the content of protein in the fractions in relation to the total biomass protein content. Note that a mechanical disruption step of the IC biomass before feed-in to the juicer as well as a drying step of the final protein concentrates is required and has been considered in the analysis but is left out here.); a) cut biomass is immediately transferred to the processing plant to avoid degradation and microbial growth; b) the cut biomass is unloaded to a feeding bin/conveyor system that transports the biomass into the washing/dewatering at constant feeding rate; c) the biomass is first washed to reduce microbial contamination and remove adhering soil, then fed into a screw-dewatering machine designed to disrupt the plant structure and separate the material into fibre and green juice fractions; d) coarse particles are separated from the green juice into a green solids fraction by a heat treatment (50-60°C) followed by a decanter centrifugation; e) the supernatant from the decanter centrifuge is adjusted to pH 4.5 to precipitate the white protein fraction followed by disc centrifugation to separate it from the brown liquor. Thus, product recovery rates, product uses and market demands were used for the economic assessment for each of the protein production pathways. For the protein production pathway B, a range of 28-48% of the total protein content of the biomass has been used (Figure 3). A shortened process with a one-step heat mediated precipitation of protein was assumed. Besides the protein fractions, both protein production pathways result in the production of a fibre pulp and a brown liquor fraction. Fibre pulp can either be used e.g. as ruminant feed and the sugar-containing brown liquor can be digested anaerobically to produce biogas (Prade, Andrzejczyk et al. 2019).

For simulating the white and green protein pathway costs, data on an extraction process with mechanical pressing for fraction separation were used as presented by Bals and Dale (2011) (Appendix Table A5). Compared to the process suggested here, the Bals and Dale process includes additional milling and a secondary pressing step, which are energy and capital intensive (Bals and Dale 2011). Our calculations therefore rather overestimate costs. For simulating the recovery of the total recoverable protein fraction, a 20 % cost reduction was assumed to account for a simpler process with direct protein precipitation. Protein fractions were dried, before sale as products, to an average moisture content of 6 % (Appendix Table A6).

For assessing the economic feasibility, market-based costs were used to estimate potential sales prices for white protein and fibre pulp (Appendix Table A7). White protein was assumed to be marketed as a premium product with corresponding sales prices, while fibre pulp has been evaluated as a bulk feed product generating low revenues. The green protein fraction and the total recoverable protein fraction are intended for marketing as a feed or feed additive product. The corresponding product value depends on the protein content, but also on other factors such as digestibility, amino acid composition and fibre content. Setting a price for these fractions would therefore require additional information on the feed value of the products, which was outside the scope of this pre-feasibility study. Therefore, for assessing the production pathway feasibility, the breakeven price for the green protein fraction (pathway A) and the total recoverable protein fraction (pathway B) was estimated for each crop, nitrogen fertilization level and harvest month. The breakeven price was here defined as the sales price per kilogram protein that would cover the difference between total production costs and revenues from white protein and fibre pulp.

4.1.3 Results

The economic assessment for extraction of white and green protein in pathway A (Figure 5) shows large differences in both costs and revenues between the different intermediate crops and harvest months. The costs for the total recoverable protein fraction (pathway B) are showing the same patterns with total costs being on average 13 % lower (range 9.7-15.9 %). As this is well within the error margin of the assessment, results are not presented here. Revenues for the fibre pulp are identical between pathways A and B.

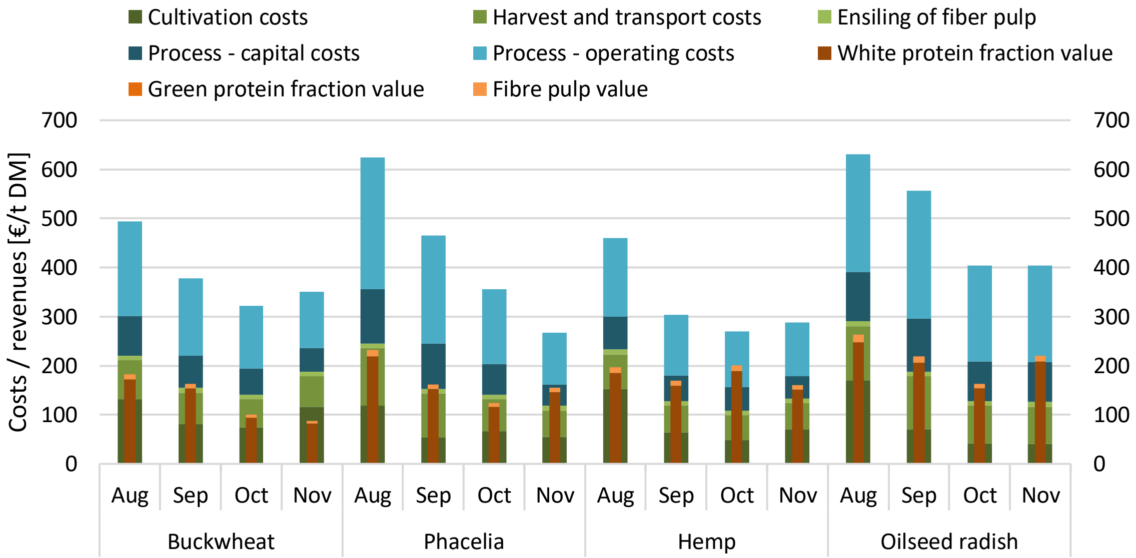

Figure 5. Costs for feedstock supply and processing of intermediate crop biomass and potential revenues from the white protein fraction and the fibre pulp for pathway A. Nota that the revenues from the green protein fraction are not included here. Months refer to the time of harvest of the IC. Data is shown for intermediate crops fertilised with 40 kg N per hectare in the form of biogas digestate.

Due to the low biomass yields per hectare in August, cost per ton DM were very high. Cost were considerably lower in September and decreased further in October. Cost in November were unchanged from October for hemp and oilseed radish, lower for phacelia and higher for buckwheat, which had already started to wither. The proportion of cost of cultivation in total costs was also varying considerably, between 10 and 34 % and between 11 and 36 % for production of white plus green and total recoverable protein, respectively. Here, low biomass yields increased cost per ton DM considerably, which also increased the proportion of cultivation costs. Costs for production of separate fractions of white and green protein were on average 9 % (5.3-12.0 %) higher compared to extraction of total recoverable protein. Revenues per ton of DM varied considerably between crops, nitrogen fertilization levels, harvest months and years for extraction of white protein and fibre pulp from pathway A

(Figure 5). Plant nitrogen content was the major factor determining the size of revenues, which is in line with earlier studies (Swanson 1990).

The breakeven prices per kilogram protein in the green protein fraction (pathway A; Figure 6) and the total recoverable protein fraction (pathway B; Figure 7) showed large variations between crop and harvest month. A threshold price level was set at 2 €/kg protein; green protein fraction or total recoverable protein fraction with breakeven prices below this level likely can be marketed as a bulk feed product. None of the investigated crops had breakeven prices below the bulk product threshold level of 2 €/kg protein.

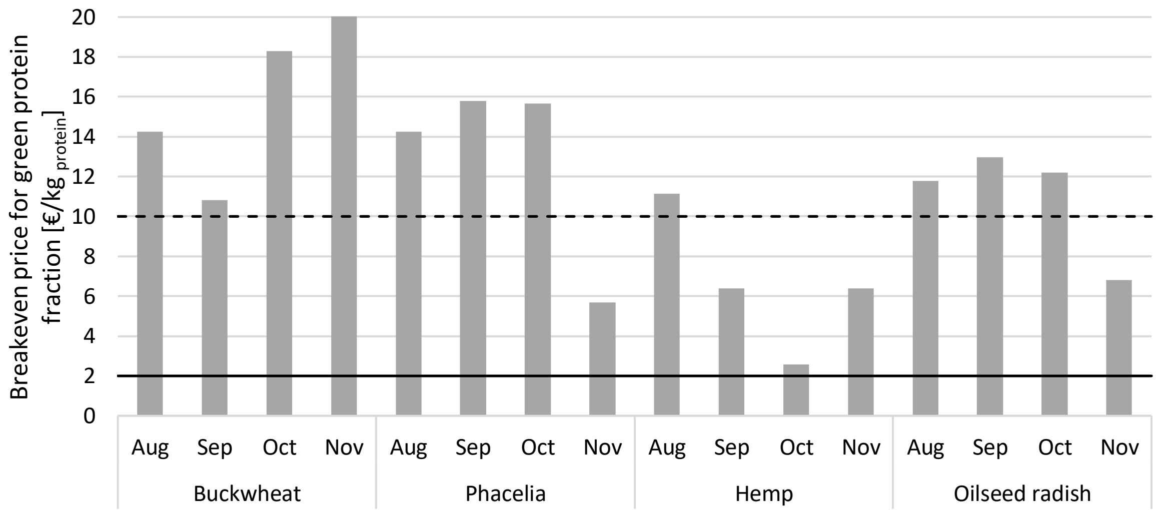

Figure 6. Breakeven prices for the green protein fraction (pathway A) defined as the sales price per kilogram protein that would cover the difference between production costs and revenues from white protein and fibre pulp. For treatments with breakeven prices below the solid line, the green protein fraction could be marketed as a bulk product. For treatments with prices above the solid line, placement as premium product was assumed necessary. Treatments with breakeven prices above the dashed line were considered not to be economical feasible.

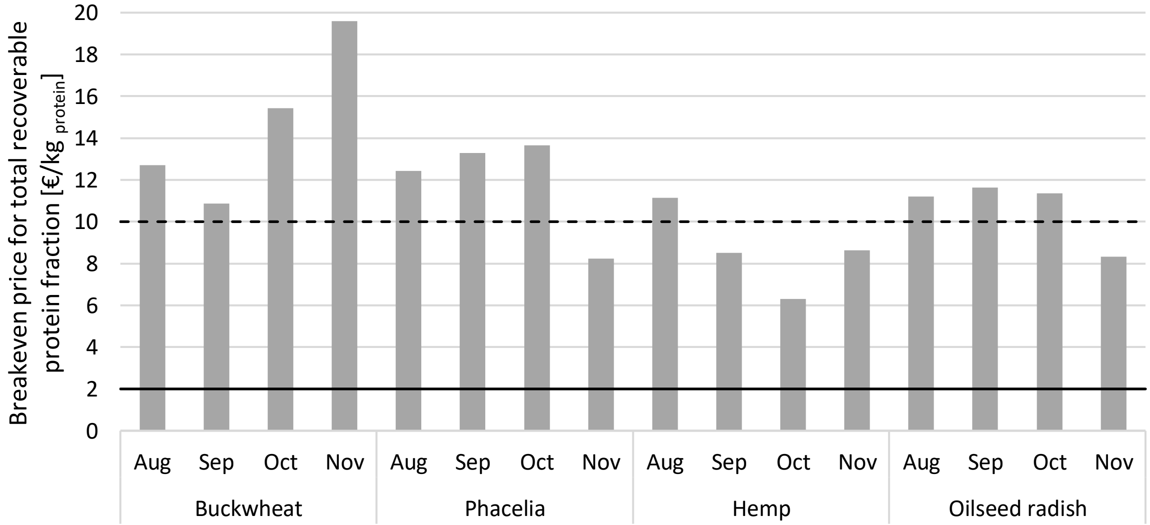

Figure 7. Breakeven prices for the total recoverable protein fraction (pathway B) defined as the sales price per kilogram protein that would cover the difference between production costs and revenues from the fibre pulp. For treatments with breakeven prices below the solid line, the green protein fraction could be marketed as a bulk product. For treatments with prices above the solid line, placement as premium product was assumed necessary. Treatments with breakeven prices above the dashed line were considered not to be economical feasible.

Breakeven prices up to the second threshold price level at 10 €/kg protein likely require marketing as a premium feed product, as is common in the horse feed market. Breakeven prices above 10 €/kg protein are considered too high for even marketing as premium products, given that packaging and distribution of the products are not included in the assessment. Phacelia and oilseed radish had breakeven prices below the premium product threshold only in November, hemp during September to November, indicating economic feasibility as a premium product

Breakeven prices for feasible IC options (below 10 €/kg protein) in pathway A were on average 2 €/kg protein lower compared with pathway B, with a variation between -1.5 and -3.5 €/kg protein (Figure 6). These rather small differences, despite the high revenue per kilogram of white protein, can be explained by the relatively low extraction efficiency of white protein.

For crops with a breakeven price below 10 €/kg protein, processing costs ranged approx. 4,150-6,520 and 3,760-5,650 € per ton protein for pathway A and B, respectively. These costs can be compared to e.g. processing cost of 1,367 and 2,448 € per ton protein extracted from microalgae, for enzymatic and alkaline extraction processes, respectively (Sari et al., 2016). Corresponding total costs for this selection ranged approx. 6,700-9,240 and 6,350-8,600 € per ton protein, i.e. all protein fractions combined.

A lower DM content in the green biomass increased transportation costs. A lower protein content and lower DM content were major factors increasing processing costs. Here, hemp profited from high DM content compared with oilseed radish. However, the approx. 20 % higher biomass yields for oilseed radish that continued to increase into November diminished this difference since hemp growth was interrupted by frost, which requires an earlier harvest in September or October.

An increased nitrogen (protein) content is desirable for e.g. optimization of IC feedstock production, but needs also to take into account the current use of unfertilized IC as catch crops, reducing nitrogen leakage from the soil and the corresponding conflict of interest. One way to increase nitrogen (protein) content in the feedstock would be to intercrop the intermediate crops with legumes. A study under publication has increased protein harvest for all four intermediate crops (Muneer, Person Hovmalm et al. 2020).

4.1.4 Technology choice

Despite promising results with close-to-complete recovery of extractable proteins, several factors might limit the economic performance of the mechanical pressing method. The required mills and presses have high capital and electricity costs. In addition, the method requires fresh biomass, which limits commercial operation to a few months per year (Bals and Dale 2011).

Aqueous extraction of proteins might prove a more economic viable option for leaf protein concentrate production, since it can be performed on dried material (Bals and Dale 2011). The value of alkaline extracted protein concentrate is currently unknown as alkaline treatment has been shown to influence solubility negatively (Deleu, Lambrecht et al. 2019). But also positive impacts of alkaline treatment on e.g. colour and flavour have been reported (Deleu, Lambrecht et al. 2019).

4.1.5 Protein extractability

Protein extractability and recovery can be very variable between different plant species and even varieties of the same plant. Upscaling of laboratory results may inherit a risk of over- or underestimation of protein extractability, for example when extracts are glutinous or tends to foam (Pirie 1978). Agronomic or plant physiological research may be needed to investigate the impact of sowing dates, fertilization levels, harvest date for different plants and varieties (Pirie 1978).

Intermediate crops are usually sown in July or August in southern Sweden and can be harvested late in October or even in November. This allows a sufficiently long growth period to accumulate an economically interesting amount of biomass for harvest. Since a prolonged vegetative growth forming biomass is desired delaying maturation of the crop, hemp and oilseed radish are to be preferred to hairy vetch and buckwheat that mature early and have less extractable protein available at later stages. For hemp, leaf stripping may be a more interesting option since this avoids harvest of the fibrous stalks that likely will require a high energy input in pulping (Pirie 1978).

The presence of phenolic substances in leaf extracts has been reported to potentially diminish protein extraction due to enzymatic formation of tanning agents. These agents can coagulate proteins and reduce their digestibility and at high concentrations may prevent protein extraction completely (Pirie 1978). Phenolic content has been identified as the factor most often responsible for small yields of LP (Butler 1982). High levels of phenolic compounds were earlier found in hemp seed oil (Teh and Birch 2013) and in the form of terpenoids in leaf extracts (Duangnin, Klangjorhor et al. 2017). Further lab research has to investigate if these compounds may impact the extractability of leaf protein negatively.

4.1.6 Location and available biomass feedstock

Skåne is the Swedish county with the highest potential to grow intermediate crops with a production potential of approx. 140,000 tons DM annually (Prade, Andrzejczyk et al. 2019). The other Swedish South Baltic Area regions Kronoberg, Kalmar and Blekinge together have a considerably lower production potential of >20,000 tons DM per year. A suitable location for the large-scale application of the suggested production concept would therefore be in Skåne.

4.1.7 Regulations

EFA crops may first be harvested or incorporated into the soil after 1 November (SBA 2019) in order for the intermediate crop to fulfil its function. This late harvest potentially results in a wilted biomass unsuitable for protein extraction, e.g. for intermediate crops that mature early such as buckwheat. Also, restrictions for the use of pesticides in intermediate crops apply (SBA 2019), which reduce a potential impact of pesticides on the suitability of protein products aimed for human or animal consumption. Further regulations prevent an economic compensation for catch crop cultivation when crops are grown as greening measures, i.e. as EFA crops (SBA 2019).

5. Sustainable development and local and regional development benefits

Implementation of intermediate crops as a feedstock for protein extraction would benefit farmers with an additional income for sale of the biomass feedstock. The increased transportation need would be benefitting logistical services in the region.

Growing intermediate crops has earlier been shown to have many additional benefits such as increased soil organic carbon contribution, weed management possibilities, reduced nutrient leakage and potentially feed for pollinators outside the common blooming season. The benefits contribute to the Swedish environmental goals of Reduce climate impact, Zero Eutrophication, A Rich Diversity of Plant and Animal Life, and A varied agricultural landscape as well as to the UN sustainable development goals (2.4, 7.2, 8.4, 9.4, 12.2, 13.2 and 13.3).

6. Conclusions

This pre-feasibility study has shown that green biomass from intermediate crops has large potential as a raw material in plant protein recovery for the production of protein-rich food and feed products. The white protein fraction contains essential amino acids and is suitable as a food ingredient or additive. Thereby, white protein from intermediate crops could contribute to fulfil the increasing demand of plant protein-rich food products. The green protein and total recoverable protein fractions with essential amino acids and a likely efficient digestibility in mono-gastric and ruminants, can fulfil demand of locally produced protein-rich feed and thereby reduce the need for imported protein-rich feed products. Harvesting month affected the IC biomass production, where a longer time for biomass growth is essential for high biomass yields. Oilseed radish, hemp and phacelia produced higher biomass and protein content compared to buckwheat.

In the economic assessment for recovery of protein concentrates from green biomass, crop nitrogen content affects the protein yield and therefore is an important factor for high profitability. Furthermore, the low DM content observed for some ICs affects transportation and processing costs negatively. Fertilized buckwheat is unlikely to be profitable even as a premium protein source due to relatively low biomass yields. The wide span of production costs indicates the need for further studies to lower the variability and corresponding risk for production, e.g. by optimizing biomass production of IC regarding the above-mentioned production factors.

Technology readiness is generally high (TRL 6-9) for the feedstock supply steps, however, the protein extraction process and product preparation, needs to be adapted and verified to produce fractions with high protein yields and quality. Concrete scaling tests are currently being performed on the investigated crops outside the scope of the BioBIGG project. These tests will allow a more detailed and concise economic feasibility assessment.

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8. References

Aronsson, H., E. M. Hansen, I. K. Thomsen, J. Liu, A. F. Øgaard, H. Känkänen and B. Ulén (2016). "The ability of cover crops to reduce nitrogen and phosphorus losses from arable land in southern Scandinavia and Finland." Journal of Soil and Water Conservation **71**(1): 41-55.

Asplund, L. and Å. Svensson (2018). Chapter 17 - Ersättning för minskat kväveläckage. Programmen och pengarna. Utvärderingsrapport 2018:3. Jönköping, Sweden, Swedish Board of Agriculture**:** 215-232.

Audu, B., P. Ofojekwu, A. Ujah and M. J. T. J. O. P. Ajima (2014). "Phytochemical, proximate composition, amino acid profile and characterization of Marijuana (*Cannabis sativa* L.)." Journal of Phytopharmacology **3**(1): 35-43.

Baker, C. G. J. and K. A. McKenzie (2005). "Energy Consumption of Industrial Spray Dryers." Drying Technology **23**(1-2): 365-386.

Bals, B. and B. Dale (2011). "Economic Comparison of Multiple Techniques for Recovering Leaf Protein in Biomass Processing." Biotechnology and bioengineering **108**: 530-537.

Bals, B. and B. E. Dale (2011). "Economic comparison of multiple techniques for recovering leaf protein in biomass processing." Biotechnology bioengineering **108**(3): 530-537.

BioBIGG (2019). State of play for the bioeconomy in the South Baltic area. Interreg project *Bioeconomy in the South Baltic Area: Biomass- based Innovation and Green Growth -* BioBIGG. Gdansk, Poland.

Blažević, I. and J. Mastelić (2009). "Glucosinolate degradation products and other bound and free volatiles in the leaves and roots of radish (Raphanus sativus L.)." Food Chemistry **113**(1): 96-102.
Butler, J. B. (1982). "An investigation into some causes of the differences of protein expressibility from leaf pulps." **33**(6): 528-536.
Court, E. (2018). Canadian Government To Invest $150 Million In Plant-Based Sector. The decision reflects increasing demand for plant-based protein. London, UK, Plant Based News.
Deleu, L. J., M. A. Lambrecht, J. Van de Vondel and J. A. Delcour (2019). "The impact of alkaline conditions on storage proteins of cereals and pseudo-cereals." Current Opinion in Food Science **25**: 98-103.
Duangnin, N., J. Klangjorhor, P. Tipparat, S. Pinmanee, T. Phitak, P. Pothacharoen and P. Kongtawelert (2017). "Anti-inflammatory effect of methanol extracts of hemp leaf in IL-1β-induced synovitis." Tropical Journal of Pharmaceutical Research **16**(7): 1553-1563.
EC (2017). Implementation of the ecological focus area obligation under the green direct payment scheme. Brussel, Belgium, European Commission**:** 14.
EC. (2019). "Dietary Protein." Retrieved 26 Jul 2019, from https://ec.europa.eu/jrc/en/health-knowledge-gateway/promotion-prevention/nutrition/protein.
Edwards, R. H., R. E. Miller, D. De Fremery, B. E. Knuckles, E. Bickoff and G. O. Kohler (1975). "Pilot plant production of an edible white fraction leaf protein concentrate from alfalfa." Journal of Agricultural and Food Chemistry **23**(4): 620-626.
GN (2019). Global Plant Based Protein Supplements Market, GlobeNewswire.
Goyeneche, R., S. Roura, A. Ponce, A. Vega-Gálvez, I. Quispe-Fuentes, E. Uribe and K. Di Scala (2015). "Chemical characterization and antioxidant capacity of red radish (Raphanus sativus L.) leaves and roots." Journal of Functional Foods **16**: 256-264.
Heaton, J. W. and A. G. Marangoni (1996). "Chlorophyll degradation in processed foods and senescent plant tissues." Trends in Food Science & Technology **7**(1): 8-15.
Hjelm, E. and R. Spörndly (2012). Densiteten tung faktor i plansilon. Arvensis. Bjärred, Sweden, HIR Skåne AB, Hushållningssällskapen i Skåne, Skaraborg, Östergötland, Kalmar-Kronoberg-Blekinge, Halland, Västmanland, HS Konsult and Växa Sverige. **4:** 2.
Holasova, M., V. Fiedlerova, H. Smrcinova, M. Orsak, J. Lachman and S. Vavreinova (2002). "Buckwheat—the source of antioxidant activity in functional foods." Food Research International **35**(2): 207-211.
Holden, M. (1974). "Chlorophyll degradation products in leaf protein preparations." Journal of the Science of Food and Agriculture **25**(11): 1427-1432.
Khan, B. A., J. Wang, P. Warner and H. Wang (2015). "Antibacterial properties of hemp hurd powder against E. coli." Journal of Applied Polymer Science **132**(10).
Kreft, S., D. Janeš and I. Kreft (2013). "The content of fagopyrin and polyphenols in common and tartary buckwheat sprouts." Acta Pharm **63**(4): 553-560.
Kruk, J., I. Baranowska, B. Buszewski, S. Bajkacz, B. Kowalski and M. Ligor (2019). "Flavonoids enantiomer distribution in different parts of goldenrod (Solidago virgaurea L.), lucerne (Medicago sativa L.) and phacelia (Phacelia tanacetifolia Benth.)." Chirality **31**(2): 138-149.
Lohrey, E., B. Tapper and E. L. Hove (1974). "Photosensitization of albino rats fed on lucerne-proetin concentrate." British Journal of Nutrition **31**(2): 159-166.
Magnusson, A. (2017). Whole crop barley silage and grass silage harvested at different stages of maturity – effects on feed intake, selection, digestibility and protein utilization in sheep. Skara, Sweden, Department of Animal Environment and Health, Swedish University of Agricultural Sciences.
Mariotti, F., D. Tomé and P. P. Mirand (2008). "Converting Nitrogen into Protein—Beyond 6.25 and Jones' Factors." Critical Reviews in Food Science and Nutrition **48**(2): 177-184.
Maskinkalkylgruppen (2019). Maskinkostnader 2019. Bjärred, Sweden, Swedish Rural Economy and Agricultural Societies Malmöhus**:** 48.
Muneer, F., H. Person Hovmalm, S.-E. Svensson, W. R. Newson, E. Johansson and T. Prade (2020). "A pre-feasibility study on protein concentrates production from biomass of intermediate crops." Journal of Cleaner Production **submitted**.

Pająk, P., R. Socha, J. Broniek, K. Królikowska and T. Fortuna (2019). "Antioxidant properties, phenolic and mineral composition of germinated chia, golden flax, evening primrose, phacelia and fenugreek." Food Chemistry **275**: 69-76.

Pandohee, J., B. J. Holland, B. Li, T. Tsuzuki, P. G. Stevenson, N. W. Barnett, J. R. Pearson, O. A. Jones and X. A. Conlan (2015). "Screening of cannabinoids in industrial-grade hemp using two-dimensional liquid chromatography coupled with acidic potassium permanganate chemiluminescence detection." J Sep Sci **38**(12): 2024-2032.

Pettersson, O., M. Sundberg and H. Westlin (2009). Maskiner och metoder i vallodling. JTI-rapport Lantbruk & Industri 377. Uppsala, JTI- Institutet för jordbruks- och miljöteknik**:** 33.

Pirie, N. W. (1978). Leaf protein and its by-products in human and animal nutrition. Cambridge, Cambridge University Press.

Prade, T., R. Andrzejczyk, M. Booker Nielsen, B. Cuypers, P. Dąbrowski, A. Ekman Nilsson, T. Kjær, J. Lund, D. Mikielewicz, M. Mittenzwei, D. Schiller, J. Wajs and M. Westkämper (2019). Biomass and innovation potential of residues, by-products and other sustainable feedstock for biobased products in four South Baltic Area regions. Interreg project *Bioeconomy in the South Baltic Area: Biomass- based Innovation and Green Growth* - BioBIGG. T. Prade. Alnarp, Sweden, Swedish University of Agricultural Sciences.

Prade, T., L. Björnsson, M. Lantz and S. Ahlgren (2017). "Can domestic production of iLUC-free feedstock from arable land supply Sweden's future demand for biofuels?" Journal of Land Use Science **12**(6): 407-441.

SBA (2017). Rekommendationer för gödsling och kalkning 2018. K. Börling, P. Kvarmo, U. Listh, J. Malgeryd and M. Stenberg. Jönköping, Sweden, Swedish Board of Agriculture**:** 104.

SBA. (2019). "Ekologiska fokusarealer." Retrieved 2019-07-24.

SCB (2019). "Energy prices on natural gas and electricity." Aquired on 23 March 2020 **scb.se**.

Strid, I., C. Gunnarsson, H. Karlsson, M. Edström and J. Bertilsson (2012). Mer och bättre vall till mjölkproduktion och återväxtvall till biogas. Uppsala, Institutionen för energi och teknik, Sveriges lantbruksuniversitet**:** 88.

Sutton, K., N. Larsen, G.-J. Moggre, L. Huffman, B. Clothier, R. Bourne and J. Eason (2018). Opportunities in plant based foods – PROTEIN. A Plant & Food Research report prepared for: Ministry Primary Industries and Plant & Food Research. Auckland, New Zealand, The New Zealand Institute for Plant & Food Research**:** 22.

Swanson, B. G. (1990). "Pea and lentil protein extraction and functionality." Journal of the American Oil Chemists' Society **67**(5): 276-280.

Tavčar Benković, E., D. Žigon, M. Friedrich, J. Plavec and S. Kreft (2014). "Isolation, analysis and structures of phototoxic fagopyrins from buckwheat." Food Chemistry **143**: 432-439.

Teh, S.-S. and J. Birch (2013). "Physicochemical and quality characteristics of cold-pressed hemp, flax and canola seed oils." Journal of Food Composition and Analysis **30**(1): 26-31.

Tenorio, A. T., J. Gieteling, G. A. De Jong, R. M. Boom and A. J. Van Der Goot (2016). "Recovery of protein from green leaves: Overview of crucial steps for utilisation." Food chemistry **203**: 402-408.

Zhang, Z.-L., M.-L. Zhou, Y. Tang, F.-L. Li, Y.-X. Tang, J.-R. Shao, W.-T. Xue and Y.-M. Wu (2012). "Bioactive compounds in functional buckwheat food." Food Research International **49**(1): 389-395.

9. Appendix

9.1 Field experimental data

Table A1. Mean (and standard deviation) of intermediate crop biomass yield and dry matter (DM) content.

Crop	Harvest	Biomass yield [t DM/ha]	DM content [%]	N content [%]
Buckwheat	Aug	2.6 (±1.2)	13.8 (±0.9)	1.7 (±0.5)
	Sep	4.2 (±1)	17.9 (±0.4)	1.4 (±0.3)
	Oct	4.6 (±1.6)	24 (±1.5)	0.9 (±0.1)
	Nov	2.9 (±1)	28.1 (±4.5)	0.8 (±0.1)
Phacelia	Aug	1.9 (±0.9)	9.3 (±1.2)	2.3 (±0.6)
	Sep	4.2 (±0.5)	11.7 (±1.7)	1.5 (±0.1)
	Oct	3.3 (±1)	18.7 (±2)	1.2 (±0.2)
	Nov	4.1 (±0.5)	32.1 (±4)	1.4 (±0.5)
Hemp	Aug	2.5 (±0.8)	17.5 (±2.4)	1.8 (±0.4)
	Sep	5.9 (±1.6)	25 (±1)	1.5 (±0.2)
	Oct	7.9 (±1.1)	28.4 (±0.3)	1.8 (±0.1)
	Nov	5.3 (±1)	30.1 (±1.9)	1.4 (±0.0)
Oilseed radish	Aug	1.6 (±0.4)	10.5 (±0.9)	2.3 (±0.6)
	Sep	3.7 (±0.7)	9.5 (±0.8)	2.0 (±0.2)
	Oct	6.3 (±1.3)	13.6 (±2.7)	1.5 (±0.4)
	Nov	6.6 (±1.7)	13.4 (±1.3)	1.9 (±0.6)

9.2 Cost-benefit assessment

A cost-benefit analysis was carried out to estimate the concept´s economic potential. A step-by-step calculation was applied that included all necessary machinery operation in the field, transport, storage and processing in a simulated protein plant.

Data for the assessment, i.e. literature results of field and laboratory studies, were modified to reflect the technical potential of the crops, i.e. biomass yields were assumed to be 90 % of hand-harvested yields. Further data used in the assessment of the intermediate crop production is presented in **Error! Reference source not found.**. Mineral nitrogen fertiliser was assumed to cost 1.0 €/kg (SBA 2017). A conversion factor of 1 SEK=0.09433 EUR = 0.10545 USD was applied.

9.2.1 Feedstock production

Table A2. *Data used for the economic assessment of the intermediate crop production and transport logistics.*

Crop	Fertilization [kg N/ha]	Harve	Seeding [kg/ha	Seeding [€/kg	DM [%]	Transport [kg/m^3]	Storage [kg/m^3]
Buckwheat	40	Aug	60	23	13.8	620	989
		Sep	60	23	17.9	476	854
		Oct	60	23	24.0	356	727
		Nov	60	23	28.1	309	677
Phacelia	40	Aug	12	12	9.3	927	1000
		Sep	12	12	11.7	740	1000
		Oct	12	12	18.7	458	835
		Nov	12	12	32.1	268	634
Hemp	40	Aug	30	60	17.5	494	873
		Sep	30	60	25.0	341	711
		Oct	30	60	28.4	299	667
		Nov	30	60	30.1	283	650
Oilseed	40	Aug	15	40	10.5	814	1000
		Sep	15	40	9.5	895	1000
		Oct	15	40	13.6	649	968
		Nov	15	40	13.4	638	985

[a] Storage density of the fibre pulp fraction.

Table A3*. Machinery costs according to branch recommendations (Maskinkalkylgruppen 2019).*

Machinery	**Specifications**	**Capacity**	**Costs[a] [€/h]**
Tractor	200 kW		81
Multi-cultivator	4 m (disc, tine, roller)	2.9 ha/h	138
Combi seed drill	4 m, 3300 L	2.0 ha/h	148
Self-loading forage wagon	56 m^3	118 t/h	133
Front loader[b]	12 t, 110 kW	Compaction: 0,4 min/t Feed-in: 85 t/h	75

[a] Including costs for driver and fuel

[b] Assuming an effective bucket volume of 4.5 m^3, 300 m transport distance, 20 km/h transport speed and a filling und unloading time each of 10 s per bucket load.

9.2.2 Fibre pulp storage as silage

Costs for storage in bunker silos were estimated using an investment calculation on data given in Table A3.

Table A4*. Economic calculations on bunker silo storage.*

Variable	Unit	Value
Effective storage volume	[m^3]	17505
Investment costs[a]	[€/m^3]	17.0
Economic life span	[a]	20
Interest	[%]	6
Cost for plastic cover[a]	[€/m^2/a]	3.0
Bunker cost	[€/m^3/a]	2.2

[a] Source: Strid *et al.* (2012)

Storage density was estimated to be 646 kg/m^3 according to Hjelm and Spörndly (2012):

$$Required\ storage\ density\ \left[\frac{kg}{m^3}\right] = DM\ content\ [\%] \cdot 3.5 \left[\frac{kg}{\% \cdot m^3}\right] + 90 \left[\frac{kg}{m^3}\right]$$

9.2.3 Processing costs

Table A5*. Cost for protein extraction and drying of final products given as cost per ton of initial feedstock.*

Fraction	Operational cost [EUR/t]	Capital cost[a] [EUR/t]	Technology used	References
Extraction				
White and green protein (pathway A)	18.7 - 23.5	8.0 - 9.6	mech. separation	(Bals and Dale 2011)
Total recoverable protein (pathway B)	15.0 - 18.8	6.4 - 7.7	mech. separation	(Bals and Dale 2011)
Drying				
White protein (pathway A)	4.1 - 26.3	1.9 - 10.5	spray drying	own estimation[b]
Green protein (pathway A)	6.6 - 42.1	3.0 - 16.8	drum drying	own estimation[b]
Total recoverable protein (pathway B)	11.5 - 73.6	5.2 - 29.5	drum drying	own estimation[b]

[a] for the drying processes estimated as 40 and 45 % of high and low operational costs, respectively.

[b] Estimated based on the energy consumption of 3-7 MJ/kg evaporated water (Baker and McKenzie 2005) and energy prices of 1.0-1.8 €-ct/MJ (SCB 2019).

Table A6. Drying operations for different fractions.

Fraction	Drying method	Proportion of the initial biomass DM treated [%]	Moisture content[a] [%]
Green protein	Drum drying	9.1	31
Total extractable protein	Drum drying	15.9	31
White protein	Spray drying	5.7	31

[a] Of the biomass entering and treated in the dryer, based on (Tenorio, Gieteling et al. 2016)

Table A7. Assumed protein revenues [€/kg].

Product	Application	Chosen value (market range)
White protein	Food	11.2 (8.6 - 13.8)[a]
Fibre pulp	Feed	0.21 (0.14 - 0.28)[b]

[a] Range as analysed on Alibaba.com (8 June 2019); when a default price of 1 US$/kg product was given as the lower price range, this was corrected by assuming the lower price limit being at 50% or the upper price limit of the same product.

[b] Assumed to have the same value as that of untreated ley crop biomass used as ruminant feed.

LEAF PROTEIN CONCENTRATE PRODUCTION FROM BROCCOLI AND KALE LEAVES

COLOURBOX1065531

LEAF PROTEIN CONCENTRATE PRODUCTION FROM BROCCOLI AND KALE LEAVES - A PRE-FEASIBILITY STUDY

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Project title – Growth	Bioeconomy in the South Baltic Area: Biomass- based Innovation and Green For information on the project please check https://biobigg.ruc.dk/
Project acronym –	BioBIGG
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Deliverable D5.2 –	Pre-feasibility and innovation programmes for innovative value chains

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Summary

The current trend towards increasing the content of plant based protein in diets has been recognized in North America, Western Europe and also other parts of the world. In the course of developing products to address this trend, new plant protein-based products are entering the market and contributing to an increase in the total volume of plant protein products used in the food industry.

This pre-feasibility study investigates the production of protein concentrates from kale and broccoli leaves. Kale and broccoli are currently grown in Sweden and especially in Skåne where the major part of the production is located. However, the production potential in Sweden is relatively low due to very low production volumes of broccoli and kale. Still, broccoli and kale leaves could become part of a feedstock portfolio of a plant protein facility and additional markets for the leaves could affect production dynamics.

This study concept aims at harvesting leaves from broccoli and to collect kale leaves in the sorting facility for use as feedstock for plant protein extraction. Protein can be extracted as white protein aimed as a food additive and a secondary green protein fraction containing cell debris and chlorophyll-related components. The green protein and the fibre pulp are evaluated as animal feed.

Results of the assessment show that leaf biomass from kale and broccoli has a potential as a raw material in plant protein recovery for producing protein-rich food and feed products. The white protein fraction contains essential amino acids and is suitable as a food ingredient or additive. The green protein and total recoverable protein fractions with essential amino acids and a likely efficient digestibility in mono-gastric and ruminant animals, can fulfil demand of locally produced protein-rich feed for e.g. horses and thereby reduce the need for imported protein-rich feed products.

Due to the need for additional harvest operations for recovering broccoli leaves, neither of the investigated production pathways is economically viable without an adjustment of the current practices of harvesting broccoli florets. Alternative harvest methodologies similar to the kale harvest could entail the harvest of the larger part of the broccoli plant with a facility based sorting procedure. However, it seems unlikely that such a harvest operation would be feasible and possible to integrate in the existing harvest methodology.

The simple process of drying and milling the leaves to formulate a health product is an interesting option mostly for kale leaves, since the current production setup does not require costly field operations for additional harvest, but with simple process adjustment can provide the feedstock with only transportation costs affecting the economic balance.

Technology readiness is generally high (TRL 6-9) for the feedstock supply steps, however, the protein extraction process and product formulation, needs to be adapted and verified to produce fractions with high protein yields and quality. Concrete scaling tests are currently being performed on the investigated crops outside the scope of the BioBIGG project. These tests will allow a more detailed and concise economic feasibility assessment.

1 Introduction

The current trend towards diets with an increasing content of plant-based protein has been recognized in North America, Western Europe and other parts of the world (Court 2018, Sutton, Larsen et al. 2018, GN 2019). There is a consumer desire to reduce the share of meat in their diet for various reasons, such as animal welfare, health concerns, weight management or environmental concerns which explains part of this trend. In order to supply more plant-based protein to fulfil this growing demand, new plant protein-based products need to be developed for this market. Furthermore, there is a desire to produce feed products from local feedstock to reduce the dependence on imported feed meals e.g. soya protein. To exploit the economic possibilities of supplying these products, this pre-feasibility study investigates the requirements and prerequisites of commercial use of novel sources of plant protein from green leaves of broccoli and kale for food and feed applications.

1.1 Project concept

This pre-feasibility study investigates the production of protein concentrates from broccoli and kale leaves. Kale leaves are currently produced as a vegetable food, but in the production process, only the best leaves without damage or discoloration proceed in the production line. Still edible food grade leaves with minor defects are discarded. Also additional kale leaves remain in the field for utilisation as green manure to fertilize subsequent crops. Similarly, broccoli leaves are currently not harvested and left in the field. We propose to recover broccoli and kale leaves from the field and the sorting process, respectively, and use them to extract plant proteins for human and animal consumption.

The project concept aims at recovering residual broccoli and kale leaf biomass and use it as feedstock for plant protein extraction. Protein can be extracted as white protein aimed as a food additive and a secondary green protein fraction containing cell debris and chlorophyll-related components. The green protein and the fibre pulp are evaluated as animal feed.

A potential production process involves separation of proteins in the leaves from the fibre pulp, a cellulosic residue that can be used as ligno-cellulosic feedstock for biofuel production (Bals and Dale 2011) or as animal feed, depending on the source. Use of fibre pulp from such an extraction process could be used as feedstock for biofuel production that could help to avoid indirect land use change (ILUC) effects and the food-vs-fuel debate.

1.1.1 Motivation

Residual broccoli and kale leaves are currently not used despite their suitability as food. This depends mainly on the common way of preparing meals with broccoli and the high customer standards regarding the visual appearance of fresh vegetables in food markets, requiring defect free products. Making use of residual food grade biomass is an effective way of increasing resource use efficiency in crop production.

1.1.2 Protein potential

Broccoli

Protein potential from broccoli production in Sweden was estimated by determining the biomass nitrogen content and multiplying it with the biomass dry matter yield and a protein factor[1]. The resulting protein potential for broccoli leaves varies between 635-1740 kg per hectare.

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[1] We applied a protein factor of 5.6 Mariotti et al. (2008). Mariotti, F., D. Tomé and P. P. Mirand (2008). "Converting Nitrogen into Protein—Beyond 6.25 and Jones' Factors." Critical Reviews in Food Science and Nutrition 48(2): 177-184..

On average during 2014-2018, 120 companies in Sweden produced 2829 tonnes of broccoli on 344 hectares, a yield of 8.2 tonnes per hectare and year (SBA 2019). Of the total, 81% of the Swedish broccoli was produced in the county of Skåne (SBA 2019).

Assuming an average technical protein potential of 1000 kg/ha and a 10-21% fraction of extractable protein (compare Figure 2), a rough estimate of the protein potential yields 0.2-2.1 tonnes of food grade white protein produced from broccoli leaves in Sweden. About 72-83% of that potential is concentrated in the county of Skåne. Scaled to the EU, based on the current broccoli cultivation area, this potential grows to 300-1700 tonnes[2] of food grade white protein produced from broccoli leaves.

Kale

Protein potential from kale production in Sweden was estimated by determining the biomass nitrogen content and multiplying it with the biomass dry matter yield and a protein factor[1]. Since the whole plant tops are harvested, the resulting protein potential for kale leaves left in the field is very low or zero. Instead, leaves sorted out at the factory are assumed to represent a protein potential of approx. 500 kg per hectare.

In 2017, 99 companies in Sweden produced 708 tonnes of kale leaves on 89 hectares, a yield of 8.0 tonnes per hectare and year (SBA 2019). 84% of the Swedish kale was produced in the county of Skåne (SBA 2019).

Assuming an average technical protein potential of 150 kg/ha and a 10-21% fraction of extractable protein (compare Figure 2), a rough estimate of the protein potential yields 0.2-2.0 tonnes of food grade white protein produced from kale leaves in Sweden. About 73% of that potential is concentrated in the county of Skåne. Scaled to the EU, based on the current kale cultivation area, this potential is probably much larger, however, reliable numbers on kale production are lacking for an estimation.

1.2 Production process and products

In the extraction of protein from plant material several products at different product quality levels are possible. Three different production pathways were investigated with respect to potential product recovery rates, product uses and market demands. The pathways include (A) milled biomass production (Figure 1), (B) production of green and white protein as well as brown liquor (Figure 2) and (C) total recoverable green protein (Figure 3).

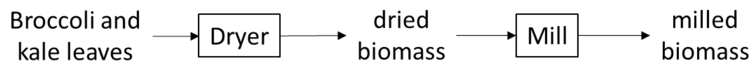

Figure 1. Material flow diagram for the use of broccoli and kale leaves for milled biomass production (pathway A).

Milled biomass would be stored as dried powder, where drum drying and conveyor drying would be the simplest methods to decrease the moisture content to approx. 4-8%. In each case the main energy consumption would be for water evaporation. For instance, a similar approach is used in the production of wheatgrass powder for human consumption.

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[2] Assuming that 25% of the cultivation area of broccoli and cauliflower in the EU28 are used for production of broccoli.

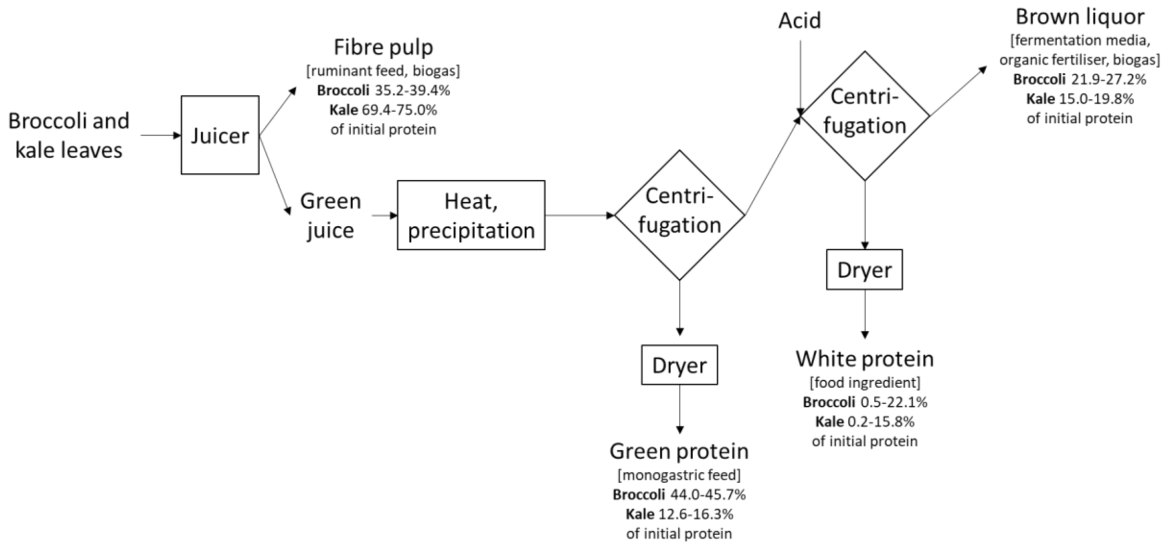


Figure 2. Material flow diagram for the use of broccoli and kale leaf biomass for production of green and white protein as well as fibre pulp and brown liquor (pathway B). Percentages denote the proportion of initial protein in the different fractions. Note that a mechanical disruption step of the leafy biomass before feed-in to the juicer as well as a drying step of the final protein concentrates is required and has been considered in the analysis but is left out here.

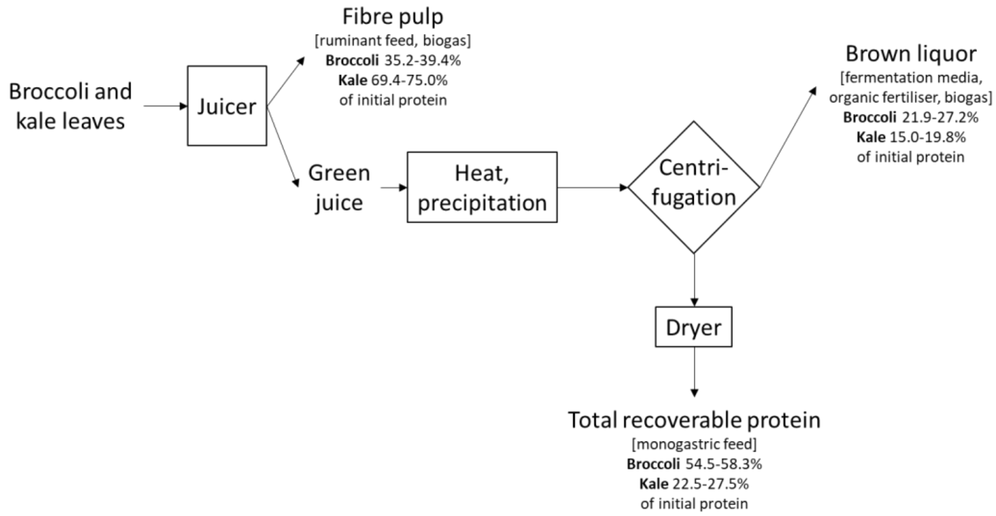


Figure 3. Material flow diagram for the use of broccoli or kale leaf biomass for green juice total extractable protein production (pathway C). Percentages denote the proportion of initial protein in the different fractions. Note that a mechanical disruption step of the leaf biomass before feed-in to the juicer as well as a drying step of the final protein concentrates is required and has been considered in the analysis but is left out here.

For the protein production pathways B and C the following steps are carried out:

- Transfer of the harvested crop to the processing plant within 4 hours to avoid degradation and microbial growth.
- Loading to a feeding and conveying system that transports the biomass into washing and dewatering at constant feeding rate.
- Washing to reduce microbial contamination and remove soil particles.
- Screw-dewatering to disrupt the plant structure and separate the material into fibre pulp and green juice fraction.

For the protein production pathway C, the total protein content of the green juice is precipitated by heat treatment at 80 °C.

For pathway B, the following additional steps are performed:

- Coagulation of coarse particles and green chloroplast proteins into a green solid fraction by a mild heat treatment (50-60 °C)
- Separation of the green protein fraction by means of a decanter centrifuge
- Adjustment of pH to 4.0-4.5 to precipitate the white protein fraction
- Separation of the white protein fraction from the brown liquor by means of a disc centrifuge

2 Project technology concept

2.1 Technology readiness of concept

The technology readiness of the presented concept was assessed in a preliminary and simplified manner in order to present a starting point. Actual TRL levels need to be assessed in close cooperation with participating business partners once an innovation program is to be implemented.

2.1.1 Feedstock supply

Technology of the feedstock supply for the suggested production process is equivalent to technology commonly used for cultivation and harvesting of broccoli and kale. These applied technologies include standard agricultural machinery for crop cultivation (TRL9), harvest technology (TRL 7) and transport logistics (TRL 6), Figure 4.

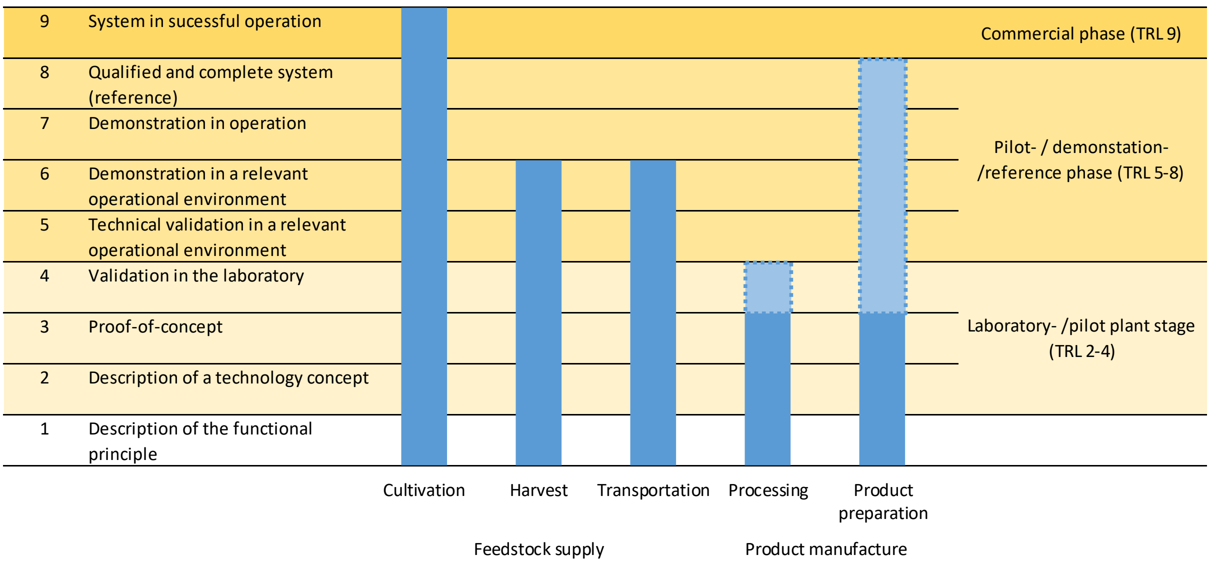


Figure 4. Technology readiness levels (TRLs) as preliminary assessed for the production steps of the concept.

2.1.2 Cultivation

Broccoli

Broccoli is cultivated on humus-rich clay soils with a pH value of 7-8 with a yield of 8-12 tons/hectare in both conventional and organic production (Persson 1988). The crop is usually sown around 1 June at a sowing depth of 2-3 cm, a row distance of 50-60 cm and a plant distance in the row of 40-50 cm (Persson 1988). At a yield of 10 tons/ha, the recommended nitrogen, phosphorus and potassium fertilization level is 195 kg/ha N; 50 kg/ha P and 175 kg/ha K (Lantbruksenheten 1999). It is common to harrow in between the rows 3 times by a row hoe and one weeding by hand during July to October, the crop is hand-harvested (Persson 1988).

The Nordic harvest routines assume that only florets of a 10-15 cm diameter and with a weight of approx. 300 g are harvested. Several harvest per year in the same field occur, which allows for continued growth and harvest of broccoli florets fulfilling the given size and weight criteria.

In the field, up to 70% of the total weight of the broccoli plant is discarded in the form of florets, leaves and stalks (Campas-Baypoli, Sánchez-Machado et al. 2009). During processing, losses correspond to 45% and 50% of the initial broccoli (head weights) with stalks being the main residues (Campas-Baypoli, Sánchez-Machado et al. 2009).

Between 2014 and 2018, approx. 120 companies in Sweden produced 2,300-3,000 tonnes of broccoli on 308-375 hectares, a yield of 6.4-8.9 tonnes per hectare and year (SBA 2019). In 2017, 84% of the broccoli was produced in Skåne (SBA 2019). Total aboveground biomass yield in the field ranges between 49 and 160 tonnes wet weight per hectare, of which only 10 to 33 tonnes per hectare are marketable, leaving 32 to 138 tonnes of harvest residues (Fink, Feller et al. 1999). Of these harvest residues, leaves constitute a share of 20-60% (unpublished data), but also shares of approx. 80 % of the wet weight have been reported for greenhouse-grown broccoli (Domínguez-Perles, Martínez-Ballesta et al. 2010).

Leaves contain ca 13-26% DM (unpublished results) at harvest of the florets. Harvest of leaves would be carried out by hand (during the last floret harvest) and would roughly double the time spent for harvesting (in the last harvest round).

Top producers of broccoli in Europe are Germany and Spain. Germany and Spain have approx. 7 and 85 times larger cultivation area (Figure 5) and approx. 11 and 175 times larger production, respectively, (Figure 6) compared to Sweden.

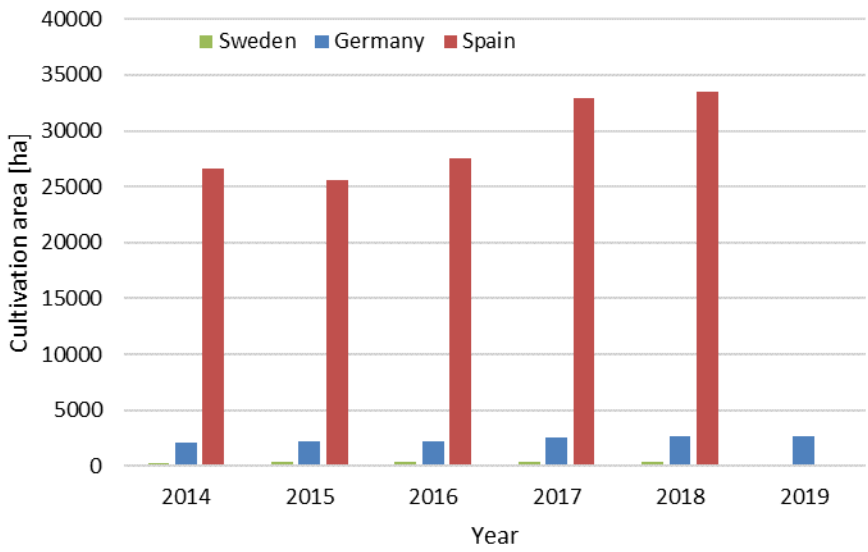


Figure 5. Cultivation area of broccoli in Sweden, Germany and Spain. Based on (ESYRCE 2017, SBA 2019, BMEL 2020).

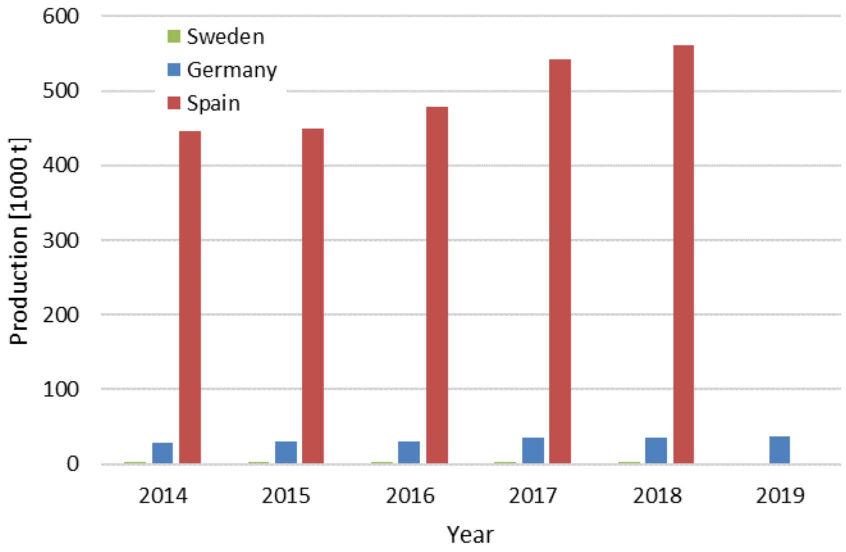


Figure 6. Production of broccoli in Sweden, Germany and Spain. Based on (ESYRCE 2017, SBA 2019, BMEL 2020) .

Kale

Kale or leaf cabbage is a biennial cultivar of cabbage (*Brassica oleracea*). Kale is grown as an annual crop for its edible shoots and young leaves. It is one of the hardiest of all brassicas, capable of withstanding winter temperatures as low as −15 °C. It is also tolerant of high summer temperatures. There are two main groups of kale, the curly-leaved types referred to as Scotch kales or borecole, and the broader, smooth-leaved types. Unlike cabbages, kales produce no head, but leaves are borne on a tall stem, the height of which is dependent on cultivar. The crop is mainly used for winter supplies when other green leafy vegetables may be in short supply (Fordham and Hadley 2003). Nowadays kale is planted earlier in the spring and harvest can start already in July in Sweden. Farmers in Sweden apply no herbicides, which would impact the crop quality, but do apply insecticides.

Between 2014 and 2017, 22-99 companies in Sweden produced 623-708 tonnes of kale on 49-89 hectares, a yield of 8.0-12.7 tonnes per hectare and year (SBA 2019). In 2017, 63% of the kale was produced in Skåne (SBA 2019). Total aboveground biomass yield in the field ranges between 21 and 65 tonnes per hectare, of which only 10 to 26 tonnes per hectare are marketable, leaving 10 to 49 tonnes of harvest residues (Fink, Feller et al. 1999).

The top producer of kale in Europe is Germany. Germany has approx. 3 times larger cultivation area (Figure 7) and approx. 7 times larger production compared to Sweden (Figure 8).

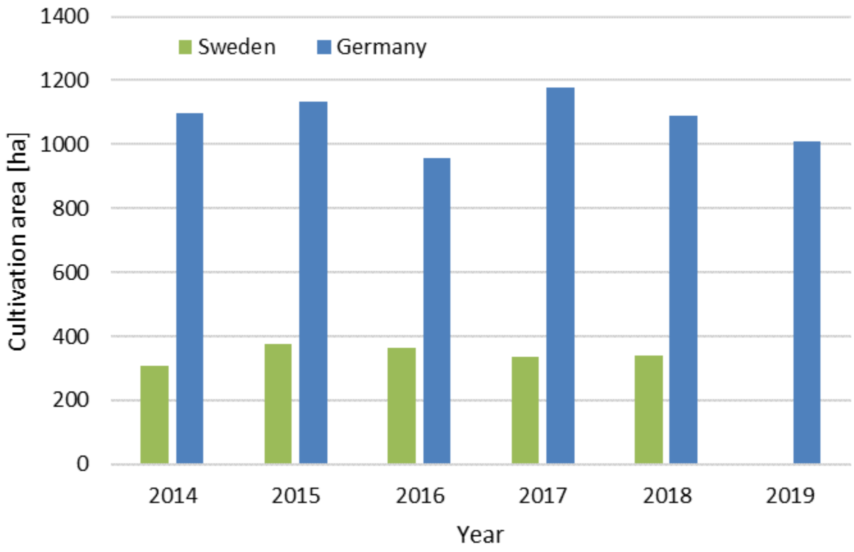


Figure 7. Cultivation area of kale in Sweden and Germany. No kale-specific data was available for Spain. Based on (SBA 2019, BMEL 2020).

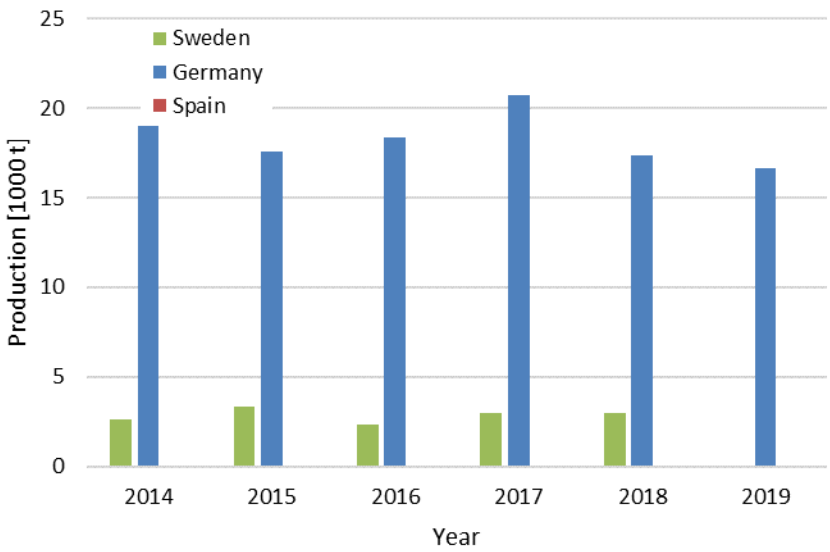


Figure 8. Production of kale in Sweden and Germany. No kale-specific data was available for Spain. Based on (SBA 2019, BMEL 2020) .

Machinery for cultivation and harvest of kale include tractors and tractor appliances already broadly used in vegetable crop cultivation. Operations for the cultivation of these crops include ploughing, seedbed preparation, harrowing and seeding or transplanting, as well as fertilizer spreading and irrigation, which are common practise in broccoli and kale production.

2.1.3 Harvest and transportation

Broccoli

Broccoli is harvested in several steps:

1) The harvesting team walks over the field in two lines. The first line of harvester looks for broccoli florets that are of the correct size and without damage. When these broccoli florets are found, they are cut from the plant with a sharp knife and passed onto the second line of the harvesters.
2) The second line of harvesters stand by the conveyer belt, which loads onto a wagon (Figure 9. Picture of the second line of harvesters on a broccoli field. The travellator and the wagon (picture: Emilia Berndtsson).). The harvesters in the second line catch the broccoli florets from the first line and inspects them. If the floret looks OK, it is put onto the conveyer belt and is loaded into the boxes on the wagon. When all the boxes are full, the wagon is driven to the cold storage.
3) This process is repeated 4-5 times, in order to harvest the broccoli heads when they are optimum (correct size is 250-350 g according to the trading standards).
4) When all the broccoli is harvested, the remaining material is usually ploughed down as a green fertiliser.

Figure 9. Picture of the second line of harvesters on a broccoli field. The travellator and the wagon (picture: Emilia Berndtsson).

Kale

The kale is harvested in two steps:

1) At the field, the kale plant is cut manually (applying a diagonal cut using a sharp knife) approximately halfway up the stem (approx. 50 cm above the ground). The top part is loaded onto boxes on a wagon. The rest which constitutes the larger, woody part of the stem and potentially a few too small leaves, is left on the field.
2) When the wagon is full, it is driven to the sorting and packaging house. There, the leaves are manually sorted, with sellable leaves in one pile and the unsellable leaves, topmost part of the plant (Figure 10), stalks and the central stem are discarded (Figure 11. *Collection of discarded kale parts at packaging (picture: Emilia Berndtsson)*).
3) When all the kale is harvested, the remaining material is ploughed down as a green fertiliser. Approximately 50% of the kale plant is harvested. Of a plant with a weight of 1500 grams, approximately 700-800 grams are sold as kale leaves. Some wholesalers do not accept any leaf stalks at all, while others want some of the stalks in the packed kale leaves.

Figure 10. One example of the discard in kale production, the central stem and some of the leaf stalks (picture: Emilia Berndtsson)

Figure 11. Collection of discarded kale parts at packaging (picture: Emilia Berndtsson)

Harvesting of broccoli leaves is not common in agriculture. Recovery as feedstock for protein extraction would require an additional round of harvest for just the leaves. As much of the harvest is manual labour, harvesting practise needs to be adjusted or additional harvesting operations need to be carried out, both of which are relatively easy to implement, but labour-intensive and therefore economically costly.

For the kale leaves, current manual sorting practises into marketable leaves and residues would need to be adjusted for a third fraction of leaves going into the protein extraction process. These leaves may have smaller defects or discolorations, with dirty or microbially contaminated leaves still going into the residual fraction, as is current practise. This additional sorting choice is considered easy to implement with no additional costs considered.

Crop biomass intended for protein extraction needs to be processed within few hours after cutting the plants to avoid cell processes that lead to deterioration of proteins as well as to avoid microbiological contamination. The lower TRLs for the harvest and transport logistics consider the demand for adjusted and optimized machinery and/or harvesting logistics. TRL-levels higher than 6 for the harvest part (Figure 4) are possible with available technology used for harvesting the main crop parts (broccoli florets and kale leaves). We assume a facility processing leaf biomass in September to November. This facility needs to process other crops and biomass feedstock during the rest of the year (e.g. green rye in May to June, sugarbeet leaves in September and October) in order to become economically feasible.

2.1.4 Processing

Several plant-based protein products are available commercially on the market, both sold as food grade and as feed grade material. Despite the availability of these soya-, wheat-, pea- or rice-based proteins, the technology readiness level (TRL) of the presented processes is currently considered to be low, TRL 3-4, mainly due to the uncertainties regarding product extraction and recovery rates and the resulting need to adjust the extraction processes to the feedstock composition (Figure 4). Details on the process design are given in the economic assessment below.

2.1.5 Product preparation

For pathway A, dewatering and drum drying are considered to be the simplest methods at TRL 5 for preparation and in each case the main energy consumption would be for water evaporation. A milling step is considered to have a TRL of 5.

For pathways B and C, once the wet protein-rich fractions are obtained via precipitation and centrifugation, they require drying to stabilise the product and avoid microbial deterioration. The necessary unit operations are standard operations, which need to be adjusted to the specific process, but the technology applied is mature and readily available with a TRL of 7-8. However, among other important steps, testing for anti-nutritional compounds must be carried out as well as taste and taste acceptance verified which reduces the overall TRL to 3 for this step.

2.2 Requirements and properties

2.2.1 Food grade production

In order to meet food grade standards, compliance with existing processing facility rules and guidelines will be required. As the products resemble leafy greens, equipment such as conveyors and washers for those products are readily available but may need to be adapted for specific crops (TRL 8). The separation of juice and fibres resembles the production of fruit juices or other dewatering processes where food grade equipment is mature and readily available (TRL 9). Protein recovery does not differ significantly from some existing food grade plant protein production using commercial equipment such as heat exchangers, pumps, piping and centrifuges etc. (TRL 9).

2.2.2 Nutritional value

A general challenge for plant proteins isolated from a single crop can be their "incomplete" essential amino acid content in respect to human nutritional demand. One way to receive a more complete nutritional amino acid content is to combine protein sources. However, these combination proteins tend to include ingredients with lower quality scores, which can affect the sales price of the ingredients and potential returns to producers and growers (Sutton, Larsen et al. 2018).

In order to gain an overview of the nutritional and anti-nutritional compounds present in broccoli and kale leaves, we briefly discuss the nutritional profile here:

2.2.3 Nutritional compounds

Broccoli residue leaves are reported to contain a variety of beneficial bioactive compounds such as polyphenols, glucosinolates, dietary fibers, vitamins and minerals, very similar to what is found in the heads/florets (Zhang, Jiang et al. 2017, Berndtsson, Andersson et al. 2020). Previous studies have reported the use of dried ground broccoli leaves as a food ingredient to improve the nutritional quality of bread, pasta and green tea (Dominguez-Perles, Moreno et al. 2011, Ranawana, Campbell et al. 2016, Angiolillo, Spinelli et al. 2019). Kale leaves have also been reported to contain high amounts of polyphenols, glucosinolates, fibers and minerals (Lisiewska, Kmiecik et al. 2008, Biegańska-Marecik, Radziejewska-Kubzdela et al. 2017). Consumption of green leafy vegetables containing polyphenols and fibers are known to have associated health benefits e.g. dietary fibers can improve digestive system function and phenols improve cardio-vascular function and lower the risk of cancer and chronic inflammations (Wang, Melnyk et al. 2011, Mackie, Bajka et al. 2016).

In addition to bioactive compounds, broccoli and kale leaves also contain proteins with attractive amino acid profile suitable for both feed and food products. Previous studies on broccoli and kale residue leaves have reported that protein contain up to 15 essential and non-essential amino acids (Lisiewska, Kmiecik et al. 2008, Campas-Baypoli, Sánchez-Machado et al. 2009). The recovery of white and green proteins fraction from sugarbeet leaves have shown that both protein fractions contain similar quantities of both essential and non-essential amino acid (Merodio and Sabater 1988). In this prefeasibility study, the white protein fraction is suggested for human consumption, and green and total recoverable proteins are suggested for animal consumption. The white protein mostly contains soluble protein fraction called Ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCo). Previous studies have confirmed the presence of RuBisCo in both green and white protein fractions. RuBisCo offers attractive functional properties for food processing such as good gelation at low concentrations and low gelation temperature (Martin, Nieuwland et al. 2014), making it a suitable alternative to egg proteins.

The green protein fraction and total recoverable proteins contain chlorophyll related components and cell debris which gives them a characteristic grassy flavour and making suitable for only animal consumption. Extraction of green proteins from alfalfa, red and white clover, and perennial rye grass have a shown a better nutritional profile compared to soyabean feed meals (Stødkilde, Damborg et al. 2019, Damborg, Jensen et al. 2020), although these proteins were deficient in sulphur containing amino acids such as methionine and cysteine. Previous studies have shown that leaf proteins based feed offer improved digestibility and are a balanced source of amino acids for mono-gastric animals (e.g. pigs) (Stødkilde, Damborg et al. 2018, Damborg, Jensen et al. 2020), and ruminants (e.g. lactating cows) (Lu, Jorgensen et al. 1988).

2.2.4 Anti-nutritional compounds

Anti-nutritional compounds present in green vegetables include nitrates, oxalates, phytates, tannins and saponins (Natesh, Abbey et al. 2017). These anti-nutritional compounds when present in higher quantities in food and feed, may have negative health impacts and in general reduce the nutritional quality of the product. The amount of these compounds in vegetables largely depends on various agronomic, environmental and genetic factors. Also, their mild to adverse health impacts on human or animals depends on factors such as how biomass is processed after harvest (cooking or blanching) and how much is consumed as food or feed. For example, the amount of nitrates in leafy vegetables depends on time and form of nitrogen fertilizer applied during crop production (Colonna, Rouphael et al. 2016). In general, consumption of leafy vegetables containing nitrates may not be harmful when consumed in smaller vegetable servings. Although when ingested in larger quantities, nitrates produce by-products such as nitrites and nitric oxide, which may have negative health impacts on humans (Huarte-Mendicoa, Astiasaran et al. 1997).

Among anti-nutritional compounds in green vegetables, the oxalates, phytates and tannins act as inhibitors to mineral absorption during digestion in both humans and animals. For example, oxalates form soluble salts of potassium and calcium during digestion and these salts make complexes with calcium and other minerals and decrease their availability for absorption in the digestive system (Erdoğan and Onar 2011). Phytates are another set of anti-nutritional compounds which make insoluble complexes with zinc and iron, and impair their digestibility in the body (Khoja, Buckley et al. 2020). In children, the minerals deficiency could lead to poor growth and increased susceptibility to infectious diseases (Umeta, West et al. 2000). Unlike oxalates and phytates, tannins are soluble phenolic compounds which not only impair the solubility of minerals such as iron but also make complexes with dietary proteins, making them unavailable for absorption in the body (Salunkhe and Chavan 1989). In animals, larger amounts of tannins could lead to poor growth, digestion problems and poor feed utilization efficiency (Butler and Rogler 1992).

The amount of compounds acting as inhibitors to mineral absorption are relatively low in broccoli and kale as compared to other leafy vegetables such as spinach (Natesh, Abbey et al. 2017). Furthermore, it is previously reported that the processing conditions such as heating and blanching may reduce the quantity of anti-nutritional compounds in the final product (Oboh 2005). In conclusion, we believe that a better understanding of anti-nutritional compound accumulation in different protein fractions is needed before marketing broccoli and kale leaf-based food and feed products.

3 Market situation

The current trend towards diets with an increasing content of plant-based protein is driving the demand for plant based protein products. A desire to reduce the share of meat in the diet for various reasons such as animal welfare, health concerns, weight management or environmental concerns is part of the motivation for this development. This increasing demand is met by a limited, but quickly developing market and supply of plant-based protein. Besides soya-based proteins that have been part of Asian diets for a long time, very few plant-based proteins have been made available commercially in large quantity. These include proteins extracted mainly from pea, wheat and rice[3]. The market value of plant-based protein is predicted to grow from 4.16 billion US$ in 2017 with a geometric progression rate of 7.5% until 2025 (GN 2019). For example, the Canadian government plans to invest 150 million CAD in the plant-based sector, reflecting the increasing demand where 43% of Canadians are trying to eat more plant-based food (Court 2018).

The choice between the three production pathways presented here is a cost optimisation problem. Costs for additional steps (secondary precipitation, purification) to extract the white protein fraction need to be covered by a higher product sales price. This is potentially possible, but likely requires marketing as high-value product, not as a bulk food additive.

Table 1. Overview over product value, market size and market readiness for application of the different fractions obtained din the protein extraction process.

Product	Application	Product value	Market size	Market readiness
Milled biomass	a) Health food product	$$$	XX-XXX	XX
	b) Food ingredient	$-$$	XXX	X
White protein (B)	a) Food additive	$-$$	XXX	XX
	b) High-value product (health food, cosmetics)	$$- $$$	XX	XXX
Green protein; total recoverable green protein	Feed for monogastric animals	$	XX	XXX
Fibre pulp	Feed for ruminant animals	$	XX	XXX

4 Economic feasibility

A cost-benefit analysis of the use of broccoli and kale leaves for the valorisation of protein for food and feed applications was conducted. Calculations were carried out as a step-by-step assessment that included all necessary machinery operations in the field, transport, storage and processing in a simulated protein extraction plant. Results of this type of pre-feasibility study usually have an error margin of up to ±30% (Bals and Dale 2011). To also present the variation of the results, we employed

[3] Own analysis based on the commercial products offered at Alibaba.com

a low and a high range analysis for each cost and revenue structure for each pathway to show the variability of the input data.

Experimental results of field and laboratory studies were modified to reflect the technical potential of the applied process. Lab experiments showed a very low white protein yield of <1% of the initial protein content (Figure 2). The lab experiments were aimed at extracting functional proteins, i.e. proteins that display functionality as foaming or dough rising agents, which is represented in the "low" range. However, with more advanced separation technology (i.e. ultrafiltration) it was assumed that 90% of the protein entering the white protein extraction step could be recovered, which is represented in the "high" range. This maximised precipitation was assumed to require ultrafiltration replacing the acidification step and to result in a protein content of 29% in the white protein fraction. The change to ultrafiltration replaces centrifuges and but uses pumps at low pressure and cooling of the pumped liquid. As centrifugation is a relatively energy-intense unit operation, this change was assumed to have no impact on the energy use and cost assessment. Regarding the cost aspect, this has to be investigated in more detail in a follow-up study. Additional data used in the assessment of the broccoli and kale biomass recovery is presented in Appendix Tables A1, A2 and A3. Cost of mineral nitrogen fertiliser was assumed to be 1.0 €/kg (SBA, 2017). Assumptions for the storage of fibre pulp are given in Appendix Table A4. A conversion factor of 1 SEK=0.09433 EUR = 0.10545 USD was applied.

4.1 Field experiments

The amount of field waste in broccoli production was measured, at a commercial farm in north-western Scania, Sweden, in August 2018. In this measurement, three squares (1.5 m x 1.5 m) were randomly placed in the field according to Strid, Eriksson et al. (2014) and 10 broccoli plants in each square were cut 2 cm above the ground, weighed, and then divided into different fractions (heads, leaves and stalks) which were individually weighed. The mean weight per 2.25 m2 square for the different fractions and for the whole plants was calculated before and after drying. Results on the field residues are given in Appendix Table A1.

Samples of the plant residues were taken within 24 hours after the last harvest of the main produce, to minimise deterioration of the residues. Since the broccoli field was harvested earlier, the sampling was only meant to reflect the fractions of leaves and stems in the residual biomass left in the field. In this sampling, plants of broccoli and kale were cut approximately 2 cm above ground (excluding the roots and the woodiest part of the stalks). Leaves already laying on the ground were not collected.

The plant samples were transported to a laboratory in Alnarp, washed to rinse away dirt, air-dried and then the plants were separated into leaves and stalks. Whole leaves were placed pairwise in bags. Stalks were divided into three parts (top, middle and base) and placed in bags. Leaves were stored at -80 °C, prior to protein extraction process.

4.2 Field and transport operations

Cost for additional harvest in the field were assessed based on the assumptions of a labour and machinery requirement in the same extension as the currently applied practise for harvest of broccoli florets and marketed kale leaves (Appendix Table A2). For kale, we also estimated costs based on the already occurring sorting practise in the factory. Instead of sorting kale leaves into marketable and non-marketable leaves, the non-marketable fraction would be further sorted into leaves suitable for protein extraction and leaves to be discarded. This distinction would mainly be done on the basis of an ocular judgement and would result in slightly damaged and discoloured leaves to be used for protein extraction, while heavily damaged leaves and leaves with microbiological defects would be discarded. The useful feedstock is considered to have no additional costs for harvest, only for transport.

Kale has a low DM content of approx. 15% (Finch, Samuel et al. 2014), which means that transport is relative inefficient and costly in relation to the amount of protein contained. Such a low DM content also means that kale leaves cannot be stacked high, since the increasing pressure would result in a premature juicing during transport. If liquids can be contained this may, however, not be a problem.

4.3 Processing

For the milled biomass (pathway A), all the dry matter in the biomass is turned into the final product, the broccoli and kale leaves were assumed to be dried in a drum dryer to a moisture content of 6%, then milled to a fine powder. For instance, a similar approach is used in the production of wheatgrass powder for human consumption.

For the extraction of protein fractions (pathways B and C), the leaf biomass in the processing plant is directly fed to a washing basin to remove surface contamination including soil particles. From the washing step the biomass is fed into a screw-dewatering machine designed to disrupt the cell structure and to separate the material into the fibrous pulp and a green juice fraction. The fibrous pulp is ensiled for later feeding to biogas production or use as cattle feed. The juice is heated to 50-60°C to coagulate and precipitate the green protein components. These green protein components and any leaf debris in the green juice are separated in a decanter centrifuge and dried to a green powder using a drum dryer. The pH of the supernatant from the decanter centrifuge is adjusted to approximately pH 4.5, to precipitate the white protein fraction. In a disk centrifuge the white proteins are separated and dried in a spray-dryer to form a white powder. The clarified brown juice is stored for later use e.g. in biogas production. Resulting protein content in the obtained fractions in pathways B and C are given in Appendix Table A3 and processing economic data is presented in Appendix Table A5.

4.4 Products

For pathway A, the final product is a fine powder with a moisture content of 4-8% resulting in a long shelf life, aimed at the premium health product section. Economic cost for the drying process are presented in Appendix Table A6.

For pathways B and C, plant proteins are considered the main product of both processes. Protein is present in concentrated form in different fractions. Protein fractions, i.e. fraction with a high protein content, need to be dried, resulting in a fine powder with a moisture content of 4-8% resulting in a long shelf life.

White protein concentrate is aimed to be an ingredient in the food industry for human consumption. DM protein yields depend strongly on the conditions for protein precipitation, typically ranging between 0-30 percent. Using ultrafiltration, protein recovery was assumed to be increased to 90% of the protein in the white juice (Fernández, Menéndez et al. 2007). An additional purification step was also assumed, that increased protein content to 85% in the final product (Edwards, Miller et al. 1975, Tenorio, Gieteling et al. 2016). Because of the harsh precipitation conditions assumed, only the nutritional value was considered in the techno-economic assessment. The product is considered an off-white powder with a protein profile suitable for human consumption.

The composition of protein, other DM content and water in the final products for the different process fractions is given in Figures 12 and 13.

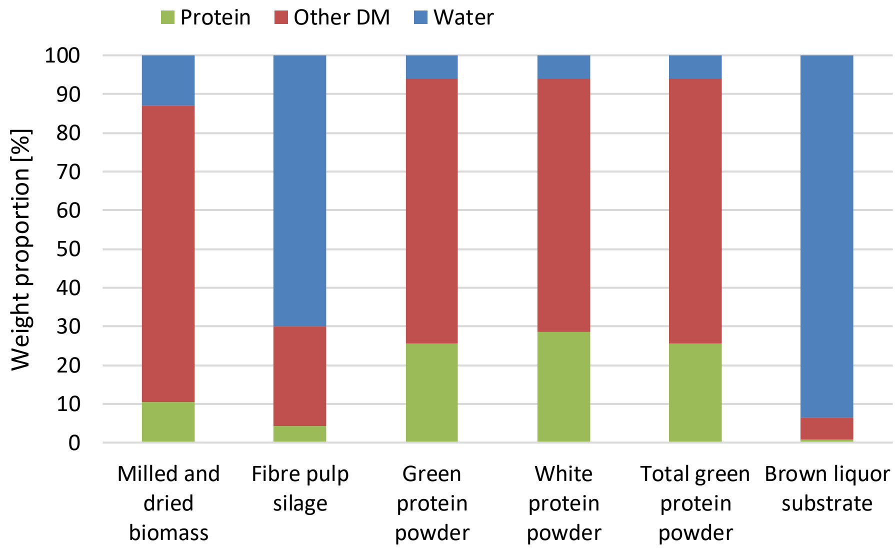


Figure 12. Weight proportions of protein, other dry matter and water in the final products processed from broccoli leaves as considered in the economic assessment.

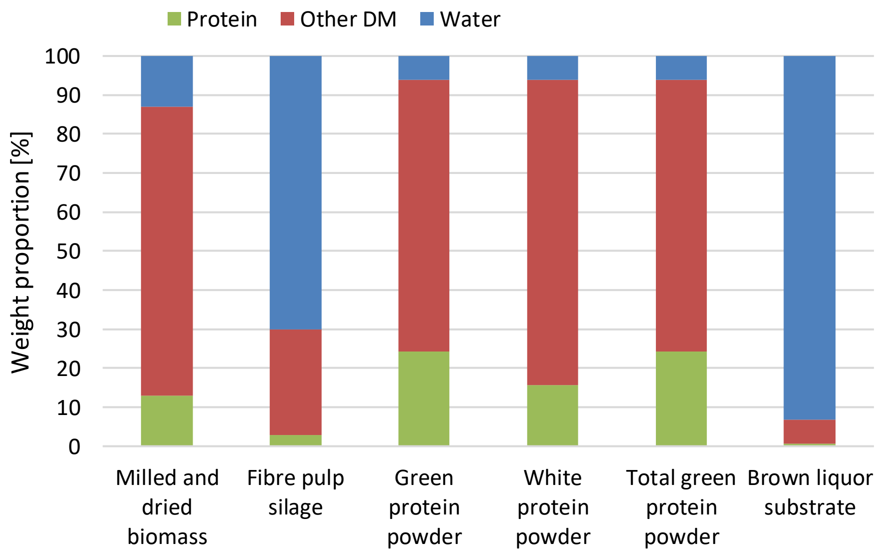


Figure 13. Weight proportions of protein, other dry matter and water in the final products processed from kale leaves as considered in the economic assessment.

The green protein fractions obtained from pathways B and C are prepared similarly as powder, but are intended for use as feed or a feed ingredient. Similar to the white protein product, the protein content was assumed to be 29 % in the final product (Tenorio, Gieteling et al. 2016). Although a protein profile suitable for use as animal feed for both monogastric animals and ruminants was assumed, the economic assessment was carried out for the use as horse feed, specifically as high-protein horse feed additive. However, similar products available on the market have a considerably lower protein content, approx. 17%, while their fibre content is similar to that of the kale product (16%) whereas the broccoli product had a lower fibre content, 11%, compared to current commercial products.

The fibre pulp fraction has a dry matter content of 30% and is ensiled, a fast, in-expensive and mature solution for conserving the biomass as feed. Similar to ley grass silages, the product can be used as feed for ruminants, e.g. cattle or sheep. The protein content of the fibre pulp fraction is approx. 4.3 and 3.0% wet basis or 14.2 and 9.9% dry basis for broccoli and kale as feedstock, respectively, which is similar to that of whole-crop barley silage (Magnusson 2017). A protein profile suitable for use as animal feed for ruminants was assumed. As an alternative, and similar to the milled biomass approach, the fibre pulp could be prepared as dried powder and sold as a health product. Here, dewatering in combination with drum drying or conveyor drying would be the simplest methods for preparation. In each case the main energy consumption would be for water evaporation. These additional costs probably require that a dried product be sold as a premium product such as a healthy food additive.

Brown liquor is a residue product containing soluble components with potential use as biogas substrate. However, due to the low DM content (approx. 10%) transport cost are expected to be high. Potential operations to increase DM content need to be balanced against product value. Since this by-product can become a cost or revenue, depending on the transport distance, revenues have not been included in the economic assessment.

Protein revenues have been estimated based on current market prices of comparable products and are presented in Appendix Table A7.

4.5 Results

Economic assessment evaluating the milled biomass pathway (A) and the extraction of white and green protein following pathways B and C showed large differences in both costs and revenues for the investigated range of low and high yields in field production and protein extraction as well as variability of process data (Figures 14 and 15).

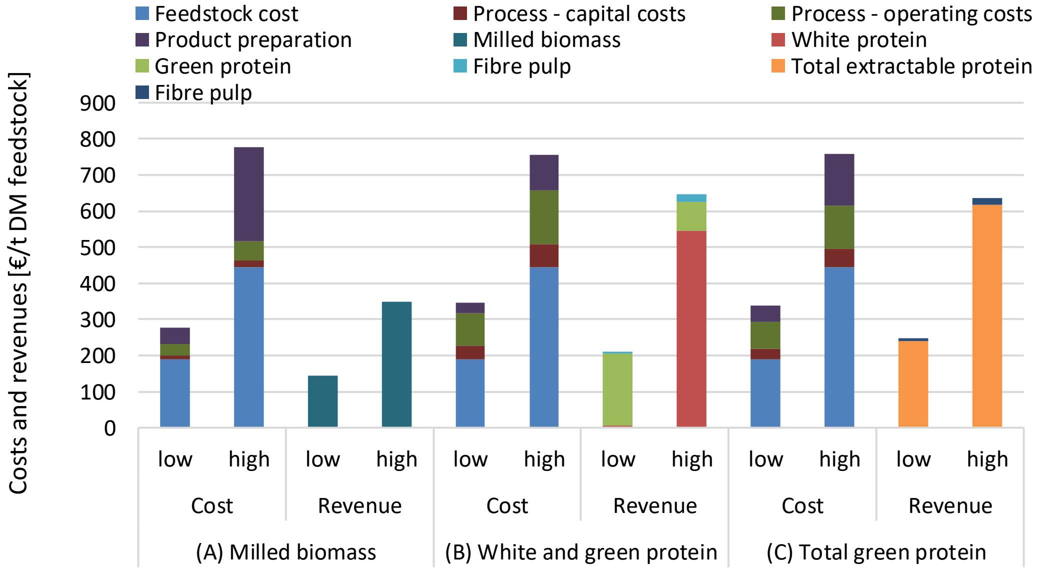


Figure 14. Cost and revenues [€/t DM of feedstock] for the three tested production pathways using broccoli leaves as feedstock. Feedstock costs include costs for recovery and transport.

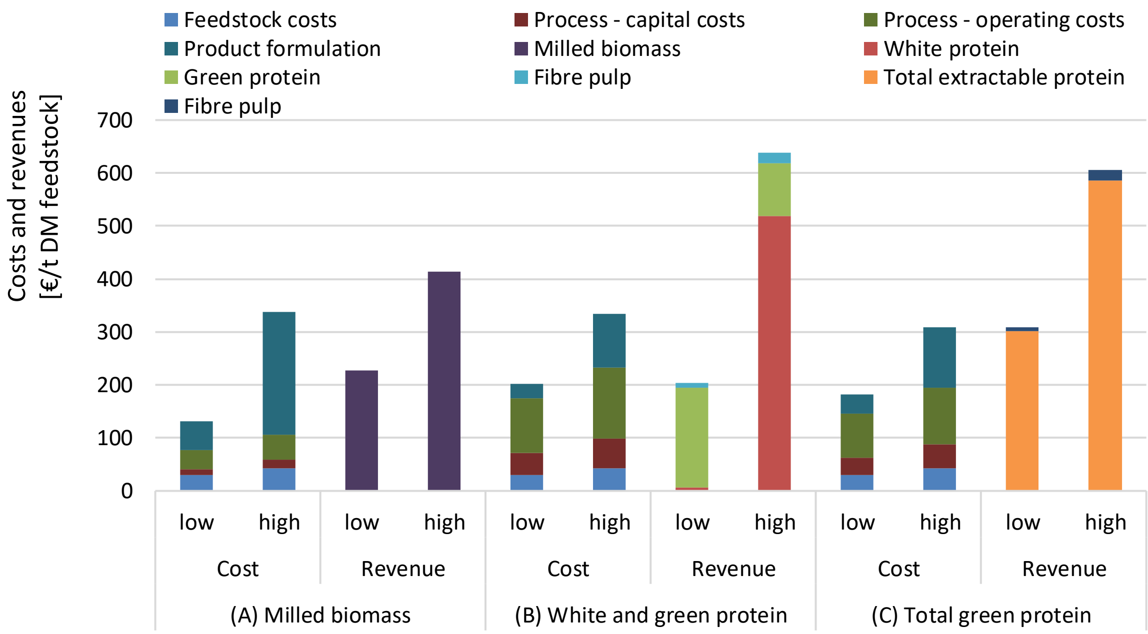


Figure 15. Cost and revenues [€/t DM of feedstock] for the three tested production pathways using kale leaves as feedstock. Feedstock costs include only transport, not additional costs for recovery.

4.5.1 Costs

Broccoli

Feedstock costs for broccoli leaves were the same for all three production pathways and with 55-68% of the total cost represented the largest share. In comparison, process capital costs, process operating costs and product preparation corresponded to 2-11, 7-26 and 8-34% of the total costs (Figure 14). The less intense processing in the milled biomass pathway (A) resulted in a considerably lower range of the relative process costs of 2-4%. On the other side, product preparation in the milled biomass pathway showed a much higher relative cost of 17-34%, due to a large amount of material requiring drying. Product preparation costs per Mg of feedstock for production of white and green protein fractions were 31-37% lower, respectively, compared to the total green protein production pathway for broccoli leaves. This was mainly due to lower extraction efficiency for white protein extraction and corresponding lower drying requirements.

Kale

Feedstock costs for kale leaves were the same for all three production pathways and with 13-22% of the total cost represented a much smaller costs compared to broccoli leaf feedstock. This was due to the availability of the leaves from the sorting facility without further harvest costs. In comparison, process capital costs, process operating costs and product preparation corresponded to 2-21, 14-51 and 14-69% of the total costs (Figure 15). The less intense processing in the milled biomass pathway (A) resulted in a considerably lower range of the relative process capital costs of 5-9%. On the other side, product preparation in the milled biomass pathway showed a much higher relative cost of 42-69%, due to a large amount of material requiring drying. Product preparation costs per Mg of feedstock for production of white and green protein fractions were 11-25% lower, respectively, compared to the total green protein production pathway for broccoli leaves. This was mainly due to lower extraction efficiency for white protein extraction and corresponding lower drying requirements.

4.5.2 Revenues

Revenues in the production pathway A ranged from approx. 150-350 and 230-410 €/Mg DM of feedstock for broccoli and kale leaves, respectively, when marketed as a health food product (Figures 14 and 15). In these numbers, value was attributed to the protein content but not to any health effect of the fibre and phenolic content of the biomass. However, the value and therefore the pricing of the product could be increased if health effects based on the phenolic content can be substantiated. Wheatgrass powder is an example of a product in the same category.

Revenues for the products in production pathway B, production of white and green protein, ranged from approx. 200 to 650 €/Mg DM of feedstock for both broccoli and kale leaves used as feedstock (Figures 14 and 15). Within this production pathway, the proportion of revenue originating from the white protein fraction varied strongly, from ca 3 to 85% for both broccoli and kale leaves. The very low share of revenue was caused by the very low extraction efficiency in the lab experiments aimed at extracting protein with functional value (e.g. for foaming properties). Assuming a more stringent recovery procedure (e.g. using ultrafiltration), revenues are likely to be increased, as presented in the high revenue case. In the low case, the revenues from the green fraction represented over 90% of the total revenues, since most of the protein that was not precipitated in the white protein extraction will precipitate in the green protein extraction step. Going from the low to the high case, the revenue for the green protein fraction decreases to approx. 12 and 16% for broccoli and kale leaves, respectively. The fibre pulp contribution to revenues ranged between 2-4%.

Revenues in the production pathway C ranged from approx. 250 to 640 €/Mg DM of feedstock for both broccoli and kale leaves used as feedstock (Figures 14 and 15). Within this production pathway, the proportion of revenue originating from the green protein fraction varied little and was approx. 97% of the total revenues, for both broccoli and kale leaves. Revenues varied mainly due to a large price variability of the market. The remaining approx. 3% were contributed from the fibre pulp.

4.5.3 Economic viability

Broccoli

For all three production pathways, revenues in the high case were higher compared to the cost in the low case, but lower than the costs in the high case, indicating that a more detailed assessment is required to evaluate if there is a potential to develop this pathways commercially. The focus of a more detailed assessment should be on product quality enabling a better value assessment and market placement.

Kale

For kale, economic feasibility is much more likely to achieve in comparison to broccoli, since kale most leaves are harvested in one step when harvesting for conventional kale leaf marketing. The leaves to made available for protein extraction are derived from the quality sorting step in the leaf processing facility were used and no further harvesting costs (except transport costs) apply. For pathway A, costs and revenues are comparable, indicating that a more detailed assessment is required to evaluate if there is a potential to develop this pathways commercially. For pathway B, the high case show a potential to become an economic feasible production, indicating, that a high white protein recovery as e.g. made possible applying ultrafiltration, is needed to achieve this. For the recovery of total green protein (pathway C), if revenue can be confirmed at the level in the high case, a good potential exists to develop animal feed products from kale leaves.

The potential to reduce feedstock supply costs for additionally harvested broccoli leaves is regarded as low, since this interferes with current practise of quality-driven harvest operations picking only florets suitable for the fresh market. A combined whole plant harvest with sorting of leaves as existing for the kale production is therefore regarded as unlikely to implement.

4.6 Technology choice

The lack of lab validation of high recovery of extractable white proteins requires more detailed lab study and scale-up projects. Furthermore, several other factors might limit the economic performance of the mechanical pressing method. The required mills and presses have high capital and electricity costs. In addition, the method requires fresh biomass, which limits commercial operation to a few months per year (Bals and Dale 2011). As mentioned above, a processing facility for protein recovery would have to also process other plant materials in order to get enough biomass input to become an economically feasible facility. Ultrafiltration is required for increasing white protein recovery from kale leaves above the threshold for economic feasibility in pathway B.

Aqueous extraction of proteins might prove a more economically viable option for leaf protein concentrate production, since it can be performed on dried material (Bals and Dale 2011). The value of alkaline extracted protein concentrate is currently unknown as alkaline treatment has been shown to influence solubility negatively (Deleu, Lambrecht et al. 2019). In contrast, positive impacts of alkaline treatment, e.g. On colour and flavour, have been reported (Deleu, Lambrecht et al. 2019).

4.7 Protein extractability

Protein extractability and recovery can be very variable between different plant species and even varieties of the same plant. Upscaling of laboratory results may inherit a risk of over- or underestimation of protein extractability, for example when extracts are glutinous or tend to foam (Pirie 1978). Agronomic or plant physiological research may be needed to investigate the impact of sowing dates, fertilization levels, harvest date for different plants and varieties (Pirie 1978).

The presence of phenolic substances in leaf extracts has been reported to potentially diminish protein extraction due to enzymatic formation of tanning agents. These agents can coagulate proteins and reduce their digestibility and at high concentrations may prevent protein extraction completely (Pirie 1978). Phenolic content has been identified as the factor most often responsible for small yields of LP (Butler 1982). Further lab research is needed investigate how compounds negatively impact the extractability of leaf protein and measures to counteract them.

The harvest and the sorting step in the process facility will determine how much of non-leaf plant parts will enter the protein extraction process. Earlier experiences with stems from kale show shat these stems did not harm the equipment. However, stems could be rotten inside, which could become a contamination problem in the protein extraction process. The stems are rather dry and might also suck up water and protein in the juicing process, reducing the extractable protein or add undesirable tastes. On the other side, the stems may add additional protein, which should be investigated more.

The juicing yield from kale was relatively low in the laboratory analyses, resulting in a high protein loss to the fibre fraction. Further investigations in suitable juicing procedures (e.g. pre-grinding, post juicing grinding with additional juicing steps) are needed to improve yields.

The feedstock of broccoli and kale leaves and other plant parts ending up in the process are food grade, which simplifies legal requirements for implementing such process facility. This is in contrast to many other crop or crop residues aimed for plant protein extraction, where the feedstock is derived from non-food crops.

4.8 Product development

Since broccoli and kale leaves can be classified as food, even the green protein fractions could be developed as food ingredients for human consumption. Green protein fractions usually have a strong grassy, green taste, which is not easy to use in food production. However, novel application such as a flavouring agent in soups could be developed, where this strong taste may enhance the final product and additionally add proteins, fibres and phenolic compounds.

Other potential products not included here but interesting for future investigations are:

- Green juice fresh - limited shelf life, must ship refrigerated and use immediately, need local fresh juice contractor or do preparation directly in the juicing process.
- Green juice dried as a powder
- Dried fibre powder (sold as fibre supplement); as an alternative, and similar to the milled biomass approach, the fibre pulp could be prepared as dried powder. Here, drum drying and conveyor drying would be the simplest methods for preparation and in each case the main energy consumption would be for water evaporation. These additional costs probably require that a dried product be sold as a premium product such as a healthy food additive.
- Green protein fraction (as dietary supplement)
- Dried white protein (high protein, low "greenness" and phenolics still in place)
- White protein concentrate (seems like low yield with these substrates)
- Dried brown juice (probably high in phenolics with intense taste – as a nutritional supplement)
- Phenols can likely be extracted from the brown juice. This is interesting since this fraction has quite high concentrations (of the DM) and all phenols are dissolved.

5 Sustainable development and local and regional development benefits

Implementation of broccoli and kale leaves as a feedstock for protein extraction would benefit farmers with an additional income for sale of the biomass feedstock. The increased transportation need would benefit logistical services in the region.

Using residual broccoli and kale for protein extraction increases resource use efficiency and provides multiple interesting products that add to sustainable development. Production of:

- White protein for human consumption: increased supply of plant-based proteins and enabling a switch to a reduced-meat derived protein diet.
- Green protein and total recoverable green protein: increased supply of locally produced feed and feed additives for monogastric animals.
- Fibre pulp: increased supply of locally produced feed and feed additives for ruminant animals.
- Brown liquor: can be used as feedstock for biogas production that when upgraded to vehicle fuel can decrease the dependency on and use of fossil fuels and possibly as a feedstock for fermentative processes. Residuals from brown liquor fermentation can be used as biofertilizer.

These benefits contribute to several of the Swedish environmental goals; Reduce climate impact, Zero Eutrophication, A Rich Diversity of Plant and Animal Life, and A varied agricultural landscape, as well as to the UN sustainable development goals (2.4, 7.2, 8.4, 9.4, 12.2, 13.2 and 13.3).

6 Discussion and conclusions

This pre-feasibility study has shown that green biomass from kale leaves has large potential in major cultivation areas as a raw material in plant protein recovery for producing protein-rich food and feed products. However, the production potential in Sweden is relatively low due to low production volumes of broccoli and kale. Still, broccoli and kale leaves could become part of a feedstock portfolio of a plant protein facility.

Due to the need for additional harvest operations for recovering broccoli leaves, neither of the investigated production pathways is economically viable without an adjustment of the current practices of harvesting broccoli florets. Alternative harvest methodologies similar to the kale harvest could entail the harvest of the larger part of the broccoli plant with a facility based sorting procedure. However, it seems unlikely that such a harvest operation would be feasible and possible to integrate in the existing harvest methodology.

The simple process of drying and milling the leaves to prepare a health product seems to be an interesting option mostly for kale leaves, since the current production setup does not require costly field operations for additional harvest, but with simple process adjustment can provide the feedstock with only transportation costs straining the economic balance.

The white protein fraction contains essential amino acids and is suitable as a food ingredient or additive. Thereby, white protein from kale and broccoli leaves could contribute to fulfilling the increasing demand for plant protein-rich food products. The green protein and total recoverable protein fractions with essential amino acids and a likely efficiently digested in monogastric and ruminant animals, can fulfil a demand for locally produced protein-rich feed and thereby reduce the need for imported protein-rich feed products. However, the nutritional and anti-nutritional effects of the investigated products is unclear, although may present a value for product marketing. We believe that a better understanding of anti-nutritional compound accumulation in different protein fractions is needed before marketing broccoli and kale leaf-based food and feed products.

In the economic assessment for recovery of protein concentrates from green biomass we already have assumed placement as premium feed products for horses. These feed products have a relatively small, but high-priced market and could be developed as regional products replacing imported feed material. However, in contrast to the ruminant feed market, little protein is imported in the horse feed market. Still, a local/regional production facility and feedstock supply could earn attention from customers.

Protein recovery levels for the white and green protein fractions were relatively low resulting in low revenues for the final products. Ultrafiltration would be an interesting technology to further investigate for its impact on protein recovery and economic feasibility. Additional values of other components of the final products could help establishing higher market prices for the product that in this assessment were only valorised for their protein content. Fibres and phenolic compounds have been found to have positive health-impacting effects and could help developing protein products based on broccoli and kale leaves as health-promoting products or food-quality enhancing food additives. A product placement in the health food area would also have positive reverberations for the revenue structure of a plant protein facility. A more detailed assessment of other constituents such as fibres and phenolic compounds is warranted and currently being performed at SLU, Sweden. Details from this assessment will be published in a scientific article.

Technology readiness is generally high (TRL 6-9) for the feedstock supply steps, however, the protein extraction process and product formulation, needs to be adapted and verified to produce fractions with high protein yields and quality. Concrete scaling tests are currently being performed on the investigated crops outside the scope of the BioBIGG project. These tests will allow a more detailed and concise economic feasibility assessment.

7 Acknowledgements

Anna-Lovisa Nynäs and Emilia Berndtsson, Swedish University of Agricultural Sciences, contributed as non-project members to this pre-feasibility. A pre-feasibility study on an extended dataset will be published as (Prade, Muneer et al. prel. 2021).

8 References

Angiolillo, L., S. Spinelli, A. Conte and M. A. Del Nobile (2019). "Extract from Broccoli Byproducts to Increase Fresh Filled Pasta Shelf Life." Foods **8**(12): 621.

Bals, B. and B. Dale (2011). "Economic Comparison of Multiple Techniques for Recovering Leaf Protein in Biomass Processing." Biotechnology and bioengineering **108**: 530-537.

Bals, B. and B. E. Dale (2011). "Economic comparison of multiple techniques for recovering leaf protein in biomass processing." Biotechnology bioengineering **108**(3): 530-537.

Berndtsson, E., R. Andersson, E. Johansson and M. E. Olsson (2020). "Side Streams of Broccoli Leaves: A Climate Smart and Healthy Food Ingredient." Int J Environ Res Public Health **17**(7).

Biegańska-Marecik, R., E. Radziejewska-Kubzdela and R. Marecik (2017). "Characterization of phenolics, glucosinolates and antioxidant activity of beverages based on apple juice with addition of frozen and freeze-dried curly kale leaves (Brassica oleracea L. var. acephala L.)." Food Chemistry **230**: 271-280.

BMEL (2020). 63. Anbau, Ertrag und Ernte von Freilandgemüse. B. f. E. u. Landwirtschaft. Bonn, Germany, Bundesanstalt für Landwirtschaft und Ernährung (BLE).

Butler, J. B. (1982). "An investigation into some causes of the differences of protein expressibility from leaf pulps." **33**(6): 528-536.

Butler, L. G. and J. C. Rogler (1992). Biochemical Mechanisms of the Antinutritional Effects of Tannins. Phenolic Compounds in Food and Their Effects on Health I, American Chemical Society. **506:** 298-304.

Campas-Baypoli, O. N., D. I. Sánchez-Machado, C. Bueno-Solano, J. A. Núñez-Gastélum, C. Reyes-Moreno and J. López-Cervantes (2009). "Biochemical composition and physicochemical properties of broccoli flours." International Journal of Food Sciences and Nutrition **60**(sup4): 163-173.

Colonna, E., Y. Rouphael, G. Barbieri and S. De Pascale (2016). "Nutritional quality of ten leafy vegetables harvested at two light intensities." Food Chemistry **199**: 702-710.

Court, E. (2018). Canadian Government To Invest $150 Million In Plant-Based Sector. The decision reflects increasing demand for plant-based protein. London, UK, Plant Based News.

Damborg, V. K., S. K. Jensen, M. R. Weisbjerg, A. P. Adamsen and L. Stødkilde (2020). "Screw-pressed fractions from green forages as animal feed: Chemical composition and mass balances." Animal Feed Science and Technology **261**: 114401.

Deleu, L. J., M. A. Lambrecht, J. Van de Vondel and J. A. Delcour (2019). "The impact of alkaline conditions on storage proteins of cereals and pseudo-cereals." Current Opinion in Food Science **25**: 98-103.

Domínguez-Perles, R., M. C. Martínez-Ballesta, M. Carvajal, C. García-Viguera and D. A. Moreno (2010). "Broccoli-Derived By-Products—A Promising Source of Bioactive Ingredients." Journal of Food Science **75**(4): C383-C392.

Dominguez-Perles, R., D. A. Moreno, M. Carvajal and C. Garcia-Viguera (2011). "Composition and antioxidant capacity of a novel beverage produced with green tea and minimally-processed byproducts of broccoli." Innovative Food Science & Emerging Technologies **12**(3): 361-368.

Edwards, R. H., R. E. Miller, D. De Fremery, B. E. Knuckles, E. Bickoff and G. O. Kohler (1975). "Pilot plant production of an edible white fraction leaf protein concentrate from alfalfa." Journal of Agricultural and Food Chemistry **23**(4): 620-626.

Erdoğan, B. Y. and N. Onar (2011). "Determination of nitrates, nitrites and oxalates in kale and sultana pea by capillary electrophoresis." Journal of Food and Drug Analysis **20**: 532-538+558.

ESYRCE (2017). ENCUESTA SOBRE SUPERFICIES Y RENDIMIENTOS DE CULTIVOS EN ESPAÑA (ESYRCE) RESULTADOS 2004-2018 ha. Madrid, Spain, Ministry of Agriculture, Fisheries and Food.

Fernández, S. S., C. Menéndez, S. Mucciarelli and A. P. Padilla (2007). "Saltbush (Atriplex lampa) leaf protein concentrate by ultrafiltration for use in balanced animal feed formulations." Journal of the Science of Food and Agriculture **87**(10): 1850-1857.

Finch, H. J. S., A. M. Samuel and G. P. F. Lane (2014). 18 - Arable forage crops. Lockhart & Wiseman's Crop Husbandry Including Grassland (Ninth Edition). H. J. S. Finch, A. M. Samuel and G. P. F. Lane, Woodhead Publishing**:** 433-453.

Fink, M., C. Feller, H.-C. Scharpf, U. Weier, A. Maync, J. Ziegler, P.-J. Paschold and K. Strohmeyer (1999). "Nitrogen, phosphorus, potassium and magnesium contents of field vegetables — Recent data for fertiliser recommendations and nutrient balances." Journal of Plant Nutrition and Soil Science **162**(1): 71-73.

Fordham, R. and P. Hadley (2003). VEGETABLES OF TEMPERATE CLIMATES | Cabbage and Related Vegetables. Encyclopedia of Food Sciences and Nutrition (Second Edition). B. Caballero. Oxford, Academic Press**:** 5932-5936.

GN (2019). Global Plant Based Protein Supplements Market, GlobeNewswire.

Huarte-Mendicoa, J. C., I. Astiasaran and J. Bello (1997). "Nitrate and nitrite levels in fresh and frozen broccoli. Effect of freezing and cooking." Food chemistry **58**(1/2): 39-42.

Khoja, K. K., A. Buckley, M. F. Aslam, P. A. Sharp and G. O. Latunde-Dada (2020). "In Vitro Bioaccessibility and Bioavailability of Iron from Mature and Microgreen Fenugreek, Rocket and Broccoli." Nutrients **12**(4).

Lantbruksenheten (1999). Bidragskalkyler för köksväxter på friland. Linköping, Länsstyrelsen i Östergötlands län.

Lisiewska, Z., W. Kmiecik and A. Korus (2008). "The amino acid composition of kale (Brassica oleracea L. var. acephala), fresh and after culinary and technological processing." Food Chemistry **108**(2): 642-648.

Lu, C. D., N. A. Jorgensen and L. D. Satter (1988). "Site and Extent of Nutrient Digestion in Lactating Dairy Cows Fed Alfalfa Protein Concentrate or Soybean Meal." Journal of Dairy Science **71**(3): 697-704.

Mackie, A., B. Bajka and N. Rigby (2016). "Roles for dietary fibre in the upper GI tract: The importance of viscosity." Food Research International **88**: 234-238.

Magnusson, A. (2017). Whole crop barley silage and grass silage harvested at different stages of maturity – effects on feed intake, selection, digestibility and protein utilization in sheep. Skara, Sweden, Department of Animal Environment and Health, Swedish University of Agricultural Sciences.

Mariotti, F., D. Tomé and P. P. Mirand (2008). "Converting Nitrogen into Protein—Beyond 6.25 and Jones' Factors." Critical Reviews in Food Science and Nutrition **48**(2): 177-184.

Martin, A. H., M. Nieuwland and G. A. H. de Jong (2014). "Characterization of Heat-Set Gels from RuBisCO in Comparison to Those from Other Proteins." Journal of Agricultural and Food Chemistry **62**(44): 10783-10791.

Merodio, C. and B. Sabater (1988). "Preparation and properties of a white protein fraction in high yield from sugar beet (Beta vulgaris L) leaves." Journal of the Science of Food and Agriculture **44**(3): 237-243.

Natesh, N., L. Abbey and S. Asiedu (2017). "An Overview of Nutritional and Antinutritional Factors in Green Leafy Vegetables." **1**: 3-9.

Oboh, G. (2005). "Effect of blanching on the antioxidant property of some tropical green leafy vegetables." LWT - Food Science and Technology **38**: 513-517.

Persson, N.-E. (1988). Köksväxt- och bärodling. Korta odlingsanvisningar. Trädgård 313. Alnarp, Sweden, Swedish University of Agricultural Sciences.

Pirie, N. W. (1978). Leaf protein and its by-products in human and animal nutrition. Cambridge, Cambridge University Press.

Prade, T., F. Muneer, E. Berndtsson, A.-L. Nynäs, S.-E. Svensson, W. R. Newson, M. Olsson and E. Johansson (prel. 2021). "Phenols, fibres and leaf protein concentrate production from broccoli and kale leaves - A pre-feasibility study ".

Ranawana, V., F. Campbell, C. Bestwick, P. Nicol, L. Milne, G. Duthie and V. Raikos (2016). "Breads Fortified with Freeze-Dried Vegetables: Quality and Nutritional Attributes. Part II: Breads Not Containing Oil as an Ingredient." Foods **5**(3).

Salunkhe, D. K. and J. K. Chavan (1989). Dietary Tannins: Consequences and Remedies. Towards plant protein refinery: Review on protein extraction using alkali and potential enzymatic assistance. Y. W. SARI, W. J. MULDER, J. P. M. SANDERS and M. E. BRUINS, CRC Press.

SBA (2019). Köksväxter på friland. Antal företag, areal, skördad mängd. År 1999, 2002-2018. Län/riket. Swedish Board of Agriculture. Jönköping, Sweden.

Strid, I., M. Eriksson, S. Andersson and M. Olsson (2014). Svinn av isbergssallat i primärproduktionen och grossistledet i Sverige. Jönköping, Sweden, Swedish Board of Agriculture.

Stødkilde, L., V. K. Damborg, H. Jørgensen, H. N. Lærke and S. K. Jensen (2018). "White clover fractions as protein source for monogastrics: dry matter digestibility and protein digestibility-corrected amino acid scores." Journal of the Science of Food and Agriculture **98**(7): 2557-2563.

Stødkilde, L., V. K. Damborg, H. Jørgensen, H. N. Lærke and S. K. Jensen (2019). "Digestibility of fractionated green biomass as protein source for monogastric animals." animal **13**(9): 1817-1825.

Sutton, K., N. Larsen, G.-J. Moggre, L. Huffman, B. Clothier, R. Bourne and J. Eason (2018). Opportunities in plant based foods – PROTEIN. A Plant & Food Research report prepared for: Ministry Primary Industries and Plant & Food Research. Auckland, New Zealand, The New Zealand Institute for Plant & Food Research**:** 22.

Tenorio, A. T., J. Gieteling, G. A. De Jong, R. M. Boom and A. J. Van Der Goot (2016). "Recovery of protein from green leaves: Overview of crucial steps for utilisation." Food chemistry **203**: 402-408.

Umeta, M., C. West, J. Haidar, P. Deurenberg and J. G. A. J. Hautvast (2000). "Zinc supplementation and stunted infants in Ethiopia: A randomised controlled trial." Lancet **355**: 2021-2026.

Wang, S., J. P. Melnyk, R. Tsao and M. F. Marcone (2011). "How natural dietary antioxidants in fruits, vegetables and legumes promote vascular health." Food Research International **44**(1): 14-22.

Zhang, Y., Z. Jiang, L. Wang and L. Xu (2017). "Extraction optimization, antioxidant, and hypoglycemic activities in vitro of polysaccharides from broccoli byproducts." Journal of Food Biochemistry **41**(5): e12387.

9 Appendix

9.1 Feedstock recovery

Table A1. Yield and properties of the recovered broccoli and kale leaves given as range for the economic assessment. Ww = wet weight.

Parameter	**Unit**	**Broccoli**		**Kale**		
		low	**hig h**	**low**	**hig h**	
Total aboveground biomass yield	[ton ww/ha]	49	160	21	65	(Fink, Feller et al. 1999)
Leaf share[a]	[%ww]	23. 5	57.9	11. 8	23.4	Field experimental data
DM content leaves	[%]	12. 5	25.7	14. 0	22.8	Field experimental data
Leaf biomass from additional harvest	[t DM/ha]	3.5	9.7	0.4	0.9	

[a] Of total aboveground biomass before harvest. For kale, number refer to the residual leaf share after harvest

Table A2. Working time requirements and related costs for additional harvest of broccoli and kale leaves based on Ascard et al. (Ascard, Håkansson et al. 2008).

Parameter	**Unit**	**Harvest: labour**		**Harvest: machinery**		**Transport: machinery[a]**	
		low	**high**	**low**	**high**	**low**	**high**
Work	[h/ha]	67	75	13	15		
Costs	[€/ha]	1257	1407	146	169	169	253

[a] Estimated at approx.. 2.8 €-ct/kg (Ascard, Håkansson et al. 2008).

9.2 Protein fractionation

Table A3. Protein content in the different fractions given as range for the economic assessment.

Parameter	**Unit**	**Broccoli**		**Kale**	
		low	**high**	**low**	**high**
White protein fraction	[%]	0.5	22.1	0.5	22.1
Green protein fraction	[%]	44.0	45.7	44.0	45.7
Green juice total extractable protein	[%]	54.5	58.3	54.5	58.3
Brown liquor	[%]	21.9	27.2	21.9	27.2
Fibre pulp	[%]	35.2	39.4	35.2	39.4

9.3 Fibre pulp storage as silage

Costs for storage in bunker silos were estimated using an investment calculation on data given in Table A4.

Table A4. Economic calculations on bunker silo storage.

Variable	**Unit**	**Value**
Effective storage volume	[m^3]	17505
Investment costs[a]	[€/m^3]	17.0
Economic life span	[a]	20
Interest	[%]	6
Cost for plastic cover[a]	[€/m^2/a]	3.0
Bunker cost	[€/m^3/a]	2.2

[a] Source: Strid *et al.* (2012)

Storage density was estimated to be 646 kg/m^3 according to Hjelm and Spörndly (2012):

$$Required\ storage\ density\ \left[\frac{kg}{m^3}\right] = DM\ content\ [\%] \cdot 3.5\left[\frac{kg}{\% \cdot m^3}\right] + 90\left[\frac{kg}{m^3}\right]$$

9.4 Processing costs

Table A5. Cost for protein extraction and drying of final products given as cost per ton of initial feedstock.

Fraction	**Operational cost** [EUR/t]	**Capital cost[a]** [EUR/t]	**Technology used**	**References**
Extraction				

White and green protein (pathway A)	18.7 - 23.5	8.0 - 9.6	mech. separation	(Bals and Dale 2011)
Total recoverable protein (pathway B)	15.0 - 18.8	6.4 - 7.7	mech. separation	(Bals and Dale 2011)
Drying				
White protein (pathway A)	4.1 - 26.3	1.9 - 10.5	spray drying	own estimate[b]
Green protein (pathway A)	6.6 - 42.1	3.0 - 16.8	drum drying	own estimate[b]
Total recoverable protein (pathway B)	11.5 - 73.6	5.2 - 29.5	drum drying	own estimate[b]

[a] for the drying processes estimated as 40 and 45 % of high and low operational costs, respectively.

[b] Estimated based on the energy consumption of 3-7 MJ/kg evaporated water (Baker and McKenzie 2005) and energy prices of 1.0-1.8 €-ct/MJ (SCB 2019).

Table A6. Drying operations for different fractions.

Fraction	Drying method	Proportion of the initial biomass DM treated [%]	Moisture content[a] [%]
Green protein	Drum drying	9.1	31
Total extractable protein	Drum drying	15.9	31
White protein	Spray drying	5.7	31

[a] Of the biomass entering and treated in the dryer, based on (Tenorio, Gieteling et al. 2016)

Table A7. Assumed protein revenues [€/kg].

Product	**Application**	**Chosen value (market range)[a]**
Green protein	Horse feed	8.5 (6.6 - 10.4)
White protein	Food for human consumption	11.2 (8.6 - 13.8)[b]
Total green protein	Horse feed	8.5 (6.6 - 10.4)
Fibre pulp	Feed for ruminants	0.21 (0.14 - 0.28)[c]
Milled broccoli leaves	Protein value / health product	1.7 (1.4 - 1.9)[d]
Milled kale leaves	Protein value / health product	2.1 (1.7 - 2.4)[d]

[a] Prices were assumed per kg of DM with a moisture content of 4-8%.

[b] Range as analysed on Alibaba.com (8 June 2019) for plant-based protein; when a default price of 1 US$ kg^{-1} product was given as the lower price range, this was corrected by assuming the lower price limit being at 50% or the upper price limit of the same product.

[c] Assumed to have the same value as that of untreated ley crop biomass used as ruminant feed.

[d] Based on a protein content of 10 and 13% in the final product from broccoli and kale, respectively, and the protein value of white protein.

9.5 Appendix references

Ascard, J., B. Håkansson and M. Söderlind (2008). Ekonomi – Kalkyler för odling av grönsaker på friland. Jönköping, Sweden, Swedish Board of Agriculture.

Baker, C. G. J. and K. A. McKenzie (2005). "Energy Consumption of Industrial Spray Dryers." Drying Technology **23**(1-2): 365-386.

Bals, B. and B. E. Dale (2011). "Economic comparison of multiple techniques for recovering leaf protein in biomass processing." Biotechnology bioengineering **108**(3): 530-537.

Fink, M., C. Feller, H.-C. Scharpf, U. Weier, A. Maync, J. Ziegler, P.-J. Paschold and K. Strohmeyer (1999). "Nitrogen, phosphorus, potassium and magnesium contents of field vegetables — Recent data for fertiliser recommendations and nutrient balances." Journal of Plant Nutrition and Soil Science **162**(1): 71-73.

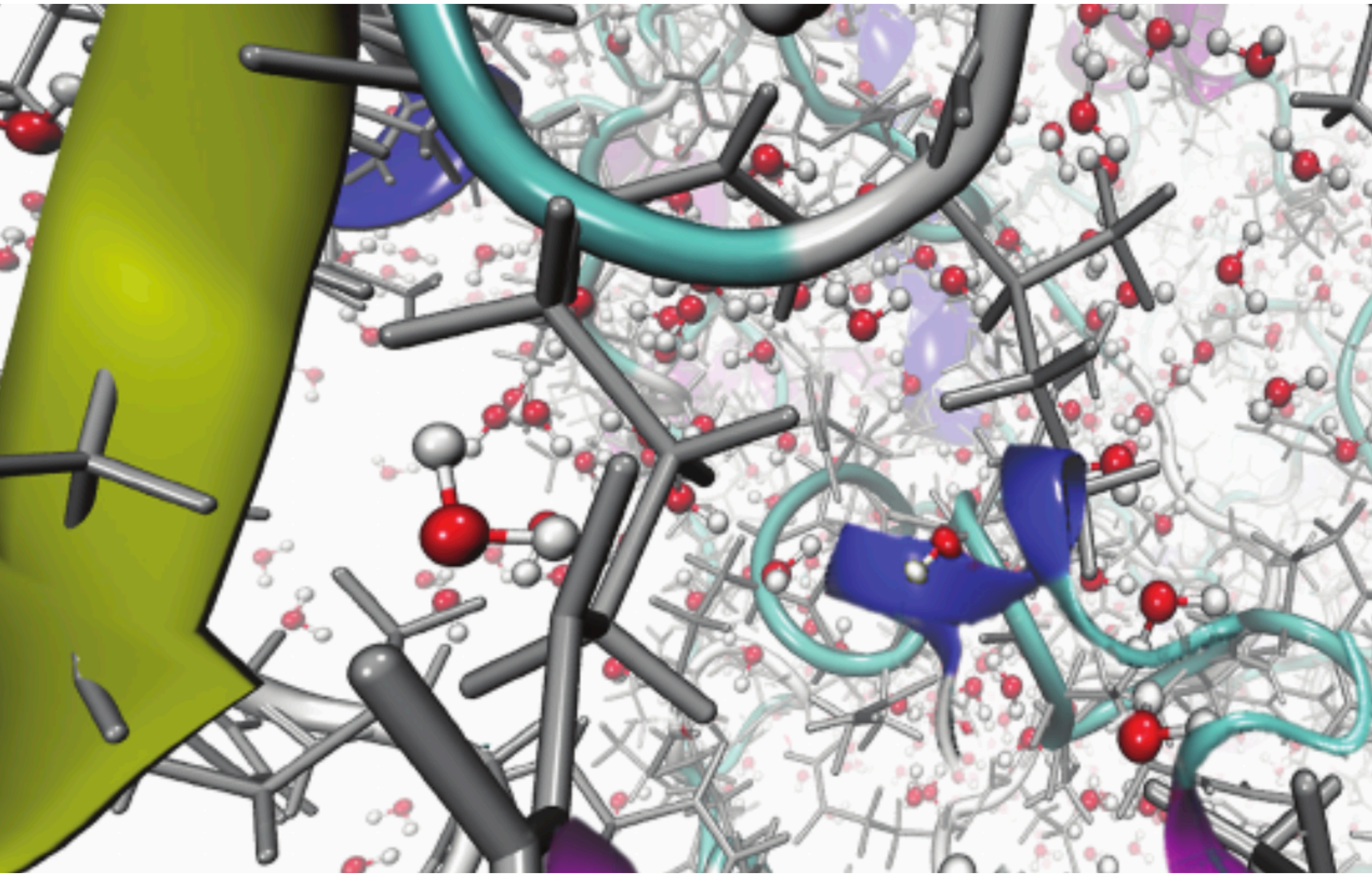
Hjelm, E. and R. Spörndly (2012). Densiteten tung faktor i plansilon. Arvensis. Bjärred, Sweden, HIR Skåne AB, Hushållningssällskapen i Skåne, Skaraborg, Östergötland, Kalmar-Kronoberg-Blekinge, Halland, Västmanland, HS Konsult and Växa Sverige. **4:** 2.

SCB (2019). "Energy prices on natural gas and electricity." Aquired on 23 March 2020 **scb.se**.

Strid, I., C. Gunnarsson, H. Karlsson, M. Edström and J. Bertilsson (2012). Mer och bättre vall till mjölkproduktion och återväxtvall till biogas. Uppsala, Institutionen för energi och teknik, Sveriges lantbruksuniversitet**:** 88.

Tenorio, A. T., J. Gieteling, G. A. De Jong, R. M. Boom and A. J. Van Der Goot (2016). "Recovery of protein from green leaves: Overview of crucial steps for utilisation." Food chemistry **203**: 402-408.

PROTEIN-BASED SUPERABSORBENT POLYMERS



PREFEASIBILITY STUDY OF PROTEIN-BASED SUPERABSORBENT POLYMERS

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Deliverable D5.2–	Pre-feasibility and innovation programmes for innovative value chains

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Summary

Superabsorbent polymers (SAPs) consist of a network of hydrophyllic polymeric chains, which allow the material to swell admitting liquids within the polymeric network. Such hydrogels are capable of retaining large amounts of water and saline solution per gram of dry SAP.

These properties have led to the extensive use of these materials in products requiring high liquid absorption and retention capacity, e.g., sanitary pads, diapers, medical pads and agricultural soil conditioners, among others. Since the 70's, the most representative application where SAP have been used is diapers, where the SAP represents up to 40 % of the product's dry weight. The SAPs contained in diapers are based on petroleum-based sodium-neutralized polyacrylic acid, which besides their non-sustainable nature are not biodegradable.

SAPs based on renewable resources, bioSAPs, are discussed as potential replacements for these conventional petroleum-based absorbent materials in order to reduce use of fossil resources and reduce of greenhouse gas emissions. Consequently, a pre-feasibility study investigating different bioSAPs based on residual protein by-products from starch production is needed to examine their greenhouse gas emissions from production and end-of-life treatment.

This pre-feasibility study has shown that biobased superabsorbent polymers (bioSAP) produced from food industry residual products have the potential to reduce emissions when replacing fossil-based SAP based on sodium polyacrylic acid.

The raw materials used for producing the bioSAP are readily available on the market and in relatively large amounts. The economic costs of replacing conventional SAPs with bioSAPs require further study in the next step of development, but raw materials are relatively low cost at prices below that of the fossil SAP counterpart.

Utilization of the residual streams from wheat and potato starch production will add to the value chain and strengthen the food production system with increased resource use efficiency and additional income. As these materials are residual by-products, their utilization for bioSAP production will not affect the food production system negatively by avoiding direct competition with resources needed in the food and feed industry.

1 Introduction

1.1 Introduction to project concept

Superabsorbent polymers (SAPs) consist of cross-linked water-soluble polymeric chains containing high amount of polar functional groups, which allow the material to swell, admitting and holding large amount of liquids within the 3D polymeric network. The crosslinks in the SAP prevent dissolving the material when in contact with water/polar liquid while allowing the formation of a gel that is capable of swelling up to 1000 of water or 100 grams of saline solution (0.9 wt % NaCl) per gram of dry SAP (g/g). These materials also can retain more than 30 g/g of the swollen saline liquid after the swelling and compression.

The aforementioned properties have promoted the extensive use of these materials in several products requiring high liquid absorption and retention capacity, e.g., sanitary pads, diapers, medical pads and agricultural soil conditioners, among others. Since the 70's, the most representative application where SAP have been used is in diapers, where the SAP can represent up to 40 % of the product's dry weight. The SAPs contained in current diapers are based on petroleum-based sodium-neutralized polyacrylic acid, which besides their non-sustainable nature are not biodegradable.

Promoting the substitution of conventional petroleum-based absorbent materials used in the hygiene industry for renewable resources-based and biodegradable SAPs is an important research objective for contributing to a sustainable society. Moreover, an SAP material fabricated using available proteins obtained from biomass may provide a fully integrated solution to conventional synthetic petroleum-based SAP. Although scientific results have shown that protein-based SAP materials can be produced, the climate impact of these materials and the actual economic feasibility assessment of introducing these into current disposable hygiene products is needed. Consequently, this case report studies different scenarios where the synthetic SAP component in baby diapers has been replaced by a variety of protein-based SAPs reported in literature. The scenarios are evaluated taking as a target value the saline swelling capacity of the synthetic SAP at 1 min.

1.2 Production process and products

1.2.1 Process outline

The process for the protein treatment to produce a bioSAP, at a pilot-scale, requires a regular polymerization reactor, a centrifugation unit and a conventional oven. For the protein pre-treatment stage, the protein is suspended in a reactor containing an aqueous alkaline solution at a temperature above 70 °C (Figure 1, step 1). Thereafter, the protein chemical modification is started by reducing the temperature of the solution to room temperature (cooling), and adding the acylation agents and NaOH to the reactor (Figure 1, step 2). The reactor must be maintained constantly under stirring. The suspension is then centrifuged to separate the modified protein fraction from the supernatant (SN) containing the excess of unreacted acylation agents (Figure 1, step 3). The material is also neutralized to make it safer for human contact at this stage (Figure 1 step 4). Once the protein has been cleaned, the material is dried in a conventional oven and ground to produce the BioSAP (Figure 1, step5).

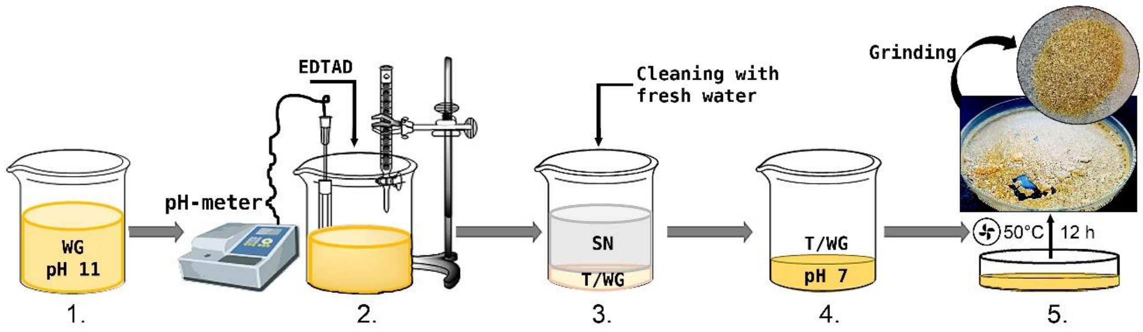

Figure 1. Scheme of the functionalization protocol used for modifying protein co-streams (e.g., Wheat gluten concentrate). The process involved dispersion of the protein in alkaline solution (1), acylation using EDTAD (2), cleaning of the unreacted EDTAD (3), neutralization of the product (4), and drying followed by a grinding of the films into powders (5). Obtained from Capezza (2020). WG = wheat gluten; SN = supernatant; T/WG = treated wheat gluten.

A general outline of the process also valid for the upscaling to e.g. pilot scale is given in Figure 2.

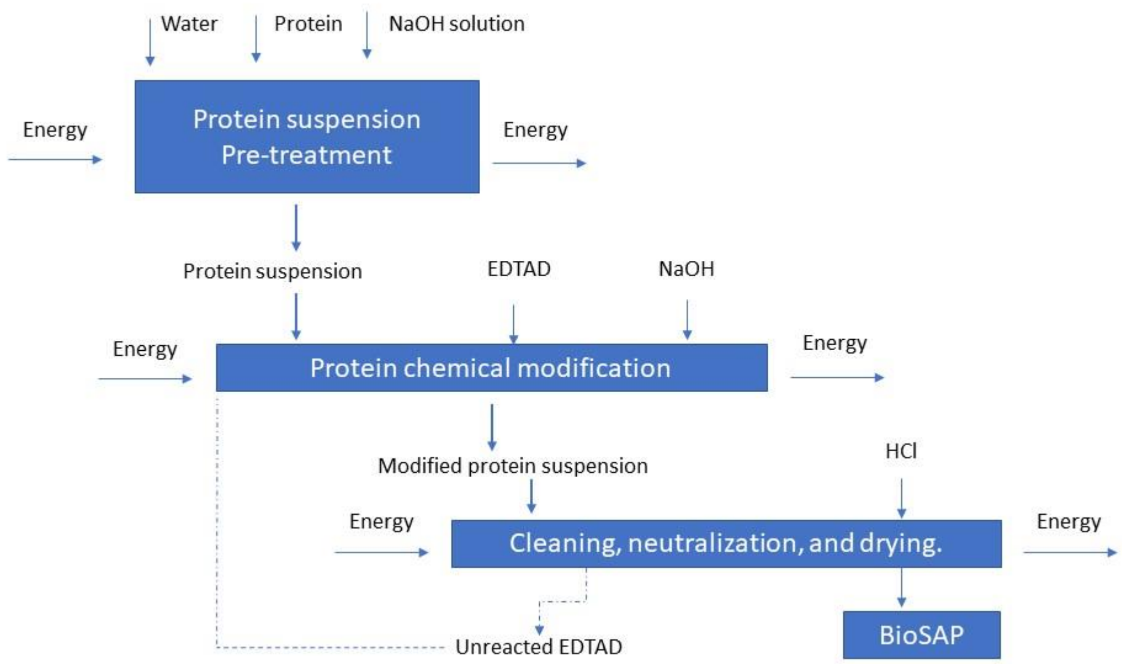

Figure 2. Schematic process of the production of bioSAP valid for the upscaling of the process to pilot scale.

2 Project technology concept

2.1 Technology readiness of concept

The technology readiness of the presented concept was assessed in a preliminary and simplified manner in order to present a starting point. Actual TRL levels need to be assessed in close cooperation with participating business partners once an innovation program is to be implemented.

2.1.1 Feedstock supply

The protein side-streams, wheat gluten and potato protein, come from the starch production industry. This industry is well established and produces side-stream proteins where ever agro-industrial processing exists for the main starch products, reaching TRL9 as an internationally traded commodity (Figure 3). For example the US wheat gluten market is expected to be 2.58 billion USD in 2022 (MaM 2020), and the world potato protein market is expected to be over 88 million USD by 2022 (MaM 2020).

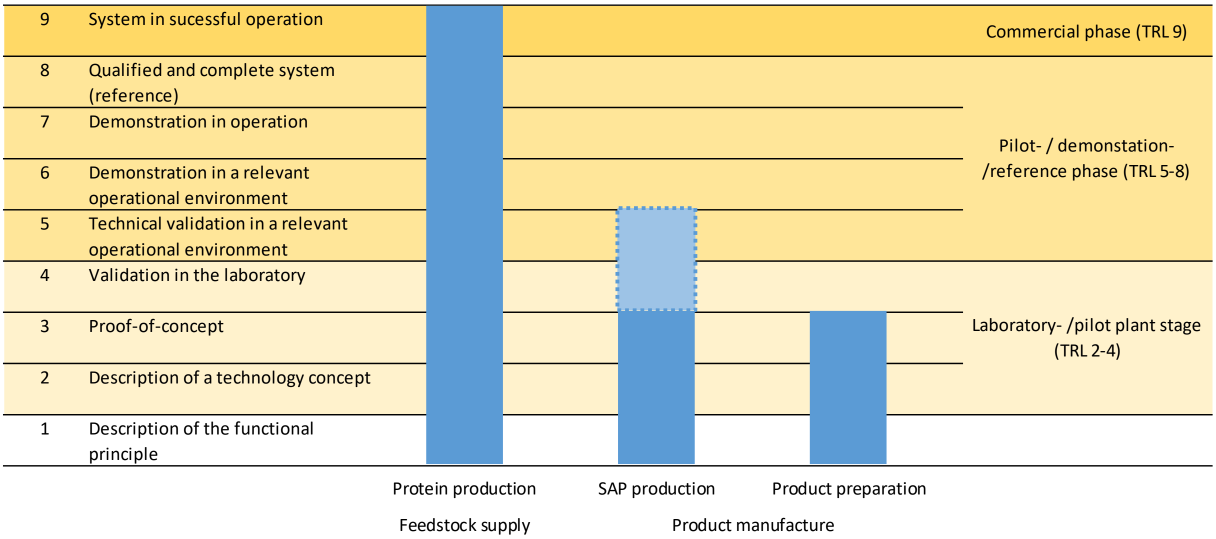

Figure 3. Technology readiness levels (TRLs) as preliminary assessed for the production steps of the concept.

2.1.2 SAP production

To our knowledge, there are currently no industrial processes being implemented for the production of protein-based superabsorbent polymers. Therefore, the development of a settled industrial product and eventual commercialization of the material will have to follow a pilot phase (TRL5).

The materials are so far developed in the laboratory scale, and reported in the literature, which have been focusing on the utilization of protein-based materials for diapers and agricultural uses (Capezza, Newson et al. 2019, Jiménez-Rosado, Perez-Puyana et al. 2020). However, new emerging possibilities have been investigated for these types of material, e.g., packaging industry, medical applications, and other applications requiring high-liquid uptake and retention. For these new emerging possibilities for the bioSAP material validation (TRL 4) is needed.

2.1.3 Product preparation

SAP products are traditionally delivered as powders ready to use in the final product preparation. Depending on the scale of the manufacturer involved, this may range from 20 kg sacks or bulk bags (ca. 700 kg) to rail car-scale deliveries. Particle sizes are typically in the range of 150-600 μm for diaper applications (HCM 2020), while in agricultural and waste remediation applications may be as large as 4 mm (EAI 2013). For product preparation of the bioSAP material validation (TRL 4) is needed.

2.2 Requirements and properties

2.2.1 Swelling capacity

The swelling capacity of SAPs is regularly assessed using the EDANA Non-woven Standard Procedure (NWSP) 240.0.R2 (Edana 2015), also known as the "Tea-bag method". This method is preferred when studying the swelling uptake of powders or material with irregular shapes. However, the liquid uptake of other types of materials such as foams can be also studied with this method. During the tea-bag test, the free swelling capacity (FSC) of the material is determined, i.e., the liquid uptake with no physical limitations. This swelling indicator provides information on the swelling speed, maximum swelling of the specific material and information about the swelling kinetics. The method is facile and allows for the rapid study of the uptake of the material in different fluids, e.g., water, saline solution, defibrinated blood, etc.

2.2.2 Other performance indicators

The free swelling capacity (FSC) represents the most common technique to determine the quality of synthetic and bio-based SAPs. However, depending on the type of application additional performance indicators are used for SAPs e.g., in the hygiene industry. The absorption under load (AUL) is extensively used in the diaper industry to assess the swelling capacity of the SAP under physical conditions such as weight pressing on the SAP. The goal of the AUL test is to determine the ability of the material to swell under pressure and retain fluids by simulating the weight of an individual on the SAP in use.

An additional performance indicator used in the SAP industry is the centrifugation retention capacity (CRC), where the swollen SAP material is centrifuged at 230 RCF for 3 min after 30 min of swelling in the test liquid. The test aims to determine the amount of bound water contained within the gel network after centrifugation.

Beside the swelling capacity, more specific performance indicators are needed for the utilization of SAP in the hygiene industry. For instance, skin contact and allergens assessments are also required for using SAP in baby diapers. More industrial parameters such as storability, degradation and micro-plastic leakage are also studied for SAPs.

2.2.3 Legal requirements

In baby diaper applications there are no direct legal requirements for SAP materials or for diapers as a consumer product in the case of the EU (ANSES 2019). In each jurisdiction there may be general requirements for products in direct skin contact or specific diaper related requirements. Depending on the use other requirements may apply. Guidelines exist based on market sector, recommend by trade associations such as EDANA in the case of diapers in the EU, including recommended safety protocols (EDANA 2016). As consumer products in the EU, diapers fall under General Product Safety Directive (2001/95/EC) (EP 2001). EU limits for products in direct contact with skin are defined in Regulation (EC) No 1907/2006 of the European Parliament and of the Council (REACH), Annex XVII (EC 2008). Depending on the specific use scenario for SAPs, the transfer of hazardous substances by distribution through re-released liquids, for example under pressure could occur. Under an abundance of caution, this scenario should be examined in light of the relevant regulations, as found in ANSES (2019).

3 Market situation

The market for diapers was 69 billion USD in 2019 (IMARC 2020), which in turn is equivalent to approximately 1.3 million tons of disposable diapers waste per year (ReportLinker 2020). With about 10-20 g of SAP per diaper and total diaper weight of 36-50 g, the market volume of SAP is approx.

360-520,000 tons per year. Disposable diapers account for approx. 75% of the total SAP market, which corresponds to a SAP value of approx. 6 billion USD (GVR 2019). Coupled with the new emerging applications for SAP materials in agriculture, the environmental impact of using petroleum-based resources for producing SAPs is important.

4 Feasibility of concept

This pre-feasibility study assesses the climate impact from the production of bioSAPs in comparison to the current fossil-based standard SAP of sodium polyacrylate (NaPA). The study does focus on the climate impact as a first step of a proof-of-concept. An economic assessment is not included in this study but is considered as one of the next steps in the development of the gluten- and potato protein-based bioSAPs.

4.1 Reference SAP

Fossil-based SAPs typically consist of polyacrylic acid, which is usually neutralized using sodium (Na+) ions. The repetitive unit of the polyacrylic acid possesses a charged carboxylic acid functional group that produces a highly hydrophilic structure with electrostatic repulsive forces in the material that causes the polymer chains to expand on wetting promoting water swelling. The presence of sodium ions also aids in the development of osmotic pressure, which is known as a driving force for the swelling. The polyacrylic acid used for the development of SAP materials is also crosslinked to avoid the material dissolving when placed in water. An illustration of the SAP material is displayed in Figure 4. Illustration of sodium neutralized polyacrylic acid network. The development of an osmotic pressure is illustrated by releasing Na^+ ions after the exposure of the SAP to water (Capezza 2017). . The polyacrylic acid is polymerized from acrylic acid monomer, synthetized from the oxidation of propylene (obtained from petroleum resources).

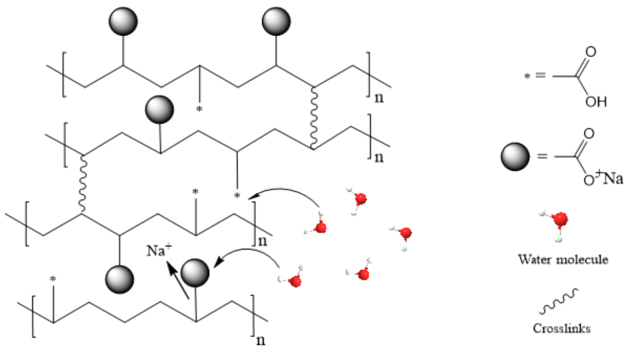

Figure 4. Illustration of sodium neutralized polyacrylic acid network. The development of an osmotic pressure is illustrated by releasing Na^+ ions after the exposure of the SAP to water (Capezza 2017).

The biodegradation of synthetic SAP materials has also been assessed in the literature, showing a biodegradation rate of ca. 0.24 % / 6 months in regular soil conditions (Wolter, Wiesche et al. 2002, Wilske, Bai et al. 2014). The low biodegradation has been attributed to the high-temperature resistance of the crosslinked SAP (showing thermal stability up to 200 °C), stability of the polymeric chains under microbial environment, and the good UV-resistance of the polyacrylic acid chains. As SAPs are the main component of single-use disposable products, and there is a risk that these products may end up in landfills or direct contact with the environment, the use of synthetic SAPs represents a challenge from both the environmental and sustainability perspective.

4.2 Investigated products

Proteins are considered one of the most important natural-based polymers encountered in nature, having fundamental functions in living organisms including transportation, catalysis, and regulation of structural tissues (Murphy 2001, Johansson, Malik et al. 2013). Compared with other naturally occurring polymers, proteins can be hydrolyzed, self-polymerized into nano-assemblies, and be functionalized to produce a variety of properties (Capezza, Newson et al. 2019). Proteins are built by amino acid residues, which are held together by peptide bonds forming a polypeptide chain, as illustrated in Figure 4. Illustration of sodium neutralized polyacrylic acid network. The development of an osmotic pressure is illustrated by releasing Na^+ ions after the exposure of the SAP to water (Capezza 2017). . While there are at least 500 known amino acid building blocks, approximately 21 are considered to be natural amino acids. Each amino acid provides a different functionality to the protein backbone, giving rise to a highly heterogeneous chain and structure (Belitz, Grosch et al. 2009). Here, the different amino acid groups can also be chemically modified to provide a different chemical functionality as well as function as crosslinking sites for creating a stronger polypeptide 3D network (Sinz 2006, McKerchar, Clerens et al. 2019). Therefore, the large availability of reactive functional groups in protein results of special interest within the material sciences field for the fine-tuning and development of possible bio-based alternatives with similar properties to fossil-based plastics (Wu, Andersson et al. 2014, Muneer, Andersson et al. 2016).

Among the different sources proving protein as raw material, the agricultural industry is currently producing large amounts of inexpensive protein co-products from different agricultural processes and crops (Capezza, Newson et al. 2019). For instance, the starch extraction from wheat and potato for the bioethanol and food industry, respectively, are producing wheat gluten protein (WG) and potato protein concentrates (PPC). Due to the availability of the raw materials and the markets where they can be used the prices of such protein concentrates are low, ranging from 1-1.2 EUR/kg. Here, the raw material prices are comparable to that of the materials used to fabricate synthetic SAPs, of ca. 1.50 EUR/kg (Capezza, Glad et al. 2019, Capezza, Cui et al. 2020, Capezza, Lundman et al. 2020). In Sweden, approximately 10,000 and 20,000 tons of PPC and WG protein co-streams were produced in 2019, respectively. The high raw material availability represents an important potential to consider these protein concentrates for the future production of protein-based SAPs, without significantly influencing the food market. The bioSAP fabrication processes herein discussed were designed according to “Green” principles excluding the utilization of any toxic chemicals or solvents. Besides, protein-based materials have previously been shown to be biodegradable in regular soil conditions after 180 days (Muneer, Johansson et al. 2014), which represents an important advantage in the development of a safer disposable product containing bioSAP vs. regular SAPs.

We have investigated four different procedures for producing bioSAP. These include two recipes based on wheat gluten and 2 based on potato protein concentrate (Table 1. Recipes for producing 1 kg of bioSAP as investigated in the economic assessment).

Table 1. Recipes for producing 1 kg of bioSAP as investigated in the economic assessment

BioSAP recipe	Protein [g]	Water [g]	EDTAD [g]	SA [g]	NaOH, 1M [g]	HCl, 1M [g]	Total [g]
Wheat gluten 1	1300	50000	325	0	2080	816	54521
Wheat gluten 2	1300	50000	0	0	624	612	52536
Potato protein concentrate 1	1300	195000	325	0	2080	816	199521
Potato protein concentrate 2	1300	10000	0	2600	2080	0	15980

SA = succinic anhydride

The resulting bioSAPs showed a various swelling capacities after 1 minute in saline solution (0.9 M NaCl), that corresponded to 20-41% of the fossil reference SAP (Figure 5).

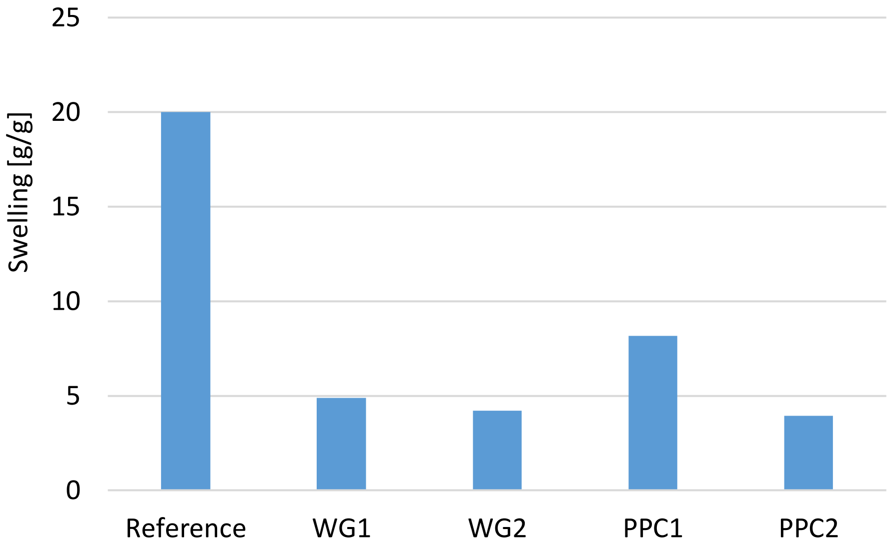

Figure 5. Swelling capacity after 1 minute in grams of saline solution (0.9 M NaCl) absorbed per gram of SAP for the reference fossil SAP and the investigated bioSAPs. WG = wheat gluten; PPC = potato protein concentrate.

4.3 Inventory data

In order to assess if bioSAPs can fulfil the requirements of a lower climate impact compared with the fossil reference, we have assessed the production of bioSAP in terms of greenhouse gas emissions. The emissions occur in processes where energy and materials are used and can be regarded as direct and indirect GHG emissions.

We assumed that the production process requirements of the bioSAP are similar to fossil SAP based on acrylic acid. From this assumption we have not studied the possible contributions of the production process but concentrated on the emissions originating from raw material use in the process.

4.3.1 Production means

The climate impact assessment was based on the GHG emission of the production means stated in the recipes in Table 1. Recipes for producing 1 kg of bioSAP as investigated in the economic assessment. However, the amounts of crosslinking and functionalization agents (EDTAD and succinic anhydride) considered in the GHG assessment were only 20% assuming an 80% recovery of unused agents from the reactor. No additional energy cost was assumed for the recovery based on a pH-driven precipitation of the agents as EDTA and succinic acid and a minor and therefore negligible energy requirement for drying of the precipitate and thermal conversion to EDTAD and succinic anhydride, respectively. The emission factors for production means used for the reference and alternative SAPs is given in

Table 2. Emission factors for fossil SAP and the compounds used in the production of the bioSAPs.

Compound	**GHG emissions [g CO_2-eq/kg]**		**References**
	Low	**High**	
Fossil SAP[a]	3290	3814	(Mirabella, Castellani et al. 2013, Gontia and Janssen 2016)
Wheat gluten (WG)	1072	1551	(Deng 2014); own calculation
Potato protein concentrate (PPC)[b]	371	1000	(Röös 2013, Tromp 2020)
EDTAD[c]	4750	5700	EcoInvent 3.6
Succinic anhydride (SA), fossil[d]	2370	3539	(Cok, Tsiropoulos et al. 2014, Patel, Bechu et al. 2018)
Succinic anhydride (SA), renewable[d]	504	870	(Moussa, Elkamel et al. 2016, González-García, Argiz et al. 2018)
Sodium hydroxide, NaOH, 1M	10	53	(Dahlgren, Stripple et al. 2015)
Hydrochloric acid, HCl, 1M	36	160	(CoW 2011)

[a] Sodium polyacrylate.
[b] Estimated from the carbon footprint of potato production and a production efficiency of 256 and 13.7 kg per ton potato of starch and PPC, respectively.
[c] Estimated from the carbon footprint of EDTA and increased with 20% for the heating required to synthesize EDTAD.
[d] Assumed same as for succinic acid based on the assumption that the energy use for the dehydration reaction is negligible.

4.3.2 End of life

For the end-of-life handling of reference SAP and bioSAP we considered combustion of the diaper including the SAP component and accounted for the emissions of carbon dioxide as a resulting product that affects the climate negatively. Only fossil greenhouse gas emissions were accounted for, biogenic carbon was regarded as not adding to the climate effect. The global warming potential emissions factors were estimated based on the carbon content of the compounds (

Table 3).

Table 3. Carbon content and proportion of renewable carbon for production means and resulting global warming potential (GWP). N/a = not applicable.

Compound	Carbon content [%]	Renewable carbon [%]	GWP [g CO_2-eq/kg]
Fossil SAP $(C_3H_3NaO_2)_n$	38.3	0	1405
Wheat gluten (WG)	n/d	100	0
Potato protein concentrate (PPC)	n/d	100	0
EDTAD ($C_{10}H_{12}N_2O_6$)	46.9	0	1719
Succinic anhydride ($C_4H_4O_3$), fossil	48.0	0	1760
Succinic anhydride ($C_4H_4O_3$), renewable	48.0	100	0
Sodium hydroxide, NaOH, 1M	0	n/a	0
Hydrochloric acid, HCl, 1M	0	n/a	0

4.4 Results and discussion

Greenhous gas emissions for the production and end-of-life combustion vary considerably between the different SAPs (Figure 6). The sodium polyacrylate (NaPA) that was used as reference SAP varied between approx. 4,700-5,200 g CO_2e per kg of SAP (low/high case). Both the low and the high case for NaPA were based on fossil-derived acrylic acid and current carbon intensity of the energy used in the manufacturing process. The bioSAP had on average 54-78% lower GHG emissions from the production and end-of-life combustion compared to the low reference case, which is the predominant production method.

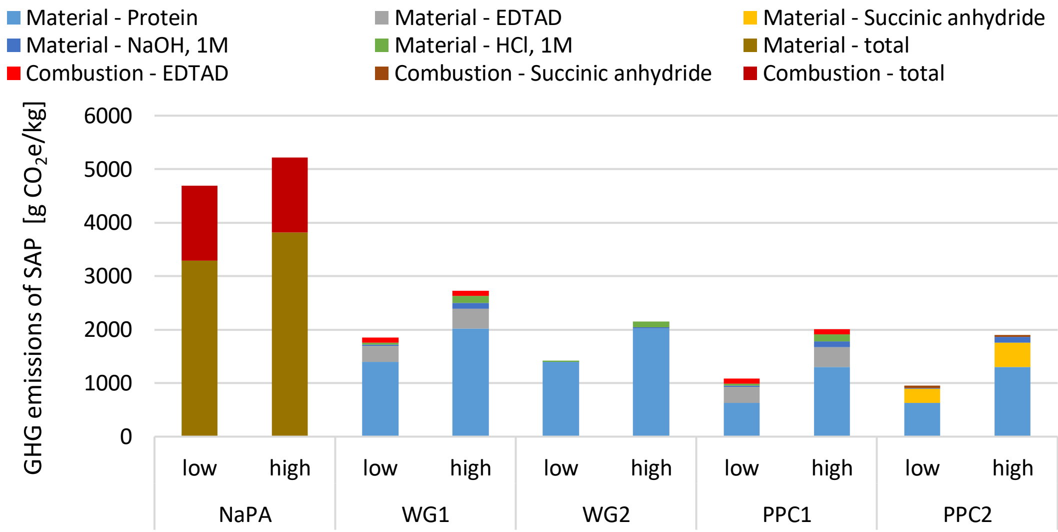

Figure 6. Greenhouse gas (GHG) emissions from 1 kg of SAP material based on emissions from SAP production and end-of-life combustion. Sodium polyacrylate (NaPA) was used as reference SAP. The low case for NaPA was based on renewable by-products and use of renewable energy sources, while the high case for NaPA was based on fossil-derived acrylic acid and current carbon intensity of the energy used in the manufacturing process.

In order to be able to compete with the fossil-based reference SAP, bioSAP needs to match the functionality of the reference SAPs. We have used the swelling capacity after 1 minute as a performance indicator and compared the different SAPs based on their emissions for providing a 500 g swelling capacity (Figure 7). Currently, the wheat gluten-based bioSAPs result on average in 71-88% higher GHG emissions compared to the fossil reference, due to their lower swelling capacity and the corresponding need to use more SAP to obtain the same effect. The potato protein-base SAP with succinic acid as functionalization agent (PPC2) performed similar to the fossil reference, while the potato protein-based bioSAP using EDTAD as functionalization agent (PPC1) may have the ability to lower GHG emissions by approx. 20% compared to the fossil reference. Recycling of the functionalization agents used in the production processes is a vital measure to reduce GHG from the bioSAP production. The crosslinkers have relatively high emission factors, which requires that the recycling step is verified and the recycling quota is updated if necessary.

There are different ways to approach a further reduction of GHG emissions of the investigated bioSAPs. The swelling performance is proportionally linked to the amount of SAP needed to match the performance of a reference SAP. The emissions of the wheat gluten protein are relatively high compared to the potato protein despite similar production processes. A more detail analysis of case-specific emission factors for protein component is necessary for an updated climate impact assessment.

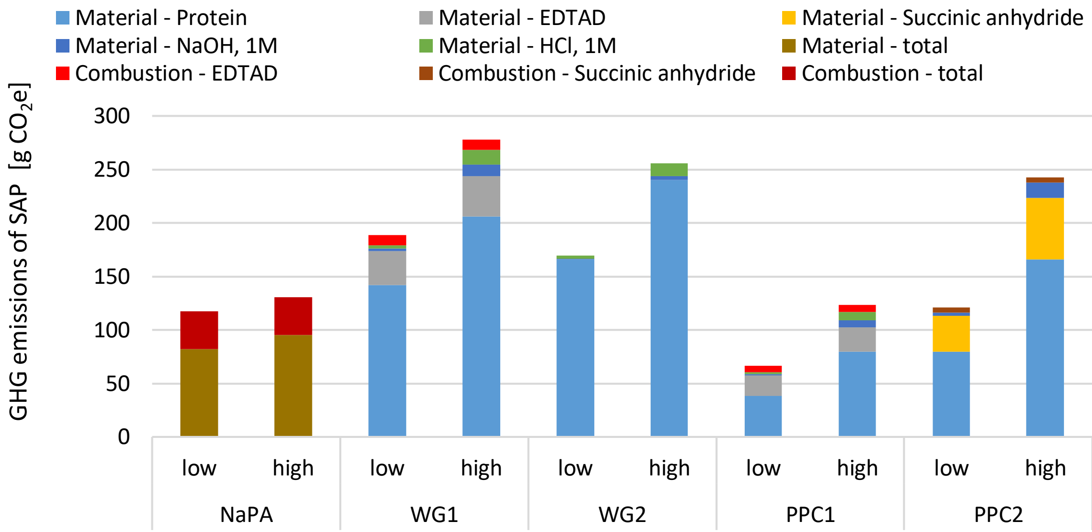

Figure 7. Greenhouse gas (GHG) emissions from the amount of SAP material that corresponds to a swelling capacity of 500 g, based on emissions from SAP production and end-of-life combustion. Sodium polyacrylate (NaPA) was used as fossil reference SAP representing the current commercial producion.

Other approaches to improve the sustainability of SAP include the use of cellulose to produce hydrogels (Alam, Islam et al. 2019) and the use of bio-based residual streams from pulp production for the production of polyacrylates (Gontia and Janssen 2016). A de-fossilization of the NaPA production process as suggested by Gontia and Janssen (2016) is likely able to reduce emissions from SAP material by 40%. However, even biobased polyacrylates suffer from a very low degradability of the SAP and may cause other environmental impacts such as higher levels of eutrophication, acidification, and ozone impacts compared to the fossil based sodium polyacrylate (Gontia and Janssen 2016).

4.5 Technology choice

The functionalization of protein using anhydrides through the attachment of carboxyl groups in aqueous solution is a proven method for manufacturing protein-based SAPs. Although it is widely used for functionalization for many purposes it requires large amounts of water to be handled and in the case of EDTAD functionalization, expensive reagents. Other methods of introducing carboxyl functionality to proteins exist such as bulk esterification with polycarboxylic acids (Chiou, Jafri et al. 2013) where bio-based non-anhydride reagents should have a lower GHG potential and reagent recycling and should be more efficient. The structure of the SAP can play a powerful role in increasing capacity where open celled foams can take advantage of capillary action to induce rapid liquid uptake while also increasing the total uptake (Capezza, Wu et al. 2019). The use of extrusion foaming techniques can provide improved structure and a convenient, energy efficient manufacturing method for obtaining these types of structures (Capezza, Robert et al. 2020). These techniques have only been demonstrated at a laboratory scale and thus have a low TRL rating but constitute possible future avenues for increased performance in both the ability to absorb liquids and reducing GHG impact for protein based SAPs.

5 Sustainable development and local and regional development benefits

Implementation of the production of superabsorbent polymers (SAP) based on renewable feedstock is a major step on the progression to a more sustainable sanitary products sector that is characterized by high consumption of use-and-discard products.

Combustion is the common end-of-life treatment in many industrial countries, where energy recovery is part of the waste treatment process. In other countries, diapers and other SAP-containing products may end up in the environment, e.g. in landfills. If products contain fossil- or renewable-based sodium acrylate SAP, this component will degrade very slowly and remain a contaminate in the environment, possibly leaching acrylic acid during long term degradation. A biobased, biodegradable SAP may therefore reduce problems with environmental loads from these polymers.

These benefits contribute to the Swedish environmental goal of Reduced climate impact, as well as to the UN sustainable development goals (7.2, 8.4, 9.4, 12.2, 13.2 and 13.3).

6 Conclusions

This pre-feasibility study has shown that biobased superabsorbent polymers (bioSAP) produced from food industry residual products have the potential to reduce emissions when replacing fossil-based SAP based on sodium polyacrylic acid.

The raw materials used for the production of the proposed bioSAP are readily available on the market and in relatively large amounts. The economic costs of replacing conventional SAPs with bioSAPs require further study in the next step of development, but raw materials are already at a relatively low cost at prices below that of the fossil SAP counterpart. Also, the cost to adapt the production lines for producing bioSAP are considered to be low, as they rely on conventional reaction methods, e.g. use of reactors and other technology that is already used industrially.
Utilization of the residual streams from wheat and potato starch production will add additional value to the agro-industrial value chain and strengthen the food production system with increased resource use efficiency and additional income. As residual by-products, utilization for bioSAP production will not affect the food production system negatively, by avoiding direct competition with resources needed in the food industry.

Acknowledgements

A pre-feasibility study on an extended dataset will be published soon. The Bo Rydins Stiftelse (grant F 30/19) is acknowledged for the financial support provided to Antonio Capezza.

References

Alam, M. N., M. S. Islam and L. P. Christopher (2019). "Sustainable Production of Cellulose-Based Hydrogels with Superb Absorbing Potential in Physiological Saline." ACS omega **4**(5): 9419-9426.

ANSES (2019). Safety of baby diapers. Maisons-Alfort, France, French Agency for Food, Environmental and Occupational Health & Safety.

Belitz, H.-D., W. Grosch and P. Schieberle (2009). Amino Acids, Peptides, Proteins. Food Chemistry. Berlin, Heidelberg, Springer Berlin Heidelberg**:** 8-92.

Capezza, A. J. (2017). Novel superabsorbent materials obtained from plant proteins. Alnarp, Sweden, Crop Production Science.

Capezza, A. J. (2020). Sustainable Biobased Protein Superabsorbents from Agricultural Co-Products. PhD, KTH Royal Institute of Technology and SLU Swedish University of Agricultural Sciences.

Capezza, A. J., Y. Cui, K. Numata, M. Lundman, W. R. Newson, R. T. Olsson, E. Johansson and M. S. Hedenqvist (2020). "High Capacity Functionalized Protein Superabsorbents from an Agricultural Co-Product: A Cradle-to-Cradle Approach." Advanced Sustainable Systems **4**(9): 2000110.

Capezza, A. J., D. Glad, H. D. Özeren, W. R. Newson, R. T. Olsson, E. Johansson and M. S. Hedenqvist (2019). "Novel Sustainable Superabsorbents: A One-Pot Method for Functionalization of Side-Stream Potato Proteins." ACS Sustainable Chemistry & Engineering **7**(21): 17845-17854.

Capezza, A. J., M. Lundman, R. T. Olsson, W. R. Newson, M. S. Hedenqvist and E. Johansson (2020). "Carboxylated Wheat Gluten Proteins: A Green Solution for Production of Sustainable Superabsorbent Materials." Biomacromolecules **21**(5): 1709-1719.

Capezza, A. J., W. R. Newson, R. T. Olsson, M. S. Hedenqvist and E. Johansson (2019). "Advances in the Use of Protein-Based Materials: Toward Sustainable Naturally Sourced Absorbent Materials." ACS Sustainable Chemistry & Engineering **7**(5): 4532-4547.

Capezza, A. J., E. Robert, M. Lundman, W. R. Newson, E. Johansson, M. S. Hedenqvist and R. T. Olsson (2020). "Extrusion of Porous Protein-Based Polymers and Their Liquid Absorption Characteristics." Polymers **12**: 459.

Capezza, A. J., Q. Wu, W. R. Newson, R. T. Olsson, E. Espuche, E. Johansson and M. S. Hedenqvist (2019). "Superabsorbent and Fully Biobased Protein Foams with a Natural Cross-Linker and Cellulose Nanofibers." ACS Omega **4**(19): 18257-18267.

Chiou, B.-S., H. Jafri, T. Cao, G. H. Robertson, K. S. Gregorski, S. H. Imam, G. M. Glenn and W. J. Orts (2013). "Modification of wheat gluten with citric acid to produce superabsorbent materials." Journal of Applied Polymer Science **129**(6): 3192-3197.

Cok, B., I. Tsiropoulos, A. L. Roes and M. K. Patel (2014). "Succinic acid production derived from carbohydrates: An energy and greenhouse gas assessment of a platform chemical toward a bio-based economy." Biofuels, Bioproducts and Biorefining **8**(1): 16-29.

CoW (2011). Winnipeg sweage treatment program - Appendix 7: CO2 emission factors database. Winnipeg, Canada, City of Winnipeg.

Dahlgren, L., H. Stripple and F. Oliveira (2015). Comparative study of virgin fibre based packaging products with competing plastic materials. Stockholm, Sweden, IVL Swedish Environmental Research Institute**:** 75.

Deng, Y. (2014). Life cycle assessment of biobased fibre-reinforced polymer composites. PhD Doctoral, University of Leuven.

EAI (2013). Magic/Novelty Superabsorbents - LiquiBlock™ 42K. Greensboro, USA, Emerging Technologies Inc.

EC (2008). Regulation (EC) No. 440/2008 laying down test methods. E. Commission. Brussels, Belgium, European Commission.

Edana (2015). Polyacrylate Superabsorbent Powders- Determination of the Free Swell Capacity in Saline by Gravimetric Measurment. Nonwoven standard procedures. Brussels, Belgium/Cary, USA, Edana/Inda. **NWSP 240.0.R2**.

EDANA (2016). Guidelines for the testing of baby diapers. Brussels, Belgium, Edana.

EP (2001). EU Directive 2001/95/EC on general product safety. E. Parliament. Brussels, Belgium, EUR Lex Europa.

Gontia, P. and M. Janssen (2016). "Life cycle assessment of bio-based sodium polyacrylate production from pulp mill side streams: case study of thermo-mechanical and sulfite pulp mills." Journal of Cleaner Production **131**: 475-484.

González-García, S., L. Argiz, P. Míguez and B. Gullón (2018). "Exploring the production of bio-succinic acid from apple pomace using an environmental approach." Chemical Engineering Journal **350**: 982-991.

GVR (2019). Super Absorbent Polymer (SAP) Market Size, Share & Trends Analysis Report By Application. San Francisco, USA, Grand View Research.

HCM. (2020). "Super Absorbent Polymer for Diapers."   Retrieved 20 Nov 2020.

IMARC. (2020). "Diaper Market: Global Industry Trends, Share, Size, Growth, Opportunity and Forecast 2020-2025."

Jiménez-Rosado, M., V. Perez-Puyana, J. F. Rubio-Valle, A. Guerrero and A. Romero (2020). "Processing of biodegradable and multifunctional protein-based polymer materials for the potential controlled release of zinc and water in horticulture." Journal of Applied Polymer Science **137**(46): 49419.

Johansson, E., A. H. Malik, A. Hussain, F. Rasheed, W. R. Newson, T. Plivelic, M. S. Hedenqvist, M. Gällstedt and R. Kuktaite (2013). "Wheat Gluten Polymer Structures: The Impact of Genotype, Environment, and Processing on Their Functionality in Various Applications." Cereal Chemistry **90**(4): 367-376.

MaM. (2020). "Potato Protein Market by Type (Isolates, Concentrates), Application (Food & beverages (Meat, Dairy, Confectionery, Processed Foods, Beverages, Sports Nutrition), Feed), and Region (North America, Europe, Asia Pacific, South America) - Global Forecast to 2022." Retrieved 20 Nov 2020, from https://www.marketsandmarkets.com/Market-Reports/potato-protein-market-117255732.html?gclid=CjwKCAiAzNj9BRBDEiwAPsL0d2GxiqlMCKL5ElufP0m0r0DRm3SFXLvIRuirNc4y21r_GaUrNH3ACxoCJioQAvD_BwE.

MaM. (2020). "Wheat Protein Market by Product (Wheat Gluten, Wheat Protein Isolate, Textured Wheat Protein, Hydrolyzed Wheat Protein), Application (Bakery, Pet Food, Nutritional Bars, Processed Meat, Meat Analogs), Form (Dry, Liquid), and Region - Global Forecast to 2022." Retrieved 20 Nov 2020, from https://www.marketsandmarkets.com/Market-Reports/wheat-protein-market-67845768.html?gclid=CjwKCAiAzNj9BRBDEiwAPsL0d6h3IE89eNc8krHt4wbybKvRqpiyqSYSNnAR7HgP8wmRQB27dqMmihoCoR0QAvD_BwE.

McKerchar, H. J., S. Clerens, R. C. J. Dobson, J. M. Dyer, E. Maes and J. A. Gerrard (2019). "Protein-protein crosslinking in food: Proteomic characterisation methods, consequences and applications." Trends in Food Science & Technology **86**: 217-229.

Mirabella, N., V. Castellani and S. Sala (2013). "Life cycle assessment of bio-based products: a disposable diaper case study." The International Journal of Life Cycle Assessment **18**(5): 1036-1047.

Moussa, H. I., A. Elkamel and S. B. Young (2016). "Assessing energy performance of bio-based succinic acid production using LCA." Journal of Cleaner Production **139**: 761-769.

Muneer, F., M. Andersson, K. Koch, M. S. Hedenqvist, M. Gällstedt, T. S. Plivelic, C. Menzel, L. Rhazi and R. Kuktaite (2016). "Innovative Gliadin/Glutenin and Modified Potato Starch Green Composites: Chemistry, Structure, and Functionality Induced by Processing." ACS Sustainable Chemistry & Engineering **4**(12): 6332-6343.

Muneer, F., E. Johansson, M. S. Hedenqvist, M. Gällstedt and W. R. Newson (2014). "Preparation, Properties, Protein Cross-Linking and Biodegradability of Plasticizer-Solvent Free Hemp Fibre Reinforced Wheat Gluten, Glutenin, and Gliadin Composites." 2014 **9**(3): 16.

Murphy, K. P. (2001). Stabilization of Protein Structure. Protein Structure, Stability, and Folding. K. P. Murphy. Totowa, NJ, Humana Press**:** 1-16.

Patel, M. K., A. Bechu, J. D. Villegas, M. Bergez-Lacoste, K. Yeung, R. Murphy, J. Woods, O. N. Mwabonje, Y. Ni, A. D. Patel, J. Gallagher and D. Bryant (2018). "Second-generation bio-based plastics are becoming a reality – Non-renewable energy and greenhouse gas (GHG) balance of succinic acid-based plastic end products made from lignocellulosic biomass." Biofuels, Bioproducts and Biorefining **12**(3): 426-441.

ReportLinker. (2020). "Superabsorbent Polymers market worldwide is projected to grow by 1 Million Metric Tons."

Röös, E. (2013). Analysing the Carbon Footprint of Food. PhD, Swedish University of Agricultural Sciences.

Sinz, A. (2006). "Chemical cross-linking and mass spectrometry to map three-dimensional protein structures and protein–protein interactions." Mass Spectrometry Reviews **25**(4): 663-682.

Tromp, M. (2020). The environmental impact of introducing a potato protein for human consumption in Sweden, Uppsala University.

Wilske, B., M. Bai, B. Lindenstruth, M. Bach, Z. Rezaie, H.-G. Frede and L. Breuer (2014). "Biodegradability of a polyacrylate superabsorbent in agricultural soil." Environmental Science and Pollution Research **21**(16): 9453-9460.

Wolter, M., C. i. d. Wiesche, F. Zadrazil, S. Hey, J. Haselbach and E. Schnug (2002). "Biological degradability of syntetic superabsorbent soil conditioners." Landbauforschung Völkenrode **52**(1): 43-52.

Wu, Q., R. L. Andersson, T. Holgate, E. Johansson, U. W. Gedde, R. T. Olsson and M. S. Hedenqvist (2014). "Highly porous flame-retardant and sustainable biofoams based on wheat gluten and in situ polymerized silica." Journal of Materials Chemistry A **2**(48): 20996-21009.

PRODUCTION OF NATURAL COSMETICS
BASED ON EXTRACTS FROM CARROT POMACE

COLOURBOX34760928

Prefeasibility study

Production of natural cosmetics based on extracts from carrot pomace

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1. Introduction

Carrots are a well-known and widely used vegetable in the food industry around the world. Thanks to the long-standing tradition of carrot cultivation, Poland is one of the world's leading producers – in 2018 in European Union Member States, Poland, together with the United Kingdom, was at the forefront of the production of this vegetable. Both of these countries produced 0.7 million tons in 2018 (a combined 27.8 % of the EU total)[1]. This creates interesting possibilities for the management of waste arising from carrot processing, taking into account the possible large source of raw material in the form of post-production waste.

A recent bioeconomy is emphasizing the cascading approach (Figure 1), which evaluates the methods of post-production waste management. It is essential to lean towards new methods of waste valorisation, producing cosmetics, medicines, food products or biodegradable materials from them, instead of using it as energy raw material. Figure 1 presents a concept of cascading approach, which depicts the value of individual management methods. Carrot waste, due to its valuable properties, can be used for new components, especially in fields of pharmaceuticals and cosmetics. Raw carrot contains many vitamins and valuable nutrients, such as alpha carotene, beta carotene, vitamins A, B6, C, fiber, polyphenols or potassium. A favorable phenomenon is that the processing of carrots for food purposes does not adversely affect the nutrient content[2]. It is therefore important to develop and implement new technologies for the use of carrot waste, because they are too valuable to be treated as an energy source, for example, in biogas plants.

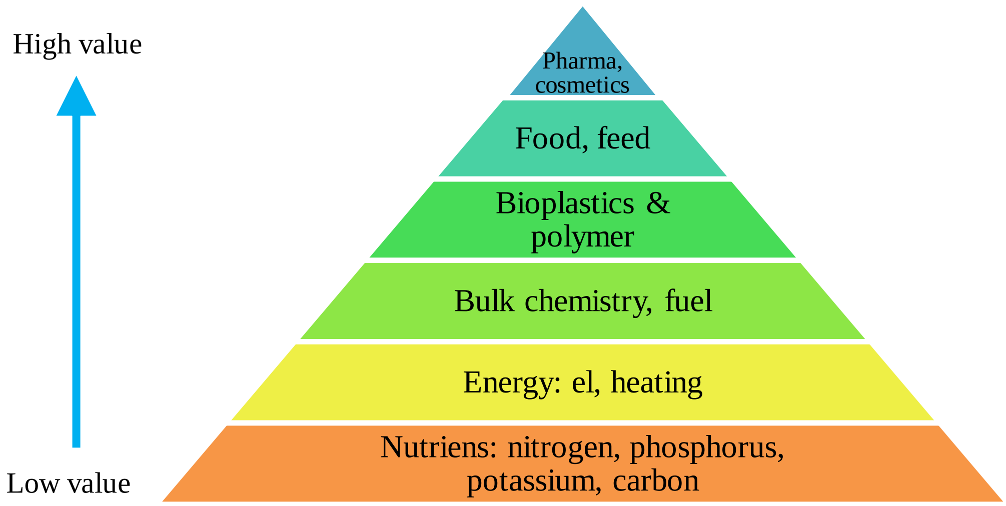

Fig. 1. The cascading approach.

2. Statistics on carrot production in Poland and in SBA regions

The carrot cultivation area in Poland has been growing slowly since 2015 and reached 22 400 ha in 2018[3], which places carrots in the third place in terms of the vegetable cultivation area in

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[1] *Agricultural production – crops*. Eurostat, 2019.

[2] Sękara A., Pohl A., Kalisz A., Grabowska A., Cebula S.: *Evaluation of selected Polish carrot cultivars for nutritive value and processing – a preliminary study.* Annals of Warsaw University of Life Sciences – SGGW Horticulture and Landscape Architecture No 35, 2014: 3–14.

[3] *Production of agricultural and horticultural crops in 2018*. Statistics Poland, 2019.

Poland[4]. In 2018, 726.4 thousand tons of crops were harvested from this area. On a global scale, in 2014, Poland was the sixth largest producer of carrots in the world, behind China, Uzbekistan, Russia, the USA and Ukraine[4].

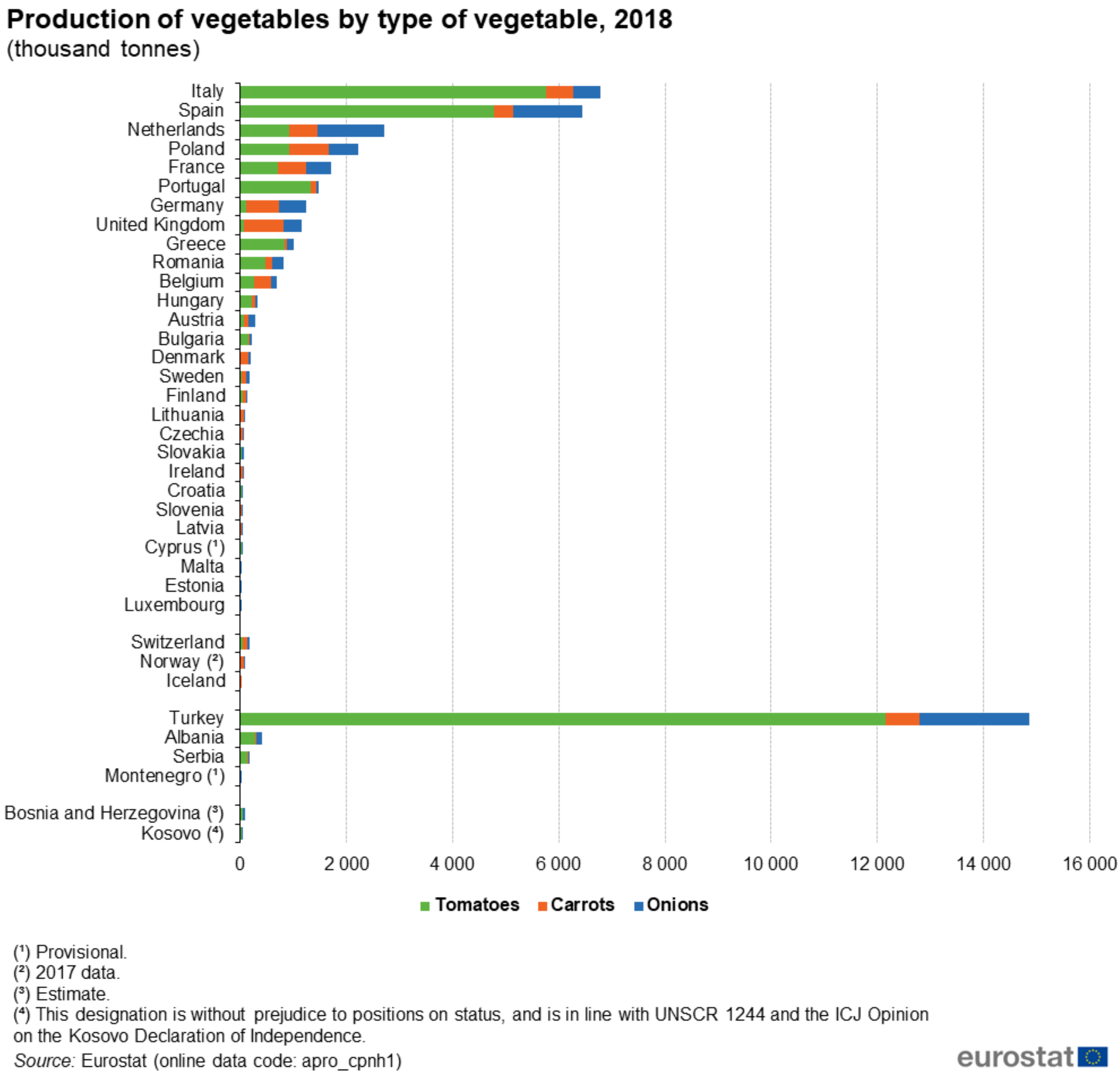

Fig. 2. Production of vegetables in EU, 2018[5]

In the South Baltic region, carrot production is not as large as in other regions, however, it is very much supported and developed by local companies from the food industry (including for example Marwit company, which produces freshly squeezed juices, salads, smoothies, soups, fresh carrots). In 2018, in the Pomeranian region carrot cultivation covered 990 ha (from which 299 318 tons of carrots were obtained), in West Pomeranian region 550 ha (with 155 045 tons of carrots), and in Warmia and Mazury region 491 ha (190 242 tons of carrots). It is worth emphasizing that in the SBA regions high yields per 1 ha were recorded, with the highest value in the country achieved in the Warmia and Mazury - 388 tons per 1 ha. The southern Baltic region, due to its mild maritime climate, much higher humidity and relatively lower

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[4] *Vegetable market in Poland*. National Agricultural Support Center, 2014.
[5] *Agricultural production – crops*. Eurostat, 2019.

temperatures than in southern Poland, allows for higher yields per hectare and high-quality carrots.

3. Wastes from carrot processing

Not only a good climate for the cultivation of high-quality carrots contributes to the development of this industry in northern Poland, but also the innovations used by producers, leading to more sustainable agriculture. In addition, the growing market of ,,one-day" shelf life juices and low-processed, chemical-free food means that the waste generated during the manufacturing of such products is of very good quality and could be used as raw material for subsequent processes.

Marwit, local company nearby Pomeranian region, is an example of company specializing in production of high quality, chemical-free food. The main processed raw materials are carrots, apples, white cabbage, celery, beets and others, depending on what seasonal flavors were released on the market in a given period. Since the juices are produced without the addition of chemicals, the process produces waste in the form of pure carrots and good quality waste water. A company wants to invest in HPP juicing technology – high pressure processing, which is an environmentally friendly cold pasteurization technique, that allows to keep original fruit or vegetable taste, color and nutrition. Also, this process allows to extend expiration date of the beverage without preservative. Pressures above 300-400 MPa inactivate the bacteria present in food, extending the products expiration date and guaranteeing food safety. These actions can additionally improve the quality of the generated waste.

During production, organic waste remains, such as:

- carrot pomace,
- post-production vegetables (peelings from carrots, apples, celery),
- waste plant mass (vegetables unfit for production, damaged, spoiled).

Annually, the plant produces about 2 000 tons of pomace and about 400 tons of post-production vegetables. In addition, due to the characteristics of the products and the short shelf life, the company has a policy of accepting returns (products not sold by stores) - annually, around 2 000 tons of expired juices goes back to the company. Carrot pomace was tested in laboratory, to check the content of specific ingredients. The composition of the carrot pomace is given in Table 1. It is worth noting that the amount of this waste depends on the volume of production, which varies significantly throughout the year (in the summer months, production is much lower due to the fact that juices spoil quickly).

Table 1. The composition of the carrot pomace

	Orange carrot root meal	Orange carrot pomace meal	Purple carrot root meal	Purple carrot pomace meal
Dry weight (%)	90.61	93.06	92.3	94.69
Crude ash (%)	7.36	6.72	6.06	5.26
Crude protein (%)	7.37	6.63	9.65	9.08
Crude fat (%)	1.58	1.01	1.02	0.81
Total carbohydrates, including fiber (%)	75.7	71.6	74.4	72.3
Fiber (%)	25.7	55.8	28.6	55.6
Acids phenols (lyophilisate, without chlorogenic acid) (µg/g)	71.02	42.41	601.73	200.87
Chlorogenic acid (mg/g)	0.47	0.17	11.87	2.53
Anthocyanins (mg/g)	-	-	12.85	3.06
Lutein (mg/100g)	2.56	0.81	8.32	2.71
Alpha-carotene (mg/100g)	17.36	8.67	-	-
Beta-carotene (mg/100g)	39.86	19.4	0.46	0.08
Total carotenes (mg/100g)	65.88	32.52	9.63	3.48

It can be seen that valuable nutrients still remain in the waste. Carotenes (Beta carotene, alpha carotene) have a positive effect on lowering cholesterol, improving eyesight, and also have a beneficial effect on the appearance of hair and skin color. They are antioxidants that are blocking free radicals, have anti-aging properties and reduce the risk of cancer. The other ingredients also have a beneficial effect on human health. Chlorogenic acid also has many properties - it reduces the absorption of sugar, thanks to which it helps people struggling with diabetes. It can be used as a dietary supplement in weight loss. Anthocyanins have an anti-cancer effect, have a positive effect on eyesight, and strengthen the body's immunity. Since they have anti-inflammatory properties, reduce swelling and have a positive effect on the overall improvement of the condition of the skin, hair and nails, they are widely used in cosmetics. Lutein also has a positive effect on the treatment of eye diseases, improves the condition of the skin, protecting it against external factors - it also has a photo-protective effect. Since it is not synthesized in the body, it must be supplied to the body with food.

4. Methods of reuse of carrot post-processing waste

Currently in the presented factory, the unsold juice goes to a biogas plant, due to the difficulty of its other management (problem with glass packaging). Carrot pomace is sold to other companies at a low price, which make spices from them. Post-production vegetables are sold to local farmers and are used as feed or fertilizer. Also, it is not possible to use post-production wastewater to irrigate the surrounding fields (despite their high quality) due to legal restrictions. However, new technologies for the use of carrot waste are being developed, which may allow for a much more profitable use of this raw material.

4.1. Food products

The main stream of research on waste from carrot processing is the creation of a new food product, or the use of waste as a food additive, which could increase nutritional properties of a meal. Zambelli et.al.[6] in their work emphasized that carrot industrial solid waste has still significant amounts of vitamin C and fatty acids, which are essential in a balanced human diet. Manjunatha et al.[7] developed a kheer mix based on carrots, skim milk powder, sugar and other ingredients. Bas-Bellver[8] et al. have also made an attempt to produce a powdered product containing antioxidants and valuable nutrients from vegetable waste (including carrot waste) from ready-to-eat production lines. Ahmad et al.[9] examined how the addition of carrot pomace affects the properties of wheat flour and products made from it. There was an increase in the content of fiber and antioxidants in products, and a decrease in the content of gluten. There has also been an attempt to add carrot waste to meat products to increase their fiber content. Fouda et al.[10] suggested adding carrot pomace to fish sausage. This improved the texture and the cooking yield and water holding. However, there are barriers related to the visual and taste appeal of such products created with addition of carrot waste, so intense research is needed in this direction.

4.2. Nutrients

Individual valuable nutrients can also be extracted from carrot waste. Hammad et al.[11] attempted to extract polyphenols from carrot pomace to add them to oat bars. Traditional maceration techniques and advanced sonication technique were used in the extraction process. The extract obtained in this way can also be used for other products and meals. Tiwari et al.[12] in their study extracted carotenoids from carrot pomace using ultrasonication and high shear dispersion techniques and flaxseed oil as green solvent. The test were made for various combinations of time and temperature to obtain maximum amount of carotenoids with high

[6] Zambelli R.A., B.C.V. Pontes, Pontes E.R., Silva M.L., Cordeiro dos Santos E.J., Pinto L. Í.F., Melo C.A.L., Farias M.M., Silva da Costa C., Caroline da Silva A.: *Broccoli and Carrot Industrial Solid Waste Characterization and Application in the Bread Food Matrix*. International Journal of Nutrition and Food Sciences. Special Issue: Advances in Food Processing, Preservation, Storage, Biotechnology and Safety, Vol. 6, No. 6-1, 2017, pp. 9-15.

[7] Manjunatha, S.S., B.L. Mohan Kumar and D.K. Das Gupta: *Development and Evaluation of carrot kheer mix*. J. Food Sci. Technol., 40, 2003, 310-312.

[8] Bas-Bellver, C., Barrera, C., Betoret, N. Seguí, L.: *Turning Agri-Food Cooperative Vegetable Residues into Functional Powdered Ingredients for the Food Industry*. Sustainability 2020, 12, 1284.

[9] Ahmad M., Wani T. A., Wani S. M., Masoodi F. A., Gani A.: *Incorporation of carrot pomace powder in wheat flour: effect on flour, dough and cookie characteristics*. Journal of Food Science and Technology, 53(10), 2016, pp. 3715–3724.

[10] Fouda Z.M.A.: *Quality attributes of fish sausage as affected by adding dietary fibers*. Annals of Agricultural Science (Moshtohor), 37(2), 1999, pp. 1287–1298

[11] Hammad N., Umar N., Sarmad S., Hira I.: *Extraction and Determination of Anti-Oxidant Activity of Polyphenols from Carrot Pomace, and Their Use in Date Oat Bar*. LOJ Med Sci 2(3), 2018, pp. 160-168.

[12] Tiwari S., Upadhyay N., Singh A.K., Meena G.S., Arora S.: *Organic solvent-free extraction of carotenoids from carrot biowaste and its physico-chemical properties*. Journal of Food Science and Technology, Vol 56, 2019, pp. 4678–4687.

oxidative stability. The resulting nutrients are intended for human consumption. Another compound, that can be extracted from carrot waste, is a citric acid, as proved by Garg et al.[13]

4.3. Others

Carrot waste is also used in other ways, not only by using the nutrients it contains. A new technique for obtaining cellulose from, among others, carrot pomace was proposed by Szymańska-Chargot et al[14], in order to obtain useful feedstocks with a potential application in the fields of fuels, chemicals, and polymers. The proposed technique made it possible to shorten the biomass fractioning process and to avoid the use of toxic chemicals, which reduced economic and environmental costs. Another way to manage carrot waste is the production of biochar, presented by Pinto et al[15]. The biochar from carrot waste obtained in their research was a promising adsorbent for phosphorus compounds recycling. Efforts were also undertaken to produce bio-plastics from carrots. Perotto et al.[16] managed to produce freestanding, flexible bioplastic films from vegetable wastes like carrot, parsley, radicchio and cauliflower, with similar mechanical properties as starch-based bioplastics. Otoni et al.[17] proposed biodegradable biocomposites based on the carrot waste, containing hydroxypropyl methylcellulose and cellulose fibers as binding and reinforcement agents. They also demonstrated the possibility of scaling the production of this type of material and proposed directions for the development of large-scale production of carrot biocomposites.

The presented applications are widely researched and extremely promising. However, due to the content of skin beneficial ingredients in the carrot waste, it becomes attractive to use it to make a cosmetic ingredient because it can be sold at a higher price than, for example, food products or plastics.

5. Natural cosmetics based on extracts from carrot pomace

Cosmetics, according to the cascading approach pyramid (Figure 1), are the most profitable use of waste. This is related to the dynamic development of the industry - the European cosmetics market was valued at 79.8 billion EUR in 2019[18]. Poland is the sixth largest national market for cosmetics products within Europe, valued at 4.1 billion EUR[18], it is therefore an attractive field of activity for new, innovative businesses. A particularly developing branch of the beauty industry, in which innovations in the use of biomass waste can be applied, are natural cosmetics.

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[13] Garg N. Hang Y.D.: *Microbial production of organic acids from carrot processing waste*. Journal of Food Science and Technology (Mysore), 32(2), 1995, pp. 119–121.

[14] Szymańska-Chargot M., Chylińska M., Gdula K., Kozioł A., Zdunek A.: *Isolation and Characterization of Cellulose from Different Fruit and Vegetable Pomaces*. Polymers, 9(10), 2017, pp. 1-16.

[15] Pinto M.C.E. , Silva D.D., Gomes A.L.A. , Santos R.M.M., Couto R.A.A., Novais R.F., Constantino V.E.L. , Tronto J., Pinto F.G.: *Biochar from carrot residues chemically modified with magnesium for removing phosphorus from aqueous solution*. Journal of Cleaner Production, 222, 2019, pp. 36-46.

[16] Perotto G., Ceseracciu L., Simonutti R., Paul U. C., Guzman-Puyol S., Tran T.-N., Bayer I.S., Athanassiou A.: *Bioplastics from vegetable waste via an eco-friendly water-based process*. Green Chemistry, 20(4), 2018, pp.894–902.

[17] Otoni C. G., Lodi B. D., Lorevice M. V., Leitão R. C., Ferreira M. D., Moura M. R. de, Mattoso L. H. C.: *Optimized and scaled-up production of cellulose-reinforced biodegradable composite films made up of carrot processing waste*. Industrial Crops and Products, 121, 2018, pp. 66–72.

[18] *https://cosmeticseurope.eu/cosmetics-industry/* Cosmetics Europe, 2019.

Fig. 3. European market for cosmetics products, 2019[18]

5.1. Market demands and supply opportunities

Increasing consumer awareness means that more and more cosmetic brands are introducing to their portfolio lines of products based on ingredients of plant origin and natural extracts, and some completely switch to the production of plant-based, environmentally friendly cosmetics. There is a significant increase in the share of natural cosmetics in beauty industry - in China in 2013 it grew by 24%, in the USA by 7%, and in Europe by 6%[19]. Consumers choose environmentally friendly natural cosmetics even in times of economic crisis, which is why this industry is growing every year[19].

Not only conscious consumers drive the natural cosmetics market in Poland. In 2020, the most popular chain of stores with cosmetics and body care products in Poland announced that it would not only significantly expand the offer of natural, vegan, *less waste* and *water less* cosmetics, but also change the way they were displayed so that they would stand out more. All these measures are aimed at supporting brands that produce their products in an ecological, certified and environmentally friendly manner. This creates a challenge for existing cosmetic brands, but also an opportunity for natural cosmetics start-ups.

Currently, the most popular trends in the natural cosmetics industry are the use of natural oils, plant extracts, cosmetics with a short, concentrated ingredients list, *water less* cosmetics (such as bar shampoos, multifunctional soaps) and recyclable or refillable packaging. A relatively new and rare practice is to use waste components from food processing. An example of this type of products in Poland is the Blueberry C-Tox line by Bielenda, which uses blueberry seed oil obtained as a by-product of juice production[20]. Another product is Paese's Nanorevit Natural Finish Longwear Everyday Foundation. According to the manufacturer, blackcurrant pomace

[19] Cosmetic Reporter, I-II-III 2014, nr 1 (46).
[20] https://bielenda.pl/katalog/blueberry-c-tox

from the production of the juice was used. The dried seeds were subjected to an extraction process at the Institute of New Chemical Syntheses in Puławy[21]. The oil obtained in this way is less susceptible to oxidation and retains its properties better. Using ultrasound technology, the oil has been encapsulated into nanostructures[21].

However, the presented examples are rare on the Polish cosmetics market. The previous practices of manufacturers show that it is advisable to look for innovations and novelties in the natural cosmetics industry to distinguish the product from others. Therefore, this study considers producing beta-carotene oil extract from carrot pomace in order to use it as an active ingredient in cosmetics made in line with the *less waste* philosophy. The presence of companies such as Marwit and the possibility of obtaining the high-grade waste material thanks to the good quality of carrots and innovative techniques for its processing, favors the development of such an idea in the regions of the South Baltic.

Fig. 4. Examples of Polish natural cosmetics with ingredients derived from food waste[20,21]

5.2. Regional market situation

In the SBA region in Poland, there are several large cosmetic production plants that could be interested in expanding their offer with a cosmetic using an extract derived from carrot waste. The largest and most famous are Ziaja Ltd, Oceanic S.A., WIBO Sp. z o.o. Sp. k and MARION Sp. z o.o. These companies are the leaders of introducing new products to the cosmetics market and are up to date with all trends, so they may be interested in buying waste-derived beta-carotene extract, and they will be able to use its origin as an additional advantage of the produced cosmetic. Ziaja itself produces 80 million cosmetic products and medicinal ointments

[21] https://paese.pl/product-pol-657-Dlugotrwaly-podklad-o-naturalnym-wykonczeniu-Nanorevit-Natural-Finish-Longwear-Everyday-Foundation-35-ml.html

annually (and aiming at 120-130 million), which creates the possibility of high demand for the extract produced from carrot pomace.

5.3. Production of natural cosmetics and supplements from carrot waste

Production of the cosmetic ingredients from carrot pomace can be approached in two ways. The first is to isolate one component, for example beta carotene, because of its beneficial effects on the skin of the face. There are several methods of obtaining extract, but not all are beneficial in terms of environmental (difficulty in disposal of solvents, cost) and quality (oxidation of components). Mirheli et al.[22] proposed a method of obtaining beta carotene extract from carrot pomace using ultrasonic-shaking incubation method. In the research they examined several possible combinations of the duration of individual processes and indicated the most favorable conditions.

According to the researchers, carrot powder mixed in the proportion of 1.5 g per 100 ml of ethanol solvent is placed in an ultrasonic bath at 50°C at a frequency of 20 kHz for 80 minutes[22]. Then it is placed in a shaker incubator at 30°C, at rotational speed of 150 rpm for 120 minutes[22]. Then the finished carrot extract is filtered from the carrot powder. The tests showed that the above conditions allow for obtaining an extract with a high beta carotene content, equal to about 54 ppm.

Assuming that all of the above-described powdered carrot waste from the juice factory is used to produce the extract, 2 000 tons of carrot pomace will be used in the final process. In Figure 5, the material flow for the production of beta carotene extract from waste is shown.

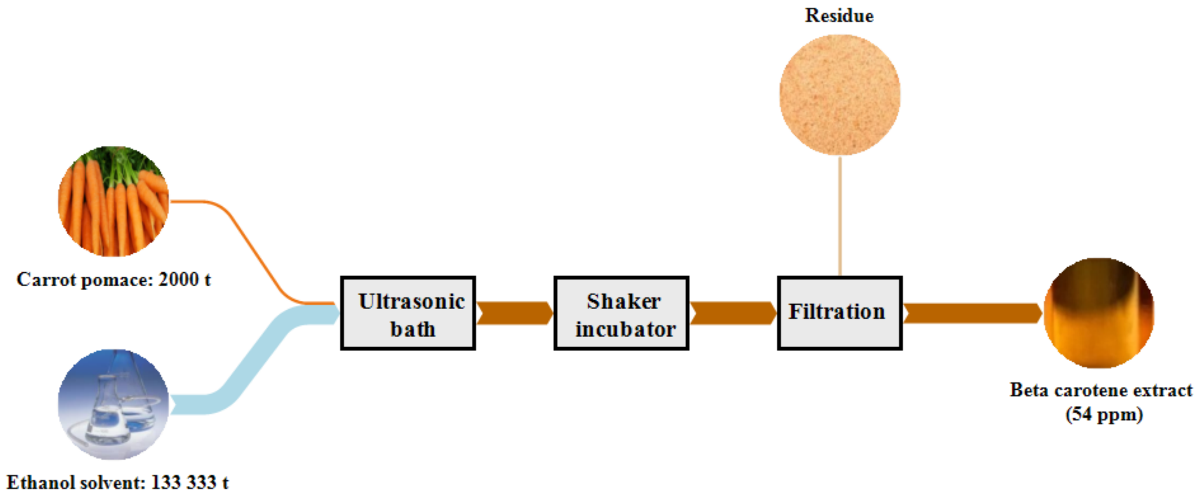

Fig. 5. Material flow of beta carotene extract production (annual values)[22]

Another way to recover from carrot waste is the maceration process. Maceration is a method of extracting components from plants, consisting in extracting components from the material by

[22] Mirheli M., Taghian Dinani S.: *Extraction of β-carotene pigment from carrot processing waste using ultrasonic-shaking incubation method*. Journal of Food Measurement and Characterization, 12(3), 2018, pp. 1818–1828.

soaking it for a long time in a solvent. The solvent may be, for example, water, ethanol, or oil with favorable cosmetic properties, which will further enhance the effect of the product. A widely used oil in herbal oil macerates is sunflower seed oil (*Helinathus Annuus*), due to its low comedogenic potential, nutritional, protective and anti-inflammatory effects. It is also locally grown in Poland. The disadvantage of this method is its duration - the process may take up to several days/weeks. As there are no studies on the maceration of carrot waste in oil and what would be the final content of desired ingredients in the finished product, preliminary laboratory tests should be carried out for this method. However, it is an interesting alternative as it requires less advanced industrial equipment.

6. Prefeasibility of the concept

There is a lot of research on new methods of obtaining beta carotene from carrot pomace undergoing in laboratories, one of which was described above. Poland is also a well-developed country in the field of cosmetic laboratories, with experience in implementing innovations - Polish companies were the first in the world to introduce folic acid and vitamin K in cosmetics as well as to use telomeres[23]. However, many technologies still require refinement to be implemented successfully on large scale, especially in Poland. It can be assumed, that proposed way of utilizing carrot waste is at TRL level 4, as it is widely proven in laboratory. There are few barriers and challenges, that must be overcome.

6.1 Barriers and challenges

The basic problem in Polish law that blocks the implementation of innovations in the field of biomass residues is the status of waste. Procedures to be followed in order to be able to use waste as raw materials in subsequent processes are very complicated. The problem is that in order to change this status, each case must be considered separately, at the request of a given company, which significantly lengthens and complicates the process. This is a kind of challenge that may discourage producers from taking steps regarding the use of waste in the production process due to the fact that each new component/waste will require a separate procedure. The examples of existing cosmetics with the use of waste substances from the food industry, cited above, show that it is possible in Poland to change the waste status and allow it to be used in the cosmetics industry. However, it should be remembered that there are only a few examples in the huge Polish cosmetics market. A faster, generalized procedure for changing the waste status should therefore be possible. Since the waste material and the cosmetic ingredient made from it must be comprehensively tested in a laboratory, it would be beneficial to support entrepreneurs in terms of access to laboratories or co-finance research on the composition of their post-production waste.

6.2 Research and Innovation needed

In order to successfully implement the proposed technology, cooperation between the carrot processing industry and cosmetic companies is needed. The described technology is relatively simple and not complex, but needs to be verified in real conditions. It would be important to

[23] Polish Cosmetics Trade Catalog: https://www.trade.gov.pl/pl/f/v/526811/PPE_PL_Cosmetics.pdf

build a pilot line for the production of beta carotene extract on a small scale, and then gradually scale it, adapting it to the demand for the product. Research on the improvement of the obtained product as well as the simplification and optimization of the process will be of key importance. The proposed extraction of oil macerate is also interesting - this process is long, but taking into account its simplicity and very small financial outlays, it could turn out to be attractive for investors. Due to the lack of literature reports on obtaining extracts from carrot waste in this way, basic laboratory research in this field is needed. Currently, bottled oil carrot macerate is sold on the Polish market, so the product could be sold directly to consumers, not to cosmetic companies, which is also interesting business idea.

An innovation could be a program associating companies from the biomass processing industry, the aim of which would be to create a database of post-production waste that they produce. The participating companies could benefit from funding or priority access to laboratories to determine the composition of waste and search for interesting ingredients in it. This would make it easier for investors or researchers and scientists to find attractive ingredients in waste substances that could be reused and start the cooperation with the company which produces it. This would facilitate the mapping of resources, the development of new businesses and the creation of partner and logistics networks.

6.3 Benefits and opportunities

The use of waste from plant processing industry certainly has many advantages and opportunities for the development of individual companies and entire regions. Activities undertaken by drugstores and perfumeries, which create entire expositions devoted exclusively to cosmetics of natural origin and created in accordance with the *less waste* philosophy, show that companies must undertake development activities towards natural cosmetics, and obtaining extracts from plant waste can be extremely promising. Since this type of raw material is practically free, the extract may turn out to be much cheaper, not to mention the fact that conscious consumers will definitely be interested in cosmetics that minimize the exploitation of the environment and use waste products.

The current trends in the cosmetics industry have a positive impact on the development of this type of business ideas and create many opportunities for entrepreneurs. As the lines that use local resources from Poland are widely popular, the new line of cosmetics could be advertised as using the benefits of local natural ingredients - extracts obtained from locally grown carrots in Polish South Baltic Area regions. It would be interesting for consumers and emphasize the uniqueness of the product. In Poland, there are already popular cosmetics that advertise themselves as using the natural resources of the region - for example, Balneocosmetics, which contain healing sulphide water from a spring in Solec-Zdrój[24] or Termissa, ecological dermocosmetics with thermal water from Podhale[25]. The successes of these brands show that it is worth emphasizing the origin of the product and its impact on quality and uniqueness. This

[24] https://balneokosmetyki.pl/
[25] https://termissa.eu/

has a positive effect not only on the company's image, but also serves as an advertisement for the whole region.

7. Conclusions

Waste from carrot processing has a number of valuable ingredients that should be recovered and reused. The presented research from one of the largest producers of carrot juice proves that carrot pomace contains ingredients that can be reused in the natural cosmetics industry. This is an attractive opportunity for many new businesses and innovations in sourcing cosmetic ingredients from waste. The increasing environmental requirements for producers of chemicals and cosmetics also stimulate the development of this sector, and the cosmetics that use waste juices from food processing that appear on the market show that there is an interest in using waste raw material. The Polish South Baltic Area regions have specialized for years in the production of quality vegetables, so it is important to encourage local companies to check the composition of waste generated in their plants in order to find reclaimable substances. The mentioned method of obtaining beta carotene extract from carrot pomace can be validated in these regions, and then further scaled and optimized.

KERATIN HYDROLYSATE PRODUCTION FROM POULTRY FEATHERS

COLOURBOX33938251

Prefeasibility study

Keratin hydrolysate production from poultry feathers

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1. Introduction

According to EUROSTAT data, in 2018 about 70% of poultry meat production in the European Union came from six countries, including as much as 16.8% from Poland.[1] These data testify to the large number of companies involved in breeding and slaughtering of poultry in this country. The northern region of Poland, which consists of three regions: West Pomeranian, Pomeranian and Warmian and Masurian Voivodeship is at the forefront in poultry production. A large amount of meat produced is also associated with a large number of slaughter waste, including blood, feathers and guts. There is therefore a real potential to use this waste in such a way as to minimize as much as possible the amount that will go directly to disposal, and thus extend the chain of use of a given raw material and increase its value. Although there are various ways of using this waste, the best, from the point of view of the cascade approach (Fig. 1), are methods for obtaining valuable products, for example ingredients of cosmetics, drugs, food products or biodegradable materials. The most advantageous solution is to use such methods to create the most valuable products at the lowest possible costs, thereby gaining a new product whose sales will generate additional revenue. One such method may be the production of keratin hydrolyzate from poultry feathers. Keratin belongs to the group of proteins and is a component of many cosmetics and drugs, so it is at the top of the pyramid showed below.

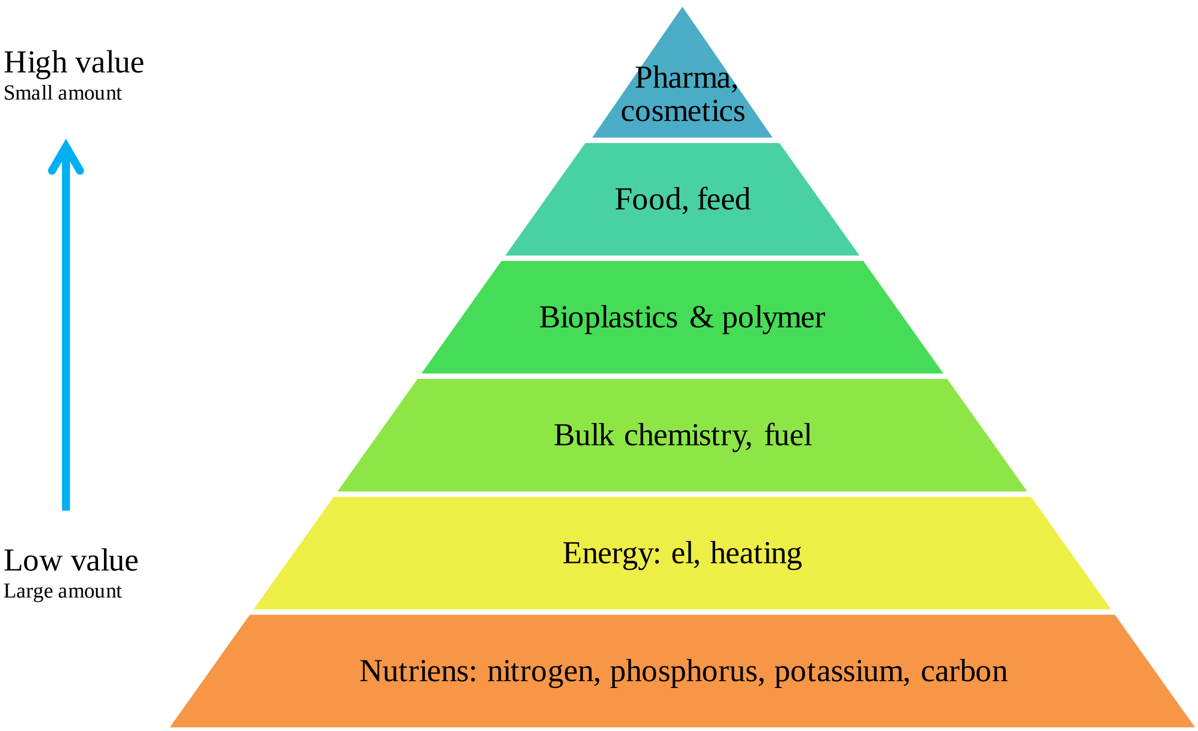

Fig. 1. The cascading approach.

[1] Website: https://www.money.pl/gielda/eurostat-produkcja-miesa-drobiowego-w-ue-wzrosla-do-15-2-mln-ton-w-2018-roku-6363117912901251a.html

2. Statistical data related to the feathers production in Poland

In Poland, in 2017 poultry production amounted to 3 307 521 tonnes.[2] Enterprises located in the northern region of Poland were responsible for producing about 17% of this value, more precisely:[2]

- West Pomeranian: 155 908 tonnes,
- Pomeranian: 129 977 tonnes,
- Warmian and Masurian: 285 189 tonnes.

Since 1999, poultry production in northern Poland has increased, while the volume of production in each of the three voivodships has changed (Fig. 2). Since 2009, poultry production has increased significantly in the Pomeranian Voivodeship.

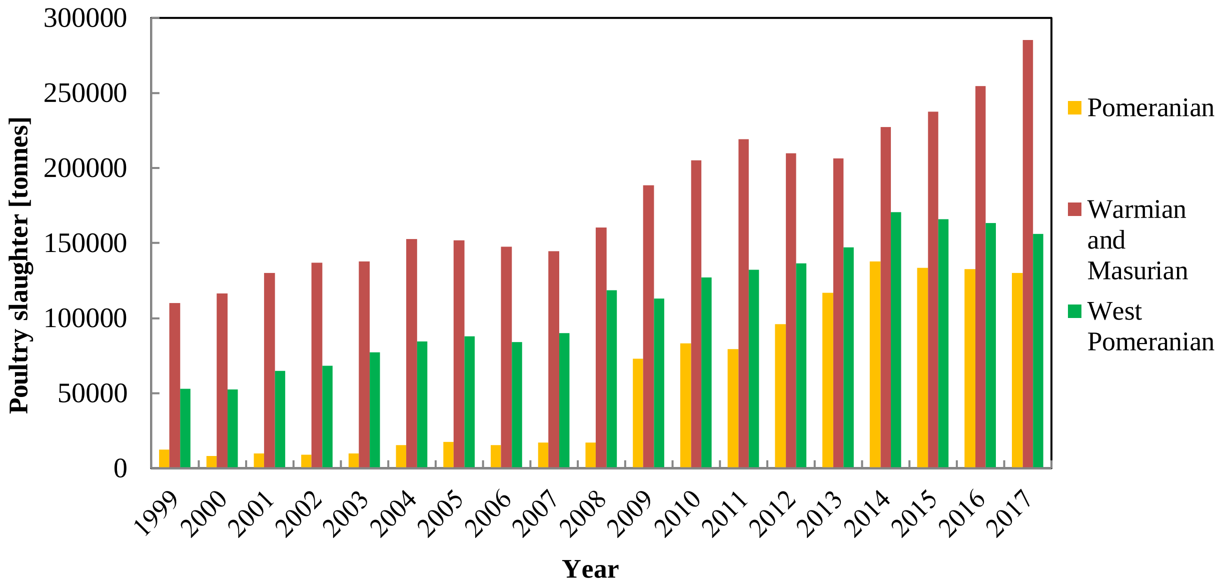

Fig. 2. Poultry production over the years for three Polish voivodeships.

According to literature sources, feathers account for about 7% of the chicken weight, and the average slaughtering enterprise generates about 7 tonnes of feathers per day.[3] It can therefore be estimated that the mass of feathers produced for individual voivodships in 2017 was about:

- West Pomeranian: 10 913 tonnes (about 30 tonnes per day),
- Pomeranian: 9 098 tonnes (about 25 tonnes per day),
- Warmian and Masurian: 19 963 tonnes (about 55 tonnes per day).

Based on the literature data[4] and an exemplary mass of poultry delivered to the slaughterhouse during one day, a scheme of its processing was prepared, along with the amount of generated waste.

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[2] Website: https://bdl.stat.gov.pl/BDL/start

[3] Staroń P., Banach M., Kowalski Z.: Keratin – origins, properties, application. CHEMIK 2011, 65, 10, p. 1019–1026.

[4] Sari O. F., Ozdemir S., Celebi A.: Utilization and Management of Poultry Slaughterhouse Wastes with New Methods. Eurasia 2016 Waste Management Symposium.

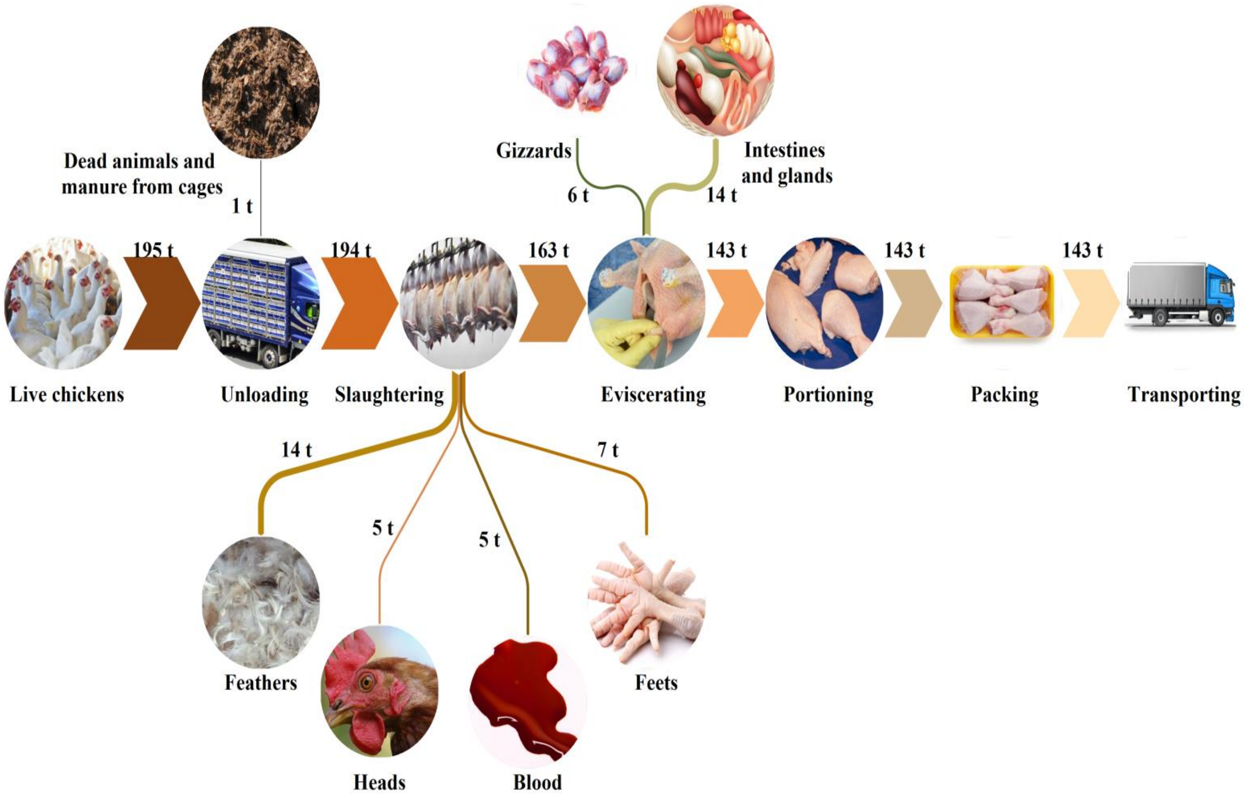

Fig. 3. The diagram of the poultry processing.

3. Methods of chicken feathers using

3.1.Feathers disposal

Feathers from slaughtering poultry can be disposed of in several ways.[5] The first way is to burn them in a waste incineration plant. The advantage of this solution is the certainty of neutralizing all infectious and dangerous agents. However, combustion is associated with emissions of carbon dioxide and carbon monoxide, nitrogen oxides and particulates that pollute the environment. In addition, by burning feathers immediately, valuable ingredients found in them are lost – including keratin, which can become a raw material in subsequent processes and thus lengthen the poultry processing chain.

The second way is feather storage in landfills. However, this process should be strictly controlled and carried out in such a way as to prevent contamination of groundwater, surface water, soil or air. Therefore, this method is not profitable - no new raw materials are obtained from the stored feathers, and investment cost is increased due to the use of appropriate methods to monitor this process.

[5] Tesfaye T., Sithole B., Ramjugernath D.: Valorisation of chicken feathers: recycling and recovery routes. 16th International Waste Management and Landfill Symposium, Sardinia 2017.

3.2.The use of feathers as a natural fertilizer and animal feed

It is more beneficial to use chicken feathers as input for other processes or as a product that can have, for example, a positive effect on soil quality.[5] Due to the content of about 13% nitrogen in feathers,[5] they are an excellent component of the fertilizer that can be used to fertilize the soil for crops requiring high demand for this element. The use of feathers as a fertilizer is troublesome due to the cross-linking with cysteine bonds, which are difficult to break down. The solution to this problem is to mix feathers with compost, whose addition positively affects their degradation. Due to the fact that the feathers contain 75-90% of protein,[4] one of the ways of their processing is the production of poultry meal, which can be used to feed fur animals.

3.3.Innovative solutions related to poultry feathers utilizing.

Currently, a number of laboratory research are conducted to determine the potential for using feathers from slaughtering poultry in various industries.[5] The low weight of the feathers and their good strength properties make it possible to use them as a component of composite materials used in the automotive or aviation industry.

Also the textile industry could become a recipient of the raw material in the form of feathers, which could replace expensive natural or synthetic fibers.

Due to the high content of keratin in the feathers, which is responsible for good strength properties, they are considered for the production of biodegradable packaging materials (e.g. films).

Keratin is also a well-accepted protein and plays an important role in medicine – among other things, it is used in the production of medicines and in tissue engineering.

Feathers from slaughtering poultry can also be a raw material for the production of biogas or biofuels (biodiesel), thereby reducing carbon dioxide emissions into the atmosphere.

4. Regional market situation

Analyzing the daily production of feathers for the northern area of Poland, it can be concluded that this area has great potential in terms of the amount of available raw material. In addition, there is no company in the said area that includes information on the production of feather keratin hydrolyzate in its business profile. Feathers are most often burned in waste incineration plants or given to companies dealing in the production of feathers meal, which is, among others, a component of animal feed (for example Sonac Uśnice Sp. z o.o.[6]). Designing and creating of a technological line in a slaughterhouse or a new company dealing in the production of keratin hydrolyzate from slaughter feathers would be a novelty not only in northern Poland, but also in the whole country. Asian companies offer keratin hydrolyzate in the form of powder, but the raw material for its production is usually sheep wool and pig feets. There are only a few offers for keratin hydrolyzate made from chicken or duck feathers. These products can be ordered via auction sites.

[6] Website: http://sonac.pl/

5. Pre-feasibility for PILOT concept

5.1. Choice of concept

The concept that was decided to propose is the processing of feathers from slaughter of poultry and the production of keratin hydrolyzate from them. This product can be used in the following industries:

- cosmetics (hair, nails, skin care products, etc.),
- pharmaceutical (a component of drugs that improve metabolism, prevent osteoporosis and delay aging),
- food (addition to bread, cakes, milk drinks, yogurt, energy drinks, a component of diets that improves digestion, especially in the elderly),
- packaging (production of biodegradable film and packaging materials).

5.2. Methods of keratin hydroluzate production

Keratin is a protein, which is characterized by the highly cross-linked network structure with numerous disulfide and hydrogen bonds as well as hydrophobic interactions and tightly packed keratin microfibrils.[7] The results is insolubility in water, solutions of weak alkali and acids, and most organic solvents which is a problem during converting it to soluble forms.[7] There are several methods for obtaining soluble keratin (keratin hydrolyzate): [7]

- **chemical hydrolysis (alkaline, acid or enzymatic)** – leads to the destruction of keratin structures, due to which its solubility in water increases. Its yield depends on the pH, temperature, reaction time and the type and concentration of the acid or base used. Increased yield can be obtained by increasing the process temperature, however, this can cause the destruction of amino acids. In the case of acid hydrolysis, a high yield is obtained, however, its disadvantage is the loss of some amino acids. Alkaline hydrolysis is characterized by a lower loss of amino acids, however it is slower and may be incomplete. In turn, enzymatic hydrolysis is characterized by low energy demand during the process, but it is carried out using chemical agents that degrade disulfide bonds. This type of hydrolysis is not applicable on a larger scale due to its low efficiency.
- **reduction or oxidation of the disulphide bonds –** reduction is a multi-stage and long-lasting process, and its most important reaction is sulfitolysis (reduction of cystine disulfide bridges, due to which the availability of protein for hydrolytic enzymes increases[8]). The reduction process can be used in industry, but some of the compounds used (for example, 2-mercaptoethanol, which allows high yield and quality of keratin) are harmful and expensive, which makes their use unprofitable. In turn, the thiol compounds used do not provide a sufficient degree of extraction that

[7] Sinkiewicz I., Śliwińska A., Staroszczyk H., Kołodziejska H. Alternative Methods of Preparation of Soluble Keratin from Chicken Feathers. Waste Biomass Valor 2017, 8, 1043–1048.

[8] Łaba W., Rodziewicz A. Biodegradation of keratin waste from the poultry industry with the bacteria of types Bacillus and Sarcina. Biotechnologia 2004, 3(1-2), 109–120)

would allow their use in industrial production. The oxidation of keratin occurs using compounds such as hydrogen peroxide, potassium permanganate and organic peracids and leads to the transformation of disulfide bonds into sulfonic acid groups.

- **thermal treatment in some organic solvents –** process used on a laboratory scale. It involves heat treatment of the raw material (in this case poultry feathers) in dimethyl sulfoxide, which is characterized by low harmfulness.
- **hydrothermal methods –** runs at a temperature of 100°C to 150°C and a pressure of 1.5 bar. However, these parameters lead to changes in the protein structure and loss of amino acids. High energy demand during the process makes it very expensive and unprofitable.

Considering process efficiency and economic considerations, the two-stage technology of alkaline-enzymatic hydrolysing, examined by Czech scientists, is the most beneficial method to obtain keratin hydrolyzate.[9] Due to the fact that it takes place at fairly low temperatures, not exceeding 70°C and slightly alkaline pH, the energy demand during the process allows it to be considered economically profitable.[9] Using the two-stage process, keratin swells in the alkaline medium, which makes the enzymes more effective on peptide bonds. An aqueous KOH solution with a concentration of 0.1 – 0.3% was used as the alkaline medium. The value of this concentration is dictated by the allowable content of inorganic solids in the hydrolyzate. The first step is to mix the feathers with a 1:50 KOH solution and incubate at 70°C for one day. After obtaining a pH of 9, the second stage of hydrolysis begins, consisting of enzymatic hydrolysis lasting 4 to 8 hours, which is carried out at a temperature of 50 to 70°C. The dose of proteolytic enzyme is from 1 to 5% by weight of degraded feathers. Depending on the concentration of the KOH solution used, the amount of degraded feathers changes - a concentration of 0.1% allows degradation of approximately 24% of the weight of hydrolyzed feathers, while a concentration of 0.3% allows to achieve a degradation level of 90.8% under the same conditions.[9] Figure 4 shows the diagram of the two-stage alkaline-enzymatic hydrolysis process.[9]

[9] Mokrejš P., Svoboda P., Hrncirik J., Janacova D., Vasek V. Processing poultry feathers into keratin hydrolysate through alkaline-enzymatic hydrolysis. Waste Management & Research, 29(3), 260–267.

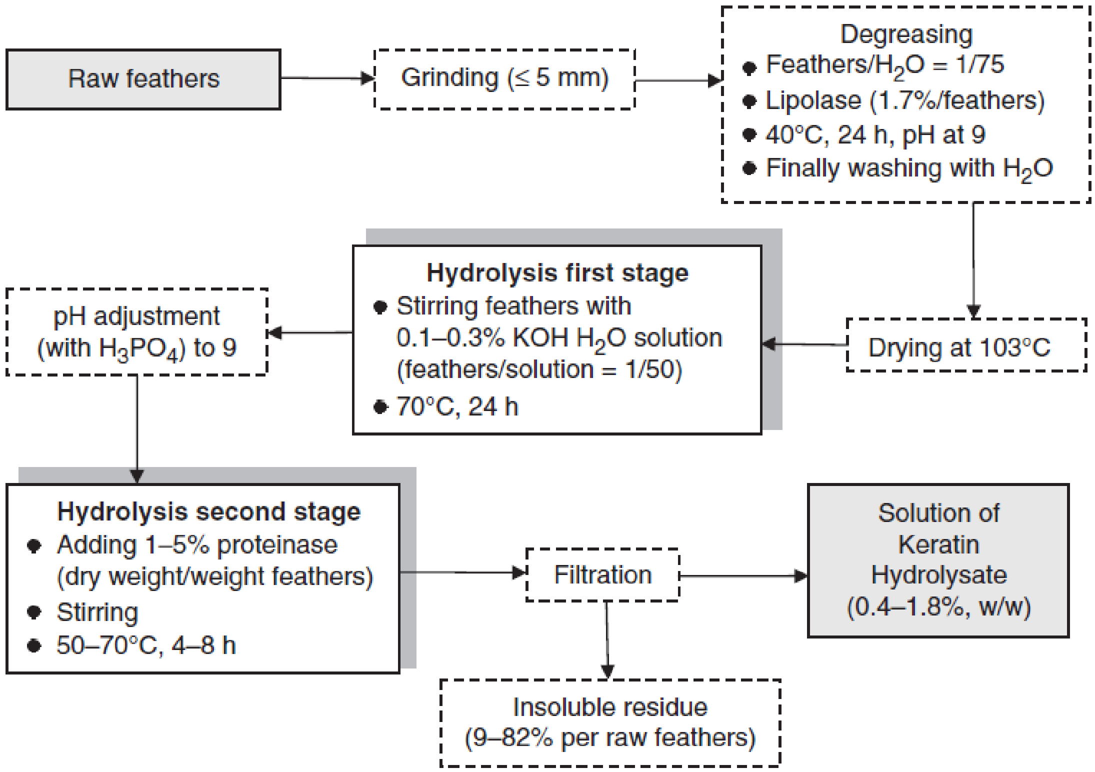

Fig. 4. Diagram of processing poultry feathers into keratin hydrolysate during two-stage alkaline-enzymatic hydrolysing.[9]

Due to the fact that the processing of feathers from slaughtering poultry in the process of alkaline-enzymatic hydrolysis is an easy process, taking place in a relatively low temperature range and at atmospheric pressure, it is possible to use this process in a pilot or industrial scale.[10] Therefore, the proposed concept can be considered as proofed in the laboratory and assigned the TRL 4 scale.

5.3.An example of the use of keratin hydrolyzate in the cosmetics industry

According to previous information, keratin hydrolyzate can be used, among others, in the cosmetics industry. Research also carried out by Czech scientists [10] have shown that the presence of keratin in the ointment base increases the hydration of the skin and has an effect on improving its protective barrier, which is responsible for reducing transepidermal water loss. The liquid keratin hydrolyzate obtained in the process of alkaline-enzymatic hydrolysis is dialyzed, vacuum dried and ground to powder. The next stage is the preparation of a cosmetic preparation in the form of an ointment. It consists of an oil-in-water emulsion where the mass of keratin is 2, 4 or 6% of the base ointment. A study carried out on 10 men and 10 women confirmed that adding keratin to the base ointment reduces water loss by 30%, ensures moisture retention – increase of hydration for women is 22%, and for men is 19%.[10]

[10] Mokrejš P., Huťťa M., Pavlačková J., Egner P. Preparation of Keratin Hydrolysate from Chicken Feathers and Its Application in Cosmetics. Journal of Visualized Experiments 2017, 129.

5.4.Research and Innovation needed

Transferring the production process of keratin hydrolyzate from a laboratory scale to a pilot or industrial scale is primarily associated with the provision of appropriate equipment to process feathers in large quantities. The tests carried out in the laboratory are based on a small mass of feathers (about 100 g), so that processes can be carried out in small devices. The situation is complicated when the large quantities of feathers are processed (for example, the daily quantity from one slaughterhouse, amounting to 14 tons) – the dimensions of equipment and their processing capacity must be correspondingly higher, which is associated with high investment costs.

In addition, scientists can develop increasingly better methods for obtaining keratin from feathers, taking into account the economic aspects and the possibility of rapid application of the method on an industrial scale. In alkaline-enzymatic hydrolysis large amounts of water (ratio of feather weight to water weight is 1:75) and aqueous KOH solution (ratio of feather weight to weight of solution is 1:50) are required. These are very large amounts, considering the daily production of feathers that could be subjected to the process.

An economic calculation should be made and the profitability of the investment estimated on an industrial scale, taking into account that the price of keratin hydrolyzate, produced from cattle hair and horns by Asian companies is between $20-100 per kilogram.[11]

6. Conclusions

The presented data on the production of poultry feathers in Poland, and especially in its northern part, belonging to the SBA region, show the potential of using this raw material for purposes other than its disposal. Various studies show that poultry feathers can be used in many ways, but some of them are only tested at the laboratory level.

One way to extend the poultry processing chain is to produce keratin hyrolyzate from feathers that are considered as waste. This production involves carrying out chemical processes under certain conditions – one of them is alkaline-enzymatic hydrolysis. As a result, keratin is obtained, which can be used in many industries, including the cosmetics and packaging industries. This method is currently being tested in the laboratory, but it is possible to use it on a pilot or industrial scale.

Due to the lack of a company in the northern region of Poland that would deal with the production of keratin from poultry feathers, the creation of such a production line or the entire company would be a novelty. Such an establishment would provide jobs primarily for people with chemical education. The keratin production line could also be created in companies producing cosmetics and using this ingredient in their products. Further improvement of the

[11] Website: http://www.bosschemical.com/

process of producing keratin from poultry feathers and construction of a pilot installation would allow estimating production costs and assessing its profitability.

It should be emphasized that the use of raw materials, which are considered as waste, is a favorable procedure from the point of view of environmental protection and the circular economy, whose mission is to better use raw materials and extend the chain of their transformation in order to produce the least amount of waste, the disposal of which can be troublesome.

BIO-PLASTIC PRODUCTION FROM POTATO WASTE

COLOURBOX26675650

Prefeasibility study

Bio-plastics production from potato waste

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1. **Introduction**

Potatoes are one of the most popular and important plants grown not only in Poland, but also worldwide. They have great economic importance due to the versatility of use – they are edible and industrial plant with low soil requirements. The South Baltic Area regions – Warmia and Masuria, Pomerania and West Pomerania – has been specializing in the production of potatoes for many years. Potato was successively cultivated here for generations and served as a basis for feeding the population of these lands. Despite the rapid decrease of the area of potato cultivation in Poland in 1996-2005, since 2015 a relatively constant value of the growing area has been observed, amounting to approx. 300.000-341.000 ha[1]. The decline in the cultivation area was partially compensated by the increase in yields. Additionally, the location of large food processing plants and starch processing factories also supports the need for this production. It is forecasted that despite the decline in potato consumption, the cultivated area will not change significantly, so it is justified to introduce new technologies for potato waste management, due to their constant value.

A recent bioeconomy is emphasizing the cascading approach (Figure 1), which evaluates the methods of post-production waste management. It is essential to lean towards new methods of waste valorisation, producing cosmetics, medicines, food products or biodegradable materials from them, instead using it as energy raw material. Figure 1 presents a concept of cascading approach, which depicts the value of individual management methods. Waste from the potato processing industry is especially interesting, because it can be used for new components from almost any section of the presented pyramid of cascading approach.

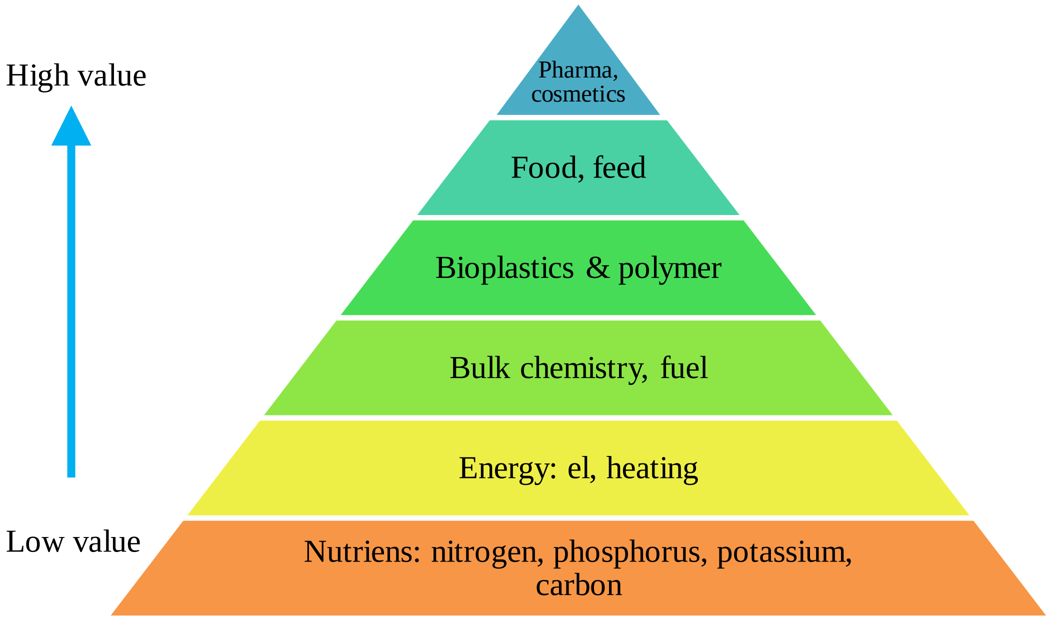

Fig. 1. The cascading approach.

2. **Statistics on potato production in Poland and in SBA regions**

The increase in potato growing area in 2015 is a positive phenomenon that breaks the long-term downward trend. The area of potato cultivation in 2017 was 329.323 ha and it was

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[1] *Crop production in 2017*. Statistics Poland, Warsaw 2018.

larger by about 6,3% compared to 2016. It is estimated that in 2018 it will be maintained at a similar level (300.000 ha)[2,3]. About 9.2 million tonnes were collected – 0.3 million tonnes (3,4%) more than the harvest obtained in 2016 and 1.2 million tonnes (15,5%) higher than the average harvest from 2011-2015. In 2017, potato yields amounted to 27.9 t / ha and decreased only by 2,4% compared to the previous year, while compared to average yields in 2011-2015 they were higher by 19,7%[2]. In 2018, Poland was third main producer of potatoes in European Union (Figure 2), producing 14,3% of all potatoes and having highest cultivated area (17,8%)[4]. Polish agricultural holdings which grew potatoes constitute about 25% in total EU stakeholders in this sector[4].

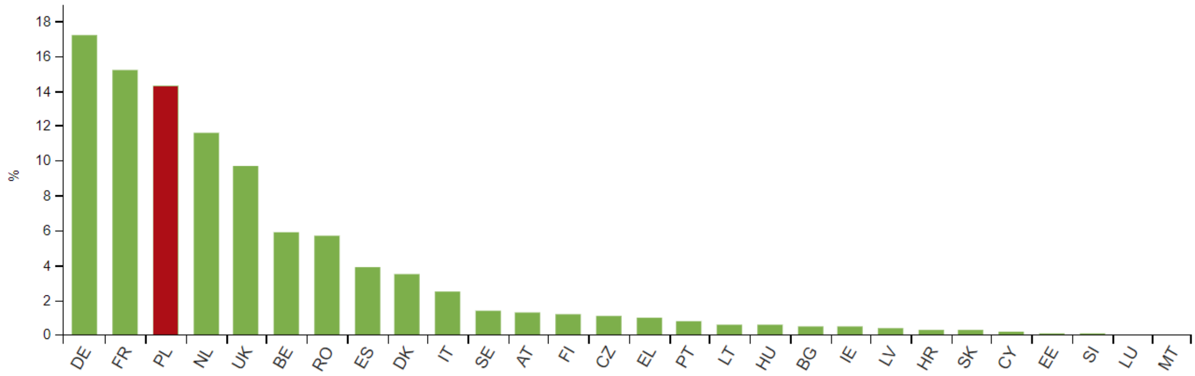

Fig 2. Production of potatoes in 2018 - share of EU-28 harvested production (%)[4]

In the Pomeranian Voivodship, the share of potatoes in the sowings structure in recent years is above 3%, i.e. around 19.000 ha and is higher than the national average. In 2017, 291 dt from1 ha was obtained (5.308.958 dt in total)[2]. In Warmian-Masurian Voivodeship in 2017 there were about 7.500 h of potato cultivation area. 247 dt form single ha was harvested, resulting in 1.866.456 dt in total[2]. In West Pomeranian Voivodeship, in 2017 about 10.600 ha was used for potato cultivation. From 1 ha, 301 dt were obtained (3.206.291 dt in total)[2]. Figure 3 presents map of yelds of potatoes in 2017 in Poland.

[2] *Production of agricultural and horticultural crops in 2017*. Statistics Poland, Warsaw 2018.

[3] *Preliminary estimate of the main agricultural and horticultural crops in 2018*. Statistics Poland, Warsaw 2018.

[4]*https://ec.europa.eu/eurostat/statistics-explained/index.php/The_EU_potato_sector_-_statistics_on_production,_prices_and_trade#Potato_production_in_the_EU_is_highly_concentrated*. Eurostat, 2018.

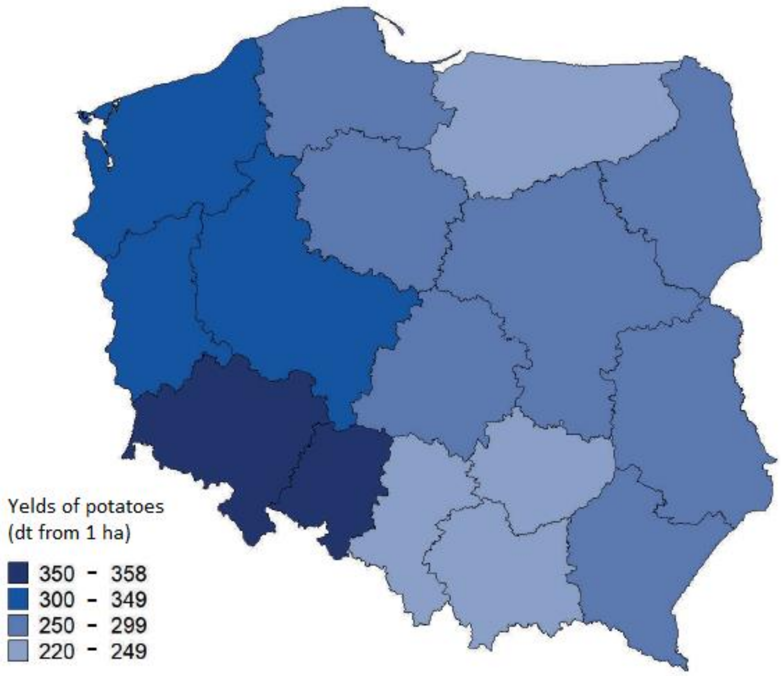

Fig 3. Yields of potatoes (dt from 1 ha) in 2017 in Poland[2]

Which is important to mention, individual farms have the largest share in the total potato growing area. In 2017, it amounted to 95.3%, while in the total production this share was - 93.8%. They are working closely with local large potato processing companies, such as Jantar Sp. z o.o. in Słupsk or, the largest one, Farm Frites Poland SA in Lębork. Also, there are starch and maltodextrin producing plants, i.e. NOWAMYL SA in Łobza.

3. Potato processing chain

In potato processing industry, a various waste is produced. An exemplary production chain of French fries in local big factory is shown at Figure 4.

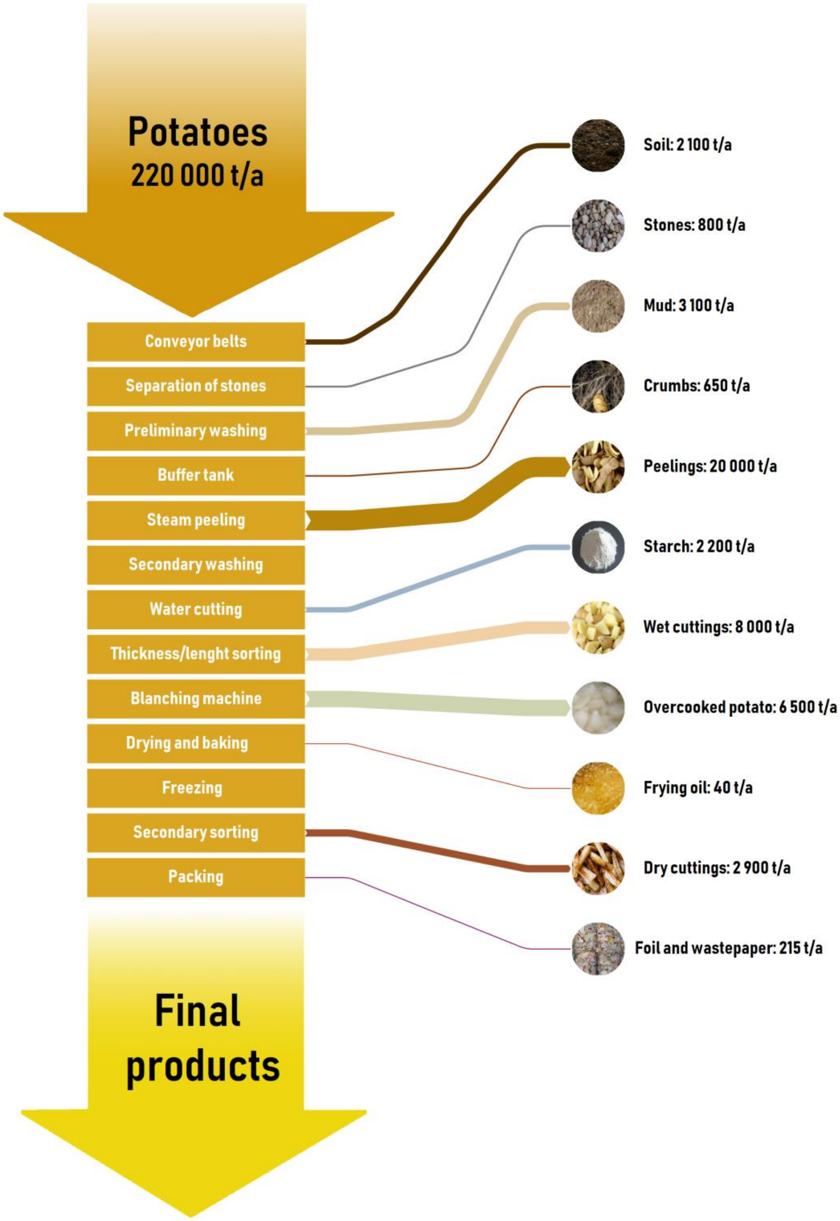

Fig 4. Potato processing chain with an indication of the place and amount of waste generated

First, during transporting potatoes on conveyor belts, soil is separated. Then, machines are detaching stones. During washing, mud is separated, and then potatoes are directed to buffer tank, where crumbs are separated from them. Potatoes are peeled by a steam under pressure, and this process results in peelings as a waste. During the process of cutting fries, the waste are crumbs, starch, so called wet cuttings. While secondary sorting, dry cuttings are separated – they are already baked French fries which are too short and do not meet the standards of length and appearance. Those are main types of wastes produced during the manufacturing process. In addition, the waste is: overcooked potato, unprofitable material (i.e. non-crispy fries), frying oil, paper and foil or sewage sludge. In described factory, approx. 107.000 French fries, 6.700 potato flakes and 2.800 potato pancakes is produced annually.

4. Methods of reuse of potato cultivating and post-processing waste

Starch is the most interesting waste produced in potato processing factories to be used in new profitable way. On the other hand, farmers cultivating potatoes often grow other grains at the same time, producing large amounts of straw as waste. Therefore, it is significant to develop strategies that allows to reuse different types of waste from the same farms for processing into other new products. There are several ways to utilize not only wastes from potato processing factories, but also straw produced in potato cultivating farms.

4.1. 3D printer filament

Starch, potatoes, as well as straw can be used for 3D printing filament production. Recently, due to the recent noticeable increase in interest in 3D printing, it is desirable to lower the filament prices and also to produce it with usage of products of natural origin. In addition, biomass-based filaments are food safe and odor free. Straw-based filament can drive down the cost of filament from 50$ to 10$[5].

Kuo et al.[6] prepared TPS/ABS alloy (TPS – thermoplastic starch) as a 3D printing filament, acquiring a material with high thermal stabilities, good flowability and excellent mechanical properties. There are many studies regarding filaments entirely composed of biomass. Liu et al.[7] investigated even more biobased filament, made entirely of mashed potatoes and starch with addition of trehalose. It was observed that objects printed with mashed potatoes with 2% of potato starch have both good extrudability and shape retention. Biome Bioplastics, located in United Kingdom, offers filaments based on potato starch, with similar properties as widely used in 3D printers PLA material, pointing out that new formula is less brittle than PLA. An additional advantage of using waste for filament production is the fact, that the apparatus used for this purpose is relatively simple and easily accessible.

4.2. Concrete with bio additives

There are also propositions of using straw for making straw fiber concrete. Additives in concrete, including biomass, are the subject of many studies. Wang et al.[8] marked that the straw fiber content between 5% and 7% can improve the material construction workability, has good impact resistance and can improve its toughness. Additionally, with the increase of straw fiber content, heat transfer coefficient of material is reduced and the heat preservation performance increased, improving thermal insulation performance[8]. Production of such concrete is relatively simple and at the same time cheap and environmentally friendly. Also, not only straw, but various raw materials and wastes of natural origin can be an addition to

[5] *http://cgworkshop.org/project/straw-based-filament-could-reduce-the-cost-of-3d-printing/*

[6] *Kuo, C.-C., Liu, L.-C., Teng, W.-F., Chang, H.-Y., Chien, F.-M., Liao, S.-J., Kuo W.-F., Chen, C.-M. (2016). Preparation of starch/acrylonitrile-butadiene-styrene copolymers (ABS) biomass alloys and their feasible evaluation for 3D printing applications. Composites Part B: Engineering, 86, 36–39.*

[7] *Liu, Z., Zhang, M., Bhandari, B., Yang, C. (2018). Impact of rheological properties of mashed potatoes on 3D printing. Journal of Food Engineering, 220, 76–82.*

[8] *Wang, G., Han, Y. (2018). Research on the Performance of Straw Fiber Concrete. IOP Conference Series: Materials Science and Engineering, 394, 032080.*

concrete, without changing its properties – coconut fiber[9], rice straw, corn cobs, hemp shiv, barley straw[10] and many others, creating many production possibilities.

4.3. Pharmaceuticals, chemicals

Potato wastes in the form of a material unfit for sale and the starch remaining from the process can be used for production of valuable chemicals, organic acids and dietary supplements.

An interesting application is lactic acid production. A lot of research is currently underway on developing technologies for obtaining this compound in the laboratory conditions and then to and then to implement it on an industrial scale. Chen and Liu[11] proposed a combined production of lactic acid and chitin from starch from potatoes unsuitable for further processing, indicating the economic justification for this production due to the high value of both these components. Lactic acid is widely used in cosmetics as moisturizing and exfoliating substance, also in food and plastics industries – including recently popular PLA (polylactic acid). Chitin is a valuable biopolymer that can be used as a pesticide, fruit preservative, medicine (natural bandage or dietary supplement), for the production of clothes and for wastewater treatment. The method proposed by the researchers for obtaining the above-mentioned ingredients is fermentation, which, according to them allows reducing the costs of the entire installation. Liang et al.[12] also developed lactic acid from fermentation, also acquiring acetic acid and ethanol, asserting that this method can potentially lower the cost of production of lactic acid because it is not only using waste, but it is not using a refined sugar feedstock, and sterile bioreactors with pure cultures[12].

Citric acid is another important chemical that can be obtained from potatoes[13], due to its many applications in various industries. Also, potato waste can be used as a substrate for production of: prebiotics, glycoalicaliods, dietary fibres, flavonoids, food antioxidants (due to its high phenol content)[14]. Moreover, an interesting property of potato peels is that it is one of the natural wound healer and can be used as a dressing.

4.4. Other

Other interesting ideas for potato peels utilisation are: innovative chipboard substitute[15] (which is produced by UK company, Chip[s] Board) and biosorbents (potato peels have an ability to adsorb heavy metals). As a result of its strong adhesion and binding properties, potato starch can be used in a range of areas, i.e. as wallpaper glue. A bio-fuel can be made both from straw and potato.

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[9] *Noor Md. Sadiqul Hasan, Habibur Rahman Sobuz, MD Shiblee Sayed, Md. Saiful Islam. (2012). The Use of Coconut Fibre in the Production of Structural Lightweight Concrete. Journal of Applied Sciences, 12, 831-839.*

[10] *Laborel-Préneron, A., Magniont, C., & Aubert, J.-E. (2017). Characterization of Barley Straw, Hemp Shiv and Corn Cob as Resources for Bioaggregate Based Building Materials. Waste and Biomass Valorization, 9(7), 1095–1112.*

[11] *Liu Y. (2005). Co-production of lactic acid and chitin using a pelletized filamentous Rhizopus Oryzae culture from cull potatoes. Doctoral dissertation, Washington State University, Department of Biological Systems Engineering.*

[12] *Liang S., McDonald A. G., & Coats E. R. (2014). Lactic acid production with undefined mixed culture fermentation of potato peel waste. Waste Management, 34(11), 2022–2027.*

[13] *Afifi M. (2011). Naturally Occurring Microorganisms of Industrial Waste for Citric Acid Production by Solid State Fermentation. Journal of Environmental Science and Technology, 4, 377-386.*

[14] *Ali Shinawar & Nawaz, Asad & Irshad, Sana & Ahmed, Aftab. (2015). Potato waste management in Pakistan's perspective.*

[15] *https://www.chipsboard.com/*

5. Starch and straw based bioplastics

The choice of the appropriate development strategy for the production of new components from waste must be dictated by the capabilities of the enterprise for their effective implementation. During interviews with local entrepreneurs from the potato processing industry, most agreed on their interest in bioplastics as the technology with the greatest chance of implementation in the SBA region.

5.1. Market demands and supply opportunities

Bioplastics are most attractive option for food industry, because it is the most dynamically developing in the sector of food packaging. According to the latest market data compiled by European Bioplastics in cooperation with the research institute nova-Institute (Figure 5), it remains the largest field of application for bioplastics with almost 65 percent of the total bioplastics market in 2018. It is promising vision for food processing sector. Reusing waste for production of biodegradable packaging will not only be environmentally friendly, but also can be profitable, as in future it could cut costs of buying packaging material from external sources.

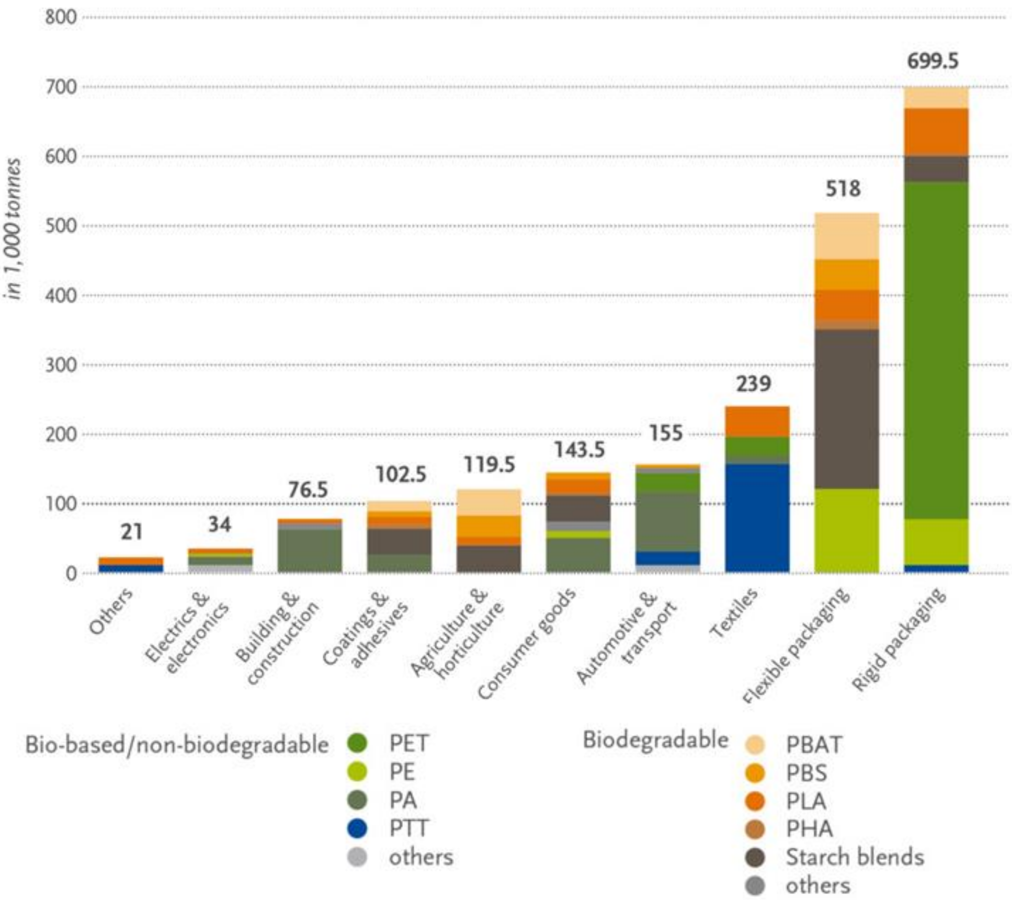

Fig 5. Global production capacities of bioplastics (by market segment)[16]

[16] *European Bioplastics, nova-Institute (2018). http://www.european-bioplastics.org/market*

There is a huge potential of bioplastics industry on the market, mainly due to the increasingly restrictive provisions of both Polish and European law. There is a high probability of launching locally pilot installations in the future. Production of bioplastics from potato and straw waste can be very useful for local companies and easier to maintain, unlike other technologies. Due to the location of two large potato processing plants operating in the market for years (Farm Frites Poland SA and Jantar Sp z o.o.), a constant inflow of waste can be ensured. Based on the data available from one of factories, it can be assumed that a minimum of 20.000 tonnes of peelings and 2.000 tonnes of starch per year can be used as a substrate for bioplastics production.

5.2 Regional market situation

In Poland, there are few companies producing fully biodegradable bio-plastics. The most known is the Biotrem company, which produces disposable dishes and cutlery from bran. Another enterprise is Maropak, which is producing packaging from sugarcane and from corn starch (PLA). However, none of these companies is operating within the SBA region as both are located in Masovian Voivodeship.

In Pomeranian Voivodeship, there are companies declaring production of recycled packaging (Plast-Box SA located in Słupsk), however, there is no information about a factory that would specialize in the production of completely biodegradable bioplastics, in particular from waste. Therefore, it would be reasonable to create a local bioplastic production line, located in the largest potato processing plant or nearby, to simplify transportation of waste.

5.3 Production of starch-based bio-plastics

Starch can be used for production of bio-plastics because it consist of amylose and amylopectin[17]. To modify its properties and increase its plasticity, modifiers such as glycerin, sorbitol or urea are added[18]. According to Keshav[19], a following steps have to be made to obtain starch-based bioplastic: hydration of starch with water; hydrolysis with a weak acid, occuring in the temperature between 90-180^{o}C; evaporation of water from the starch solution; addition of plasticizer and other additives to improve properties of the final product. The manufactured material can be formed like traditional plastics[19], i.e. in extruders.

Based on a project proposed by Keshav, a bio-plastic plant can be divided for three main stages: extraction of starch, production of the polymer, and processing the final product[19]. Due to the fact, that there is no need for a separate starch preparation section, which is already obtained from a potato products factory, it can be assumed that laboratory apparatus for the production of material and industrial apparatus for molding final product should be taken into account. Assuming that there is 2.000 tonnes of starch available annually, and that bio-plastic line is working 350 days in a year (with two weeks of technical stoppage), the line must be able to process approx. 5,71 tonnes of starch per day. With that amount of starch, approx. 36,52 tonnes of starch polymer per day can be produced[19]. After drying and

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[17] *Lörcks J. (1998). Properties and applications of compostable starch-based plastic material. Polymer Degradation and Stability, 59(1-3), 245–249.*

[18] *Abolibda, Tariq Ziyad Y. (2015). Physical and Chemical Investigations of Starch Based Bio-Plastics. Doctoral dissertation, University of Leicester.*

[19] *Keshav S. (2016). Production of bioplastics using potato starch. Doctoral dissertation, University of Mauritius.*

pelletising, this quantity is reduced to 19,24 t/d. The next steps require extruder unit, surface treatment unit and distribution unit[19]. It can also be assumed, that the price of final starch-based product is between 2,5 and 5 €/kg[20]. A production line with such capacity would produce 6.734 tonnes of bio-plastic annually (Figure 6).

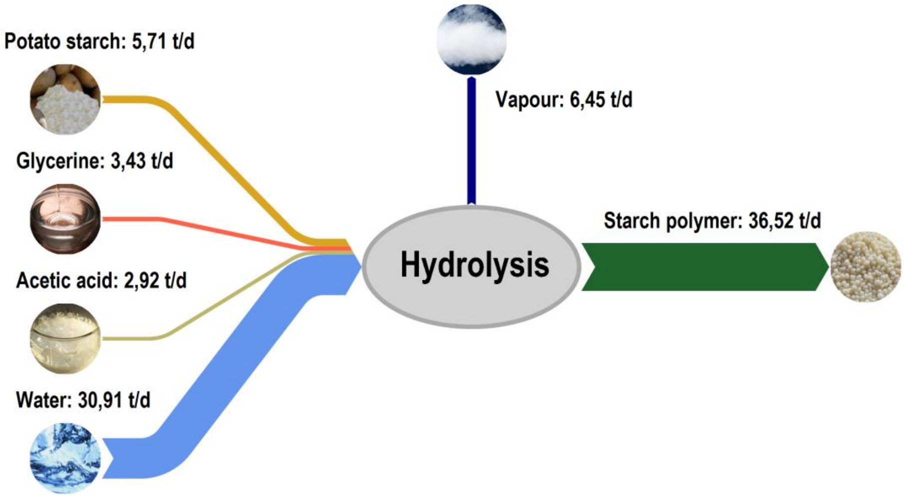

Fig 6. Material flow in starch-based bio-plastics production[19]

6. Feasibility of the concept

There is a lot of research on new methods of obtaining bio-plastics from potato starch undergoing in laboratories, one of which was described above. However, many technologies still require refinement to be implemented successfully in Poland. It can be assumed, that proposed way of utilizing potato waste is at TRL level 4, as it is widely proven in laboratory. There are few barriers and challenges, that must be overcome.

6.1 Barriers and challenges

It is difficult to adapt the properties of the raw material to its processing in traditional apparatus. Most of the companies uses its own patented machinery, adapted to the dedicated input material used in factory. There is some apparatus, dedicated for starch-based polymer production proposed by foreign companies (Figure 7, 8) – unfortunately, there may be a problem with their availability or price. Also, some of proposed production lines assume the addition of artificial polymers, which improves the product's ability to process, however, reduces the pro-ecological value.

[20] *https://www.ifbb-hannover.de/files/IfBB/downloads/EV_Processing-of-Bioplastics-2016.pdf*

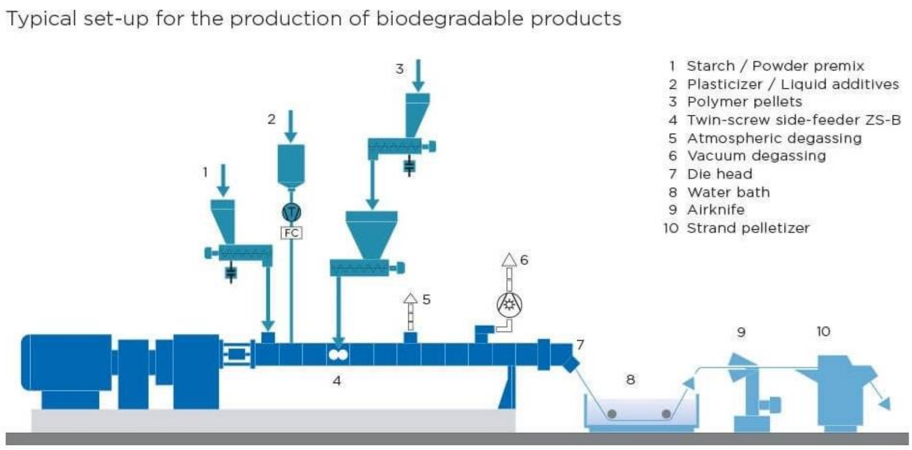

Fig 7. Typical set-up for the production of biodegradable products proposed by Coperion GmbH[21]

Fig 8. Starch sheet extruder Microtec Engineering Group PTY LTD[22]

The main problem can be a price of a bags and packaging made of starch-based bio-plastics in comparison with traditional plastic bags. Price of HDPE (high-density polyethylene), which is a material of which most of plastic bags are made of, amounts in about 1.3 €/kg[23] - which is over 3 times lower than a starch-based polymer prices (2.5 to 5 €/kg).

It is also still problematic to obtain a material that would have mechanical and thermophysical properties competing with traditional plastics. For example, commercially available containers are often not resistant to high temperatures and can only be used for cold drinks / products.

[21] *https://www.coperion.com/en/industries/plastics/bio-plastics*
[22] *https://microtecco.com/bio-plastic-production-machines/starch-sheet-extruder/*
[23] *http://www.wrap.org.uk/content/plastic*

6.2 Research and Innovation needed

The basic need is a determined development of new technologies related to the production of bio-plastics from locally available waste. It is necessary to create such a material that would be competitive in terms of properties with traditional plastics. Therefore, it is important that research centers focus their research on locally available raw materials. Cooperation of universities and research laboratories with companies in the SBA region is also important. Currently, this is often difficult due to the lack of sufficient knowledge about production processes, its capacity and used apparatus, so the communication between entrepreneurs and researchers is difficult.

The availability of knowledge in the design of specialized equipment must increase. It is necessary to support projects and test pilot installations based on new technologies. There is a need of a balanced development of the bioplastics industry both from the chemical, but also the mechanical and manufacturing point of view. This industry presents many challenges not only due to the production process, but also due to transport, storage and distribution. The availability of machines dedicated to bio-plastics production on the Polish market should be increased.

The problem of high costs of producing bio-plastics from starch can be solved by appropriate regulations from Poland's state and EU. A move away from non-degradable plastics is inevitable. In the future, it is assumed to use only biodegradable ingredients, so companies and factories should start research and implementation as soon as possible, especially if they are in possession of waste that can be used as a raw material.

6.3 Benefits and opportunities

The bio-plastic industry is extremely forward-looking - it is at an early stage of development, and therefore creates opportunities for the region to develop and create new jobs. In Pomeranian Voivodeship not only valuable waste from potatoes is produced, but also from other crops, such as wheat, cereals or corn in significant quantities, which can be used to produce bio-plastics. It would be possible to organize several production lines within one factory or plant.

If material suitable for processing in traditional plastic production equipment is developed, creating such a line at the plant or a separate factory is profitable - they are publicly available, easy to use and maintain. Also, there is an opportunity for for research centers, not only in the field of chemical composition of bio-plastics, but also in terms of the development of modern production lines.

Moreover, some steps have been made to overcome the barriers identified above. Chemists from the Gdańsk University of Technology have developed biodegradable cutlery. Part of the material was replaced by potato starch. The inventors assure that they have tested the patented material on traditional machines and the test results are promising.

Interviews and local visions carried out as part of the BioBIGG project also allow the identification of production processes and problems of local entrepreneurs, which will help orientate research on relevant topics.

Bio-plastics remains the most likely and appropriate for implementation in SBA region, as their production process, as opposed to obtaining chemical compounds from potato, is similar to that of existing factories (there is no need to invest in a modern laboratory and build a separate infrastructure). This technology has a significant degree of TRL and numerous publications, studies and prototype installations around the world confirm the legitimacy of attempts to implement it.

7. Conclusions

Potential from potato processing waste was indicated and determined. There are many ways to manage this waste, but not all of them have adequate implementation potential in the SBA region. Many interesting applications cannot be used due to too high potential costs of implementation, production, transport, infrastructure. However, given the long tradition of potato cultivation in the SBA, conditioned by large potato processing plants, steady flows of potato waste should be expected. However, given the long tradition of potato cultivation in the SBA, conditioned by large potato processing plants, steady flows of potato waste should be expected.

Due to the cooperation of local farmers with these plants, there is already a transport and logistics network. The location of the bio-plastic production line in the nearby location of the potato processing plant is the most economically justified solution.

Currently, bio-plastic production technologies are underdeveloped to be implemented in SBA voivodeships. This is due to the insufficient availability of ready-made solutions from manufacturers and the insufficient local knowledge regarding this type of installations. Further actions aiming at raising awareness and encouraging entrepreneurs to undertake the implementation of new technologies is significant.

A WAY TO MANAGE SPENT MUSHROOM SUBSTRATE

Prefeasibility study

A way to manage the Spent Mushroom Substrate

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Rafał Andrzejczyk
Paweł Dąbrowski
Dariusz Mikielewicz

1. Introduction

In the global production Poland is one of the biggest producers of mushrooms worldwide. Moreover, if we take a look at European Union, Poland is the top mushroom producer, see Fig. 1. According to Eurostat, Poland holds also the first place in the EU mushroom exporters, with the share of the market exceeding 50%[1].

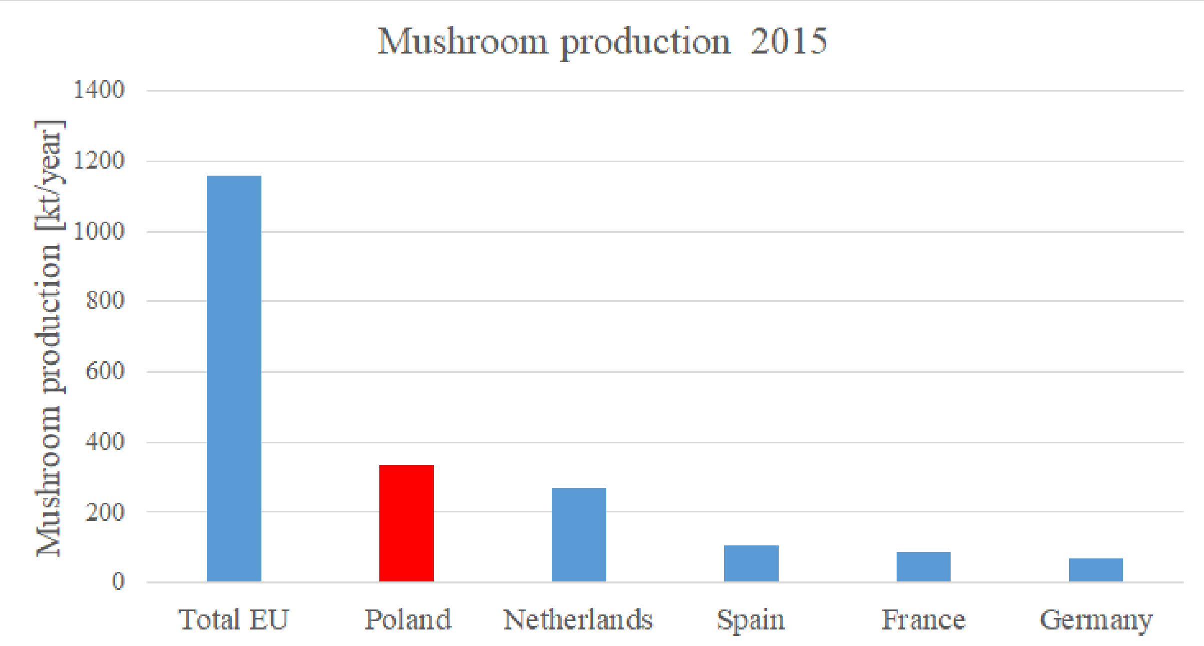

Fig. 1 Total mushroom production in different countries

The production of mushrooms in Poland is constantly growing (see, Fig. 2). Most of the production is exported to Germany and other EU countries. It should be noted that about 1/3 of the mushrooms consumption in European Union comes directly from Poland [2].

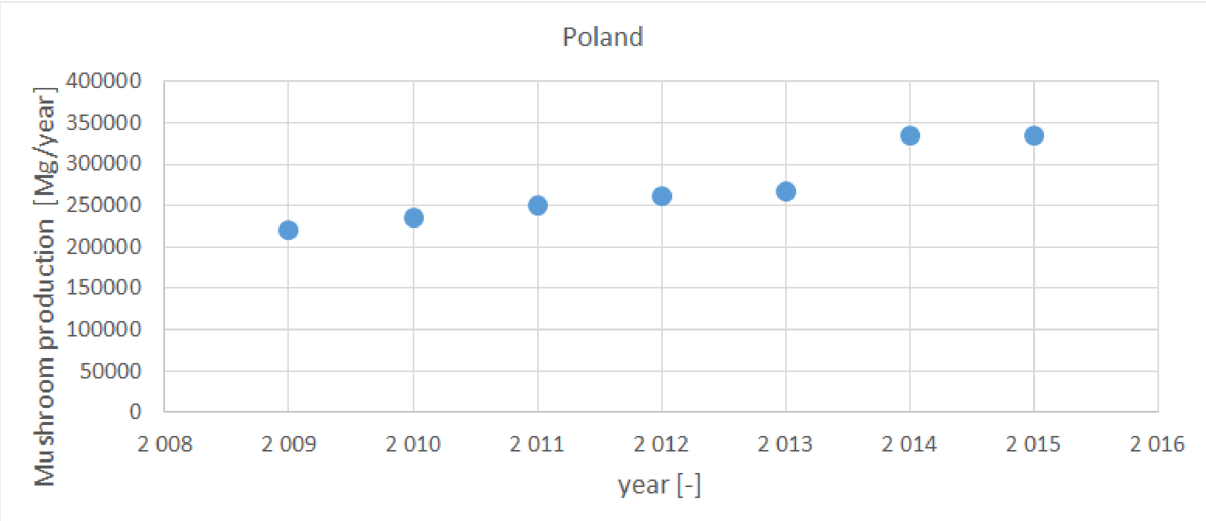

Fig. 2 Change in mushroom production in Poland over the years

According to one of the biggest mushroom producing companies in Poland, namely the Pieczarki Mazurskie Fedor Company, the production of spent mushroom substrate amounts to 5 tonnes for every single tonne of mushroom product. Taking the data showing the mushroom

[1] https://www.freshplaza.com/article/9199577/poland-is-now-largest-producer-of-eu-button-mushrooms/
[2] https://www.freshplaza.com/article/2143031/poland-is-europe-s-largest-mushroom-producer/

production and the correlation between yearly production and spent mushroom substrate (SMS) it is possible to estimate the annual potential of SMS (Fig. 3).

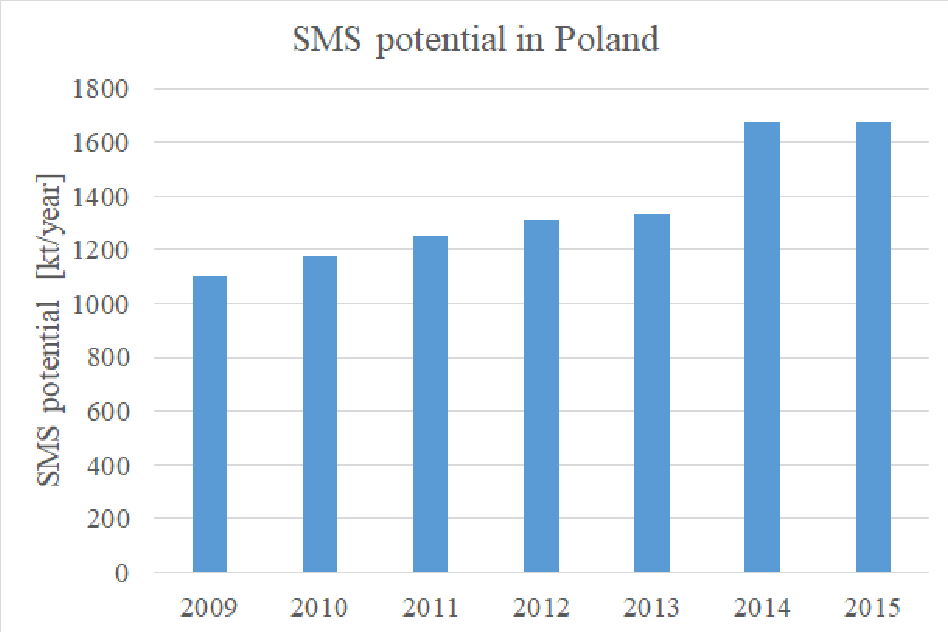

Fig. 3 Change in spent mushroom substrate production in Poland over the years

SMS is a very good natural fertilizer that can be readily reused, which is also the typical way of its disposal. Usually there is no problem to sell SMS directly to farmers or garden industry. This is however not bringing of much income. Below in Table 1 is presented the chemical composition of the spent mushroom substrate. In the table is also presented a comparison of that resource with the composition of other well-known fertilizers. Comparison shows attractiveness of SMS as a fertilizer, indicating its superiority to other ones considered.

Table 1 Chemical and biochemical composition of spent mushroom substrate[3]

% dry matter and macroelements in fresh weight of fertilizers						
	Bovine manure	Pig manure	Horse manure	Sheep manure	Straw	**Spent mushroom substrate**
Dry mass (D.M.)	20.99	21.44	24.71	26.82	90	**40**
N	0.47	0.51	0.54	0.75	0.6	**0.69**
P_2O_5	0.28	0.44	0.29	0.38	0.2	**0.36**
K_2O	0.65	0.68	0.9	1.19	1.5	**0.92**
CaO	0.43	0.44	0.43	0.58	-	**4.8**
MgO	0.15	0.18	0.16	0.19	-	**0.28**
Na2O	0.1	0.11	0.06	0.12	-	-
P	-	-	-	-	-	**0.16**
K	-	-	-	-	-	**0.76**
Ca	-	-	-	-	-	**3.43**
mg / kg micronutrients in the fresh mass of fertilizers						
B	20.9	15.9	13.6	18.4	0.6	-

[3] The spent mushrom substrate chemical and biochemical compostion, Pieczarki Mazurskie Fedor own data

Cu	21.5	22.5	12.3	18.4	0.2	**7.9**
Mn	345	288	270	290	1.6	**110**
Mo	1.66	1.57	0.94	1.23	-	**-**
Zn	173	213	94	112	-	**51**
Co	1.8	1.46	1.02	0.86	-	**-**

Mushroom production is organised in cycles. That is why the amount of production is fluctuating in time and it is primarily a function of mycelium development process. In Fig. 4, the flow chart for mushrooms production cycle is presented.

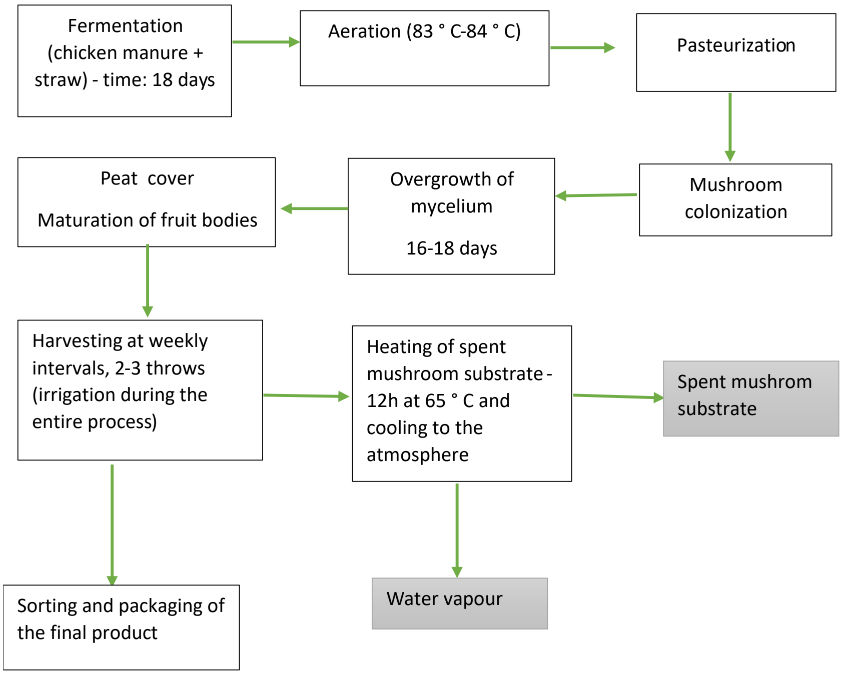

Fig. 4. Flow chart for the mushroom production

SMS seems to be a quite valuable resource in the circular economy. Except of directly using spent mushroom substrate as a fertilizer there are several other possibilities of exploitation of such resource (Fig. 5)[4].

[4] https://mushroomclasses.com/6-uses-of-the-spent-mushroom-substrate/

Spent mushroom substrate possible applications

Fig. 5 The potential application of spent mushroom substrate

It should be noted that according to the present legislation the animal feed could be potentially used only in case of bugs or fishery production. Fertilizer production is one of the most popular application of bio-residues in Poland. However, some technical difficulties can be expected with its utilization as fertilizer for example during the winter conditions due to the lack of demand for it from farmers side. Hence, an alternative application of SMS other than a fertilizer should be sought. All of the potential applications mentioned in Fig. 5 are challenging and require significant technical advancements. One of the solutions is to use such material during winter conditions to produce for example biotabs (spent mushroom substrate in the form of pellet/tab) and then use it for bioremediation purposes (to remove and neutralize soil or water contaminants). One of other applications of the pellets produced in such a way can be the use for energy purposes. In such case the part of SMS should be exposed to the process of drying to be suitable for energy production purpose (preferably in the combined production of electricity and heat). The rest of pellets/tabs could be directly pelletized without drying for fertilizing purposes. Although the processes involved in the production of pellets/tabs seem to be relatively simple, they are very significantly energy consuming, especially due to the drying process. Such an approach can reduce the volume of produced SMS which will reduce the cost of its logistics and hence will contribute to decrease the CO_2 emission due to transport of this material to stores/magazines/farmers. Also the enzyme production is not an easy task to implement because of the epidemiological hazard. Spent mushroom substrate gives very good conditions for development of bacteria and fungi, some of which are posing a threat to human health. Taking into account such issues, it seems that energy feedstock application could be the best solution to utilize SMS. Especially, considering the fact that mushroom production has a very large demand for energy (heat/cooling and electricity) to create proper climate conditions for mushrooms growth. It is associated with special requirements of humidity and temperature in climate chambers for mushroom colonies.

2. Regional market situation

All of the mushroom producing factories due to sanitary requirements have to be away from cities and larger villages. That is the reason that most of the mushrooms companies are located in the countryside areas featuring small density of population. One of the resulting consequences is the problematic transport of SMS. Usually, there is a lack of hardened roads which is especially difficult for bigger transport vehicles in winter conditions. There are four mushroom producing companies located in Pomeranian, West Pomeranian and Warmia and Mazury regions. The biggest factory is the Poland Pieczarki Mazurskie Fedor (Fig.6), which is a primary focus of scrutiny in the present study.

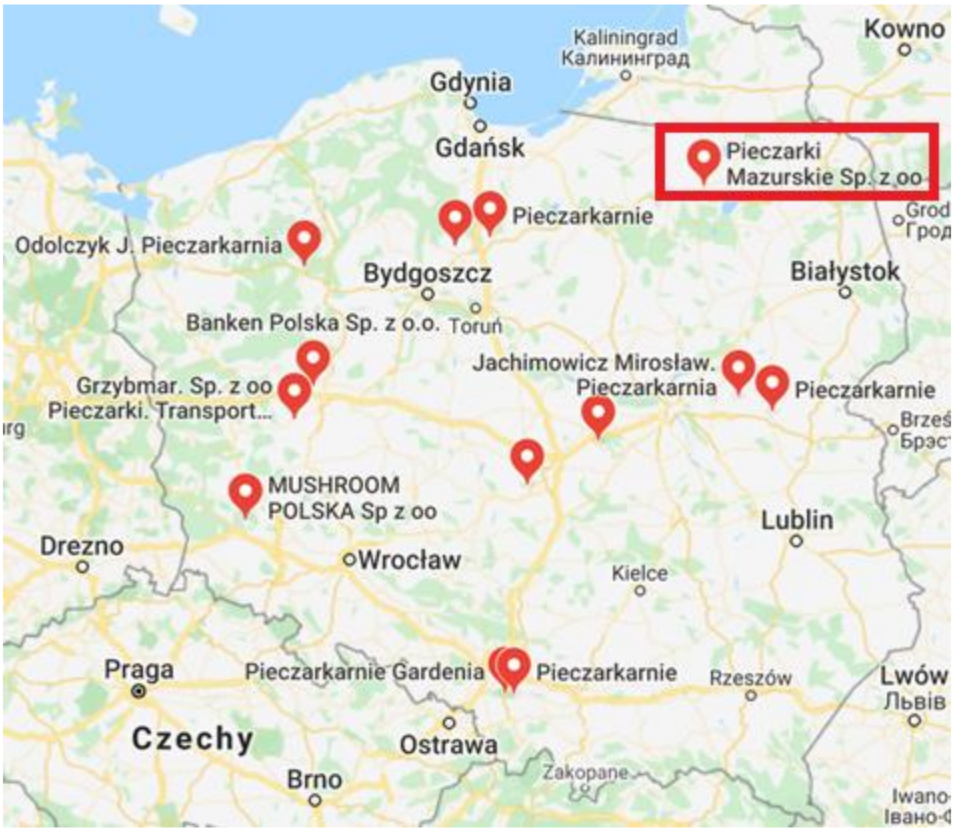

Fig. 6 The biggest mushroom companies in Poland

Directly in the Polish South Baltic Area there can be found three small mushroom farms (Fig. 7). These companies are rather small enterprises with a insignificant market share and small amount of SMS being produced during the process. Nevertheless, there is still a possibility to use it in a more practical way than storing it in a pile and selling as a fertilizer. For example it would be a good idea to start a new small company with a novel mobile pellet-producing machine that would visit a mushroom farm, e.g. once a week and produce pellets from available SMS. The amount of waste available from three locations can be attractive and processing it may start to pay off as a dedicated bussiness. It is also possible to build a complete facility to recycle all wastes from these three locations. It might be a good solution also due to the fact that the distance between companies is not too significant.

Fig. 7 Geographical distribution of mushrooms farms in South Baltic Area.

3. Project technology concept in regard to TRL-scale

Due to the fact that the amount of spent mushroom substrate is fluctuating during the year, the material must be stored. As it has been already stressed, due to sanitary requirements, the stores cannot be located in the direct neighborhood of the mushroom farm. Usually this residue is stored in extensive heaps located at considerable distances from the mushroom farm. According to Polish law (act 1980.17.62) the distance of cumbersome facility from residential buildings should be larger than 15 m. However if facilities are extremely cumbersome, e.g. due to odor and/or bacterial hazards the distance should be larger than 100 m. In case of Pieczarki Mazurskie Fedor the distance is larger than 1000 m. This induces some logistic difficulties. Therefore it seems to be a very good idea to use SMS directly in the place of production, for example for energy production purposes or alternatively for biotabs production. The use of spent mushroom substrate for energy purpose is not a new idea, but regretfully this way of management of the waste has not been introduced widely to the industrial practice yet. It has been shown in many literature studies, that spent mushroom substrate humidity is too excessive for good quality and efficient combustion processes[5]. However, using novel drying technologies may improve the process economy. Moreover, the heat of combustion is markedly lower compared to the heat of combustion of popular other pellets, e.g. wood pellets or straw pellets. However, it should be highlighted that there are significant differences in literature data for this parameter[6,7,8,9]. (3.2 kJ/kg to 4.6 kJ/kg for wet material and from 11 MJ/kg to 17.47 MJ/kg for pre-dried SMS). That is why the authors of the present study have been carried out their own experiment at GUT premises to estimate the heat of combustion of the spent

[5] Karen Nicola Finney, BSc, MSc (Eng.), GradEl, Energy recovery from spent mushroom compost and coal tailings, Department of Chemical and Process Engineering The University of Sheffield, A thesis submitted to the University of Sheffield for the degree of Doctor of Philosophy October 2009

[6] S. MccaheyJ. T. McmullanB. C. Williams, Consideration of Spent Mushroom Compost as a Source of Energy, May 2008Asia-Pacific Journal of Chemical Engineering 11(1-2):43 – 53

[7] Monika Czop, Krzysztof Pikon, Use of casing soil from spent mushroom compost for energy recovery purposes in Poland, Architecture Civil Engineering Environment, 1/2017

[8] B.C.Wiliams, J.T.McMullan, S. McCahey, An initial assessment of spent mushroom compost as a potential energy feedstock, Bioresource Technology 79 (2001) 227-230

[9] Nur Syahirah Kamal Baharin1 & Vidya Cundasari Koesoemadinata1 & Shunsuke Nakamura1 & Nadia Farhana Azman1 & Muhamad Ali Muhammad Yuzir1 & Fazrena Nadia Md Akhir1 & Koji Iwamoto1 & Wira Jazair Yahya2 & Nor'azizi Othman2 & Tamio Ida3 & Hirofumi Hara1, Production of Bio-Coke from spent mushroom substrate for a sustainable solid fuel, Biomass Conversion and Biorefinery https://doi.org/10.1007/s13399-020-00844-5

mushroom substrate. The sample has been taken directly from Pieczarki Mazurskie Fedor company. The company has already tried to cooperate with other industrial and academic partners to test the possibility of using SMS as a combustion material (see the pellet samples from the company in Fig. 8).

Fig. 8 Example of pellet from spent mushroom substrate

To obtain the value of heat of combustion the standard calorimetry method has been used. For the tested material, the heat of combustion value varied from 12.08 MJ/kg to 17.39 MJ/kg, which is in line with literature data. The discrepancy in the heating value, in authors opinion, is rendered by the significant heterogeneity of the samples. The spent mushroom substrate is generally a mixture of peat, straw and residues of mushrooms, which after combination result in the uneven proportions. As can be seen in Fig. 8 the material has not been milled before the pelletization. Next challenging issue is the high level of material humidity. The humidity level could be lowered if the material would be stored in buildings or at least under a protecting cover against rain and moisture penetration from the ground.

The promising results for SMS utilised for energetic purpose has been obtained for co-firing that material with coal[10]. However the amount of SMS inside the incinerated material was not significant, usually around 5%. Some problems with corrosion of boilers have been reported.

In order to manage the resources of available spent mushroom substrate the strategy of preparing it as a pellet or biotabs should be launched. Before pelletization processes the material should be homogenized (milled) and if necessary subjected to a drying process. The amount of material for energy purposes could be a function of the mushroom farm energy demand. The rest of SMS could be utilized for biotabs production and sold to the market.

Figure 9 shows the idea of spent mushroom substrate processing. Due to high moisture content it should first be dried. One of the novel approaches to the required drying process would be that it can be realized using adsorption heat pumps fed by waste heat from the mushroom farms cooling system. According to literature the SMS could be successfully dried, also in the process of biological drying. The temperature of the material at that process could reach above 57°C and reduce the amount of moisture content at about 76%[11]. This type of drying is cheap, however is long lasting. It seems that a better idea is to dry SMS in higher temperatures of about

[10] Monika Czop, Krzysztof Pikon, Use of casing soil from spent mushroom compost for energy recovery purposes in Poland, Architecture Civil Engineering Environment, 1/2017

[11] Domińczyk-Kuderko, A. Krzystek, L. Ledakowicz, S. Olczak, M., Biologiczne suszenie podłoża po uprawie pieczarki, Inżynieria i Aparatura Chemiczna, Nr 6/2016, 223-225

90°C-105°C[12],[13] . This processes normally takes approximately 24 h (see Fig. 10). As said before, mushrooms require a large amount of cooling capacity to create appropriate climate conditions for mushrooms so the waste heat from compressors would also be significant. However only about 10%-15% of the waste heat from refrigeration unit can be used for driving the adsorption device. This type of devices reach optimal level of operation in case of cooperation with the heat source featuring temperature larger than 65°C[14]. To reach this temperature, in commercial vapour-compressor chillers, it is possible to use only the heat of overheating. In that case it is possible to reach hot fluid temperature equal to 100°C which could be easily used in the drying process.

After drying the SMS should be granulated, preferably milled. As mentioned earlier, large variations of the heat of combustion values may be caused by high heterogeneity of SMS. The milling process would make it more homogeneous so it will be easier to design the facility of combustion process due to stable and predictable heat of combustion value. The last step before combusting is to pelletize the SMS to make it easier to use, store or sell.

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[12] Divine Damertey Sewu[a]Patrick Boakye Hwansoo Jung Seung HanWoo, Synergistic dye adsorption by biochar from co-pyrolysis of spent mushroom substrate and *Saccharina japonica,* Bioresource Technology, Volume 244, Part 1, November 2017, Pages 1142-1149

[13] Iffah Nabilah Mohd Ariff1 · Ezyana Kamal Bahrin1 · Norhayati Ramli1 Suraini Abd-Aziz, Direct Use of Spent Mushroom Substrate from *Pleurotus pulmonarius* as a Readily Delignified Feedstock for Cellulase Production, Waste Biomass Valor (2019) 10:839–850

[14] https://ecoprius.pl/pl/agregaty-adsorpcyjne-chlodzenie-z-ciepla.html

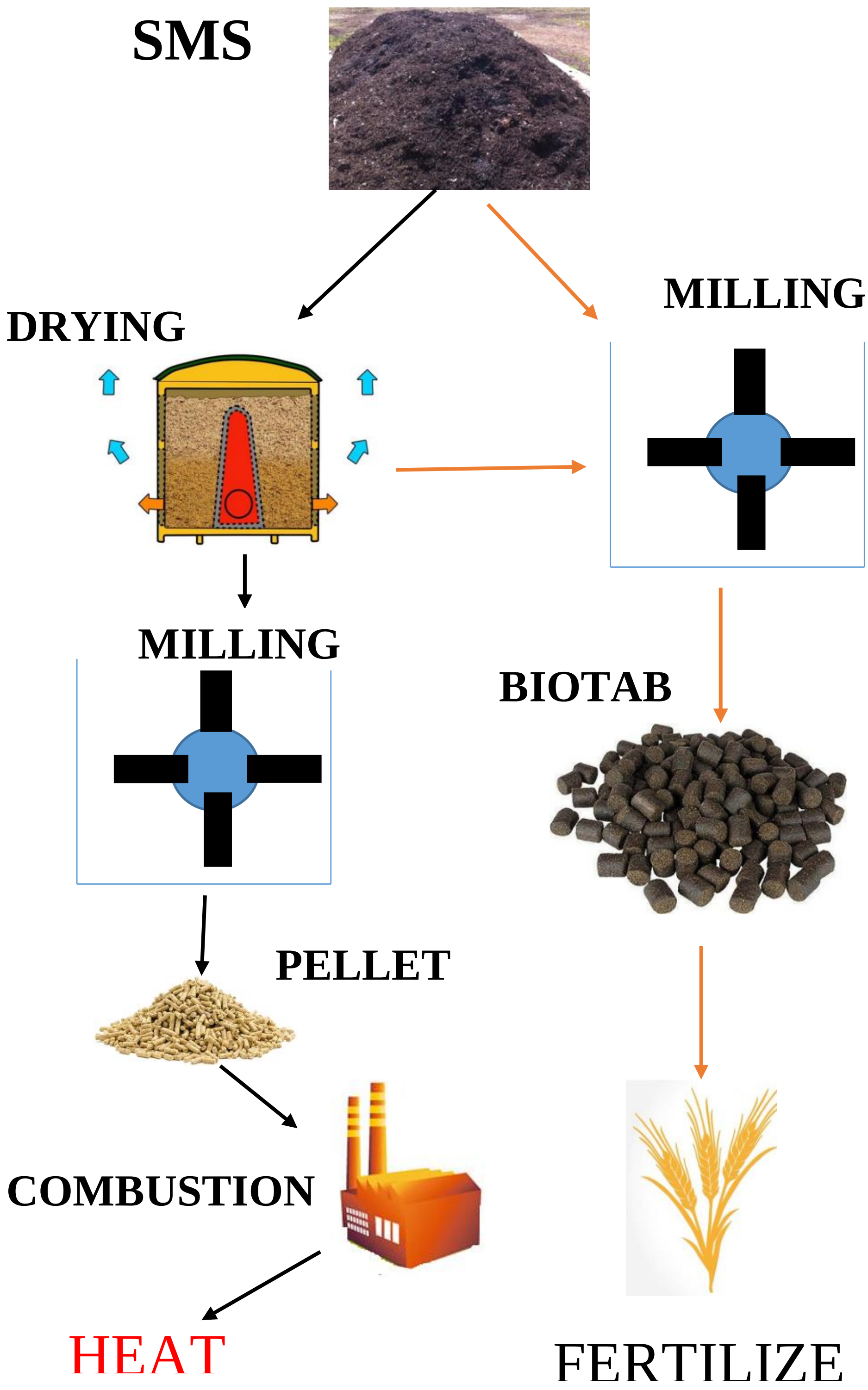

Fig. 9 Idea of spent mushroom substrate valorization

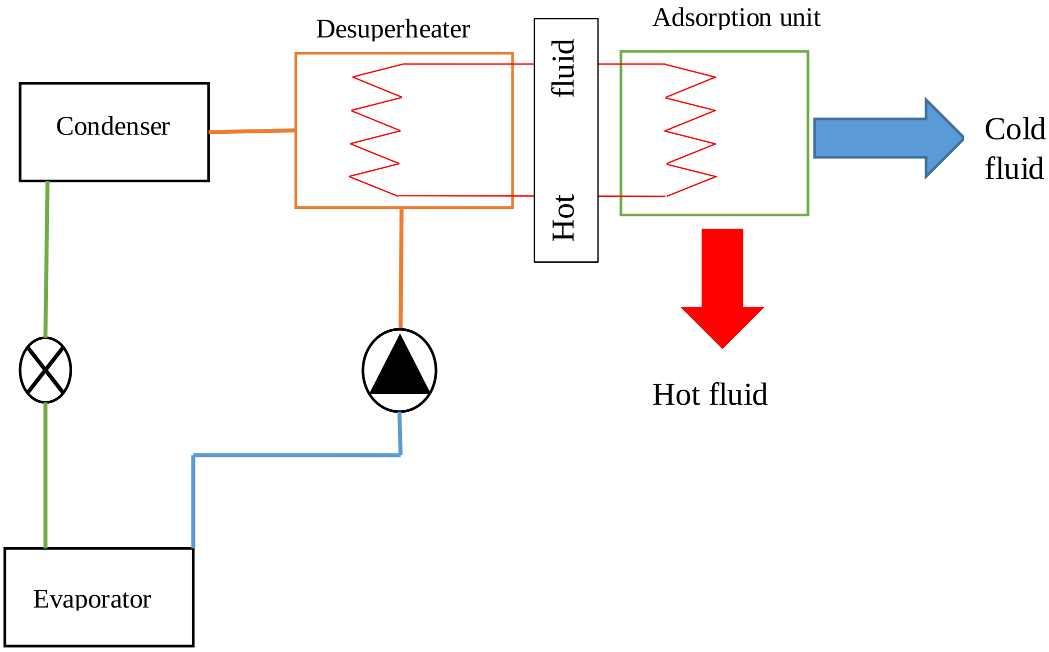

Fig. 10 Idea of heating medium generating system for the drying process of spent mushroom substrate

The amount of SMS produced in Poland is significant. As mentioned earlier, at the time of producing 1 tonne of mushrooms, almost 5 tonnes of SMS are generated. This estimation has been also confirmed by Pieczarki Mazurskie Fedor company own data (Fig. 11).

Fig. 10 Material flow in the mushroom production company

The idea of producing pellets for combustion and tabs will be rather an attractive option only for large scale mushrooms farms. At the moment, these companies are usually selling the spent mushroom substrate as a fertilizer. One of the factors preventing from further examination of

SMS management options is its market price, which is even lower than that of straw. Sometimes the mushroom farms exchange their SMS waste directly for straw. As mentioned earlier it is potentially problematic during the winter time when there is a lack of demand from farmers side. This is mainly connected with the difficulties of bioremediation of such material during winter conditions. The problem will be sorted out by biotabs production. That product is easy to transport and store, and as a product could be sold throughout the year to local, national or even international market. However, due to the large heat demand by mushroom farms over the period of a year it is also justified to use SMS onsite as combustion material for energy purposes, preferably in the form of electricity and heat.

All the above discussion of the described idea of utilization of SMS points at the Technology Readiness Level (TRL) of 2, namely technology concept has been defined. Although the spent mushroom substrate has been already used as a fertilizer it has been not yet used as a pellet for energy production purposes. What is more important, it has been not studied possibility to preparation of the production process enabling the production of pellets and biotabs at the same time.

4. Combined production of electricity and heat - feasibility of concept

Any idea for a project, especially the one with a low TRL (at the pilot level) has many weaknesses, causes difficulties, problems, challenges and has some barriers.
Unfortunately, due to the fact that spent mushroom substrate properties could vary, the usefulness of this substrate may also be numerous. The chemical composition of it as a potential fuel is crucial, especially for energy applications. For that moment there are no reports on the use of this material for the purposes of heat production in a big scale. However there has been studied the possibility of co-firing spent mushrooms substrate with different kinds of solid fuels (e.g coal). The larger amount of SMS than 5% in the fuel requires the use of boilers with a special design. What is more, the quality of fuel must be controlled. This requires preparation of a proper production process of fuel co-firing. The crucial is to control the amount of humidity in the material and the ash content. According to UE regulations (EN 14961) for non-wood biomass the moisture content for that kind of fuel should not be larger than 20% and the ash content no larger than 10%.
The next barrier is the need for special requirements for devices performing the milling and drying cycle. These devices are however known, and should not bring about any difficulties in implementation. Despite the fact that there is some literature data it is needed to perform experimental investigations to obtain optimal value for pellet composition as well as the times required for drying to obtain a required final value of moisture content. Additionally required are pellet physical parameters as density, durability, tensile strength as well as the combustion parameters in order to design an optimal combustion process. The physical parameters of SMS can differ significantly depending on the type of fungus and the technological process used. However the technical parameters of the obtained pellets should be as adapted as possible to the existing combustion systems. The next issue is to obtain similar parameters for biotabs. Only such complementary studies could gave a complementary information for a properly designed process. At the end the pellet from spent mushroom substrate should achieve comparable parameters to others pellets from non-wood biomass. Table 2 presents the selected physical parameters for different kinds of pellet.

Table 2 Selected parameters for different kind of pellets

Kind of pellet	Wood	Wheat straw	Palm shells	Jatropha seed cake	SMS as received	SMS after drying
Total average moisture %	7.79	6.4	7.46	7.96	69.6	20
Ash content %	1.49	6.33	3.33	5.48	9.28	27.25
Heat of combustion MJ/kg	17.93	19.19	18.59	19.11	3.76	12.92

At the moment, the company possesses their own source of heat in the form of two boilers with a 500 kW thermal capacity each. The boilers are fired with wood pellets. One of the boilers is used to produce technological steam (p=3 bar, T=200°C) and the second one is used for hot water production (80°C). The company also requires electricity to run the chillers to cool down mushroom growing chambers and for the technological processing of compost. Assuming that these two boilers operate with their optimal performance, it can be calculated that amount of generated heat is equal to 31.536 TJ/year. On the other hand, if all spent mushroom substrate would be used to pellet production the amount of generated heat will be about 225 TJ, which is seven times more. It should be emphasized that the produced amount of pellet will be enough for supplies two boilers in 100% and the rest of the pellet (more than 85% of production capacity) could be sold on the market or the rest of spent mushroom substrate could be utilized for bio-tabs production. Anyway, in this scenario both boilers have to be changed to new ones. That gives an opportunity that alternatively the pellet could be utilized in a cogeneration system such as for example Organic Rankine Cycle (ORC) system, see Fig. 11. The term organic denotes that it is another fluid, not water, which undergoes processes in the technology to produce electricity and heat. This scenario seems to be the most attractive. From the technical point of view the combustion of pellet from SMS needs to be done in a specially designed boiler. The ORC systems also features a boiler, in which SMS pellets could be burnt to produce heat for converting working fluid in the cycle to the parameters of vapor required before the turbine.

It should be noticed that in Poland due to the relatively cheap coal and wood pellet prices the economy of modern installation is still non-economical but the proposed solution is one of the most appropriate for that kind of activities. If own pellet will be used to produce heat and electricity in one unit this idea will be more attractive for investors. It is because of fact that electric energy price in Poland and other UE countries grows fast for last few years. Especially in case of mushroom production companies the heat and electrical energy is need for all of the year to ensure appropriate climatic conditions for mushroom growth.

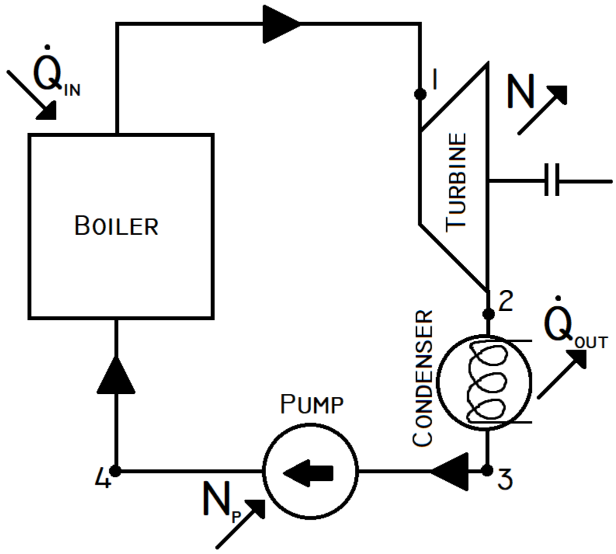

Fig. 11. General idea of combined production of electricity and heat in ORC installation.

Let's follow the example. If the assumed working fluid in ORC be ethanol and assumed boiling temperature be T_b = 220°C whereas the temperature of condensation be T_{cond} = 60°C, there will be capability of producing electricity and heat in such installation. Available at the company is about 15 000 tonnes per year of SMS for further management. Assuming for calculations the mean value of the heat of combustion, LCV = 15 MJ/kg and time of annual operation of the plant t = 8 000 h, which is appropriate as the heat and electricity demand at the company is evenly balanced throughout the year, enables to determine the potential mass flow rate of available fuel $\dot{m} = \frac{m}{t} = \frac{1.5\times10^7}{2.88\times10^7} = 0.52\ kg/s$. That yields the potential rate of heat from burning SMS in the boiler, $\dot{Q}_{in} = \dot{m} * LCV = 0.52 * 15 = 7.8\ MW$ and the potential heat from burning SMS in the boiler, $Q = m * LCV = 1.5 \times 10^7 * 1.5 \times 10^7 = 2.25 \times 10^{14}\ J = 225\ TJ$.

Above indicates that an ORC installation with an electric power of 2 x 500 kW_{el} can be built. With the assumed ethanol parameters, in order to obtain the assumed electric power on the turbine, the heat flow rate should be adjusted to 1 869 kW. The total potential heat from burning SMS in the boiler is much higher, so SMS will provide heat demand, even with efficiency lower than 50%. The produced electrical energy will be about 40 694.4 MWh annually. Assuming the price of 1 MWh at the level of PLN 200, the proposed ORC installation will provide more than 8 million PLN annually, so approx. 1.78 million Euros (1 € = 4.5 PLN). The heat generated in the condenser could be used in mushroom drying process.

The cost of ORC installation is hard to be predicted due to the novelty of such installation. However, assuming the parametric approach, 3 levels of costs can be assumed, namely 3 000 €/kW_{el}, 4 000 €/kW_{el} or 5 000 €/kW_{el}, then the whole ORC installation would cost 3 million €, 4 million € and 5 million € respectively. Simple payback time return the result that the investment will pay off 1.7 years, 2.2 years and 2.8 years, respectively. Presented estimates indicate the attractiveness of the investment. The skills required to design and manufacture the presented ORC installation are present at the Department of Energy and Industrial Apparatus of Gdańsk University of Technology.

5. Conclusion

Constant growth of energy prices in EU market enforces the search for savings among enterprises. The mushroom farms due to a peculiar characteristic of production have a big energy demand over the year. What is more important such companies have large heat demand not only during the winter but also throughout a year. It is because of humidity control system requirements. Growing competition on the market causes the consolidation of plants and the growing advantage of large farms. Such companies are more and more interested in energy saving technologies. What is more, such companies have a large potential for spent mushrooms substrate over the year. The large farms have usually already multi-year contacts and contracts with farmers and the horticultural industry. All this creates the potential for SMS processing into pellets and biotabs.
Many studies have been focused on the possibility to use spent mushroom substrate for energy purposes. There are also many studies concerned on the use of SMS as fertilizer. However, there are no studies focused on both ways of production in the same technological process. This idea could potentially diminish production costs and allows reaching a larger market penetration. However, this approach creates additional barriers. There is a need to be clarified not only the pellet parameters (geometrical and physical) but also the biotabs parameters. This is, among others, to obtain the right shape, density or humidity of the pellet to increase the efficiency of the combustion process. Also bio-tabs intended as a fertilizer should have an appropriate degree of humidity and strength (crushing resistance).The idea is to obtain parameters similar so that it is possible to reduce costs of the technological process.

The clear benefits of use of spent mushroom substrate for energy purposes and for biotabs production involve also the generation of new jobs. The pelletization of waste material can also reduce the volume of SMS which will reduce the cost of transport and hence to decrease the CO_2 emission from transport of this material to stores/magazines/farmers.

Table 3 SWOT analysis

STRENGTH	WEAKNESSES
• growing demand of fertilizers at the market • possibility of energy costs reduction at mushroom farms • decrease of CO_2 emissions from transport	• difficulties with maintaining the repeatable quality of fuel (pellet) • high initial costs of project • problems related to the optimized parameters of the production process
OPPORTUNITIES	**THREATS**
• increasing the value of the product • reduction of mushroom farms production costs • possibility of selling waste throughout a year • production of electricity and heat	• difficulties to obtain optimal parameters for pellet production (density, heat of combustion, humidity) • difficulties to service of combustion system with the use of SMS as a fuel component

BREWERS' SPENT GRAIN FOR LOW-ALCOHOL NOURISHING BEVERAGES

COLOURBOX13707495

Prefeasibility study

Low-alcohol nourishing beverage with a high amount of fiber and plant-based protein

A new way to manage the Brewers' Spent Grain (BSG) by small local breweries

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Rafał Andrzejczyk
Dariusz Mikielewicz

1. Introduction

The brewing industry in Poland belongs to one of the fastest-growing branches of the economy. The reason for this is a gradual increase in beer consumption, which is becoming the most popular beverage in the country, which results from the change in consumer preferences, who are choosing increasingly weaker alcohols [1].

The beer from malt production in Poland was rising significantly in the last years. Almost 40 years ago the beer production was about 11 million hectoliters per year. Nowadays the annual production is 4 times larger. Detailed production of beer throughout Poland over the years has been presented in Fig. 1 [2].

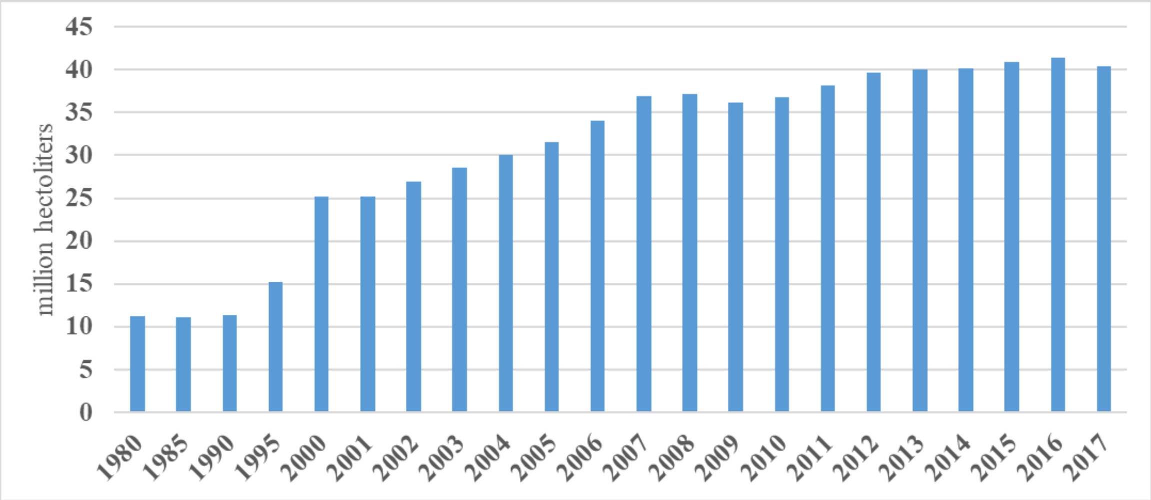

Fig. 1 *Production of beer from malt in Poland*

Also, the production of beer per capita is growing year by year [2]. Now it is over 100 liters per capita (Fig. 2). In 2015 Poland was fourth in Europe (behind the Czech Republic, Germany, and Austria) in terms of beer consumption per capita. Moreover, in terms of total beer production, the amount of 40.4 million hectoliters of beer placed Poland in third place in Europe, behind Germany and Great Britain [1].

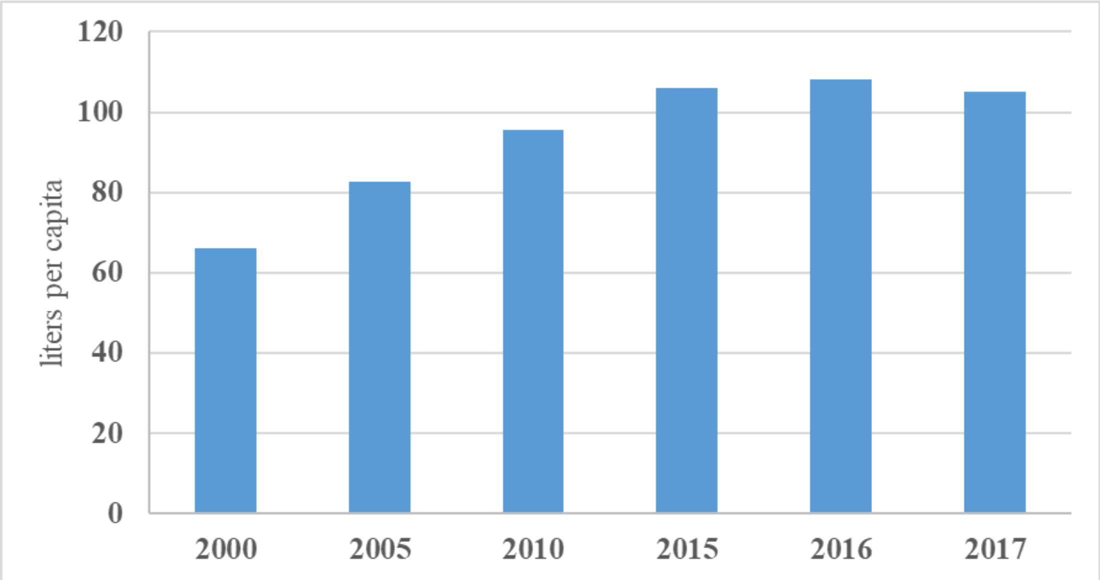

Fig. 2 *Production of beer from malt per capita in Poland*

At the end of October 2016, there were 238 brewing establishments in Poland. Of these, it can be distinguished by 3 types of breweries:

- small - annual production up to 20 000 hectoliters,
- medium - annual production at the level of 20 000 hectoliters up to 200 000 hectoliters,
- large - annual production at the level above 200 000 hectoliters.

This division directly refers to the tax exemption thresholds excise duty depending on the production of the brewery [1].

The value of revenues of the public finance sector generated by the brewing industry in 2014 amounted to PLN 9.9 billion. The largest share in them was excised tax, which amounted to PLN 3.56 billion. In 2014, in the entire supply chain, the brewing industry generated 205 000 jobs. Three main brewing companies, which account for over 82% of the beer sales in Poland, are the most responsible for such high production, supply and consumption of beer in Poland. These are Kompania Piwowarska, Grupa Żywiec and Carlsberg Polska [1].

The brewing industry generates relatively large amounts of by-products and wastes; spent grain, spent hops and yeast being the most common. However, as most of these are agricultural products, they can be readily recycled and reused. Thus, compared to other industries, the brewing industry tends to be more environmentally friendly [3].

The main by-product which represents around 85% of total by-products generated during beer production is Brewers' Spent Grain (BSG). This lignocellulosic material is made during the mashing process and contains about 28% of lignin, 12–25% of cellulose, 19.2–41.9% of hemi-cellulose, and 14–31% protein on a dry weight basis [3,4]. The composition of the BSG is very promising and allows its very wide use, e.g. as a food ingredient in animal or human nutrition, for energy purposes, in charcoal production, as a building material, in a paper manufacture, as an adsorbent, in a biotechnological processes, as an additive in brewing or substrate for cultivation of microorganisms or enzyme production [3]. The potential application is very wide as can be seen in Fig. 3. Nevertheless, BSG is still sold primarily as a low-value feed for cattle [5,6].

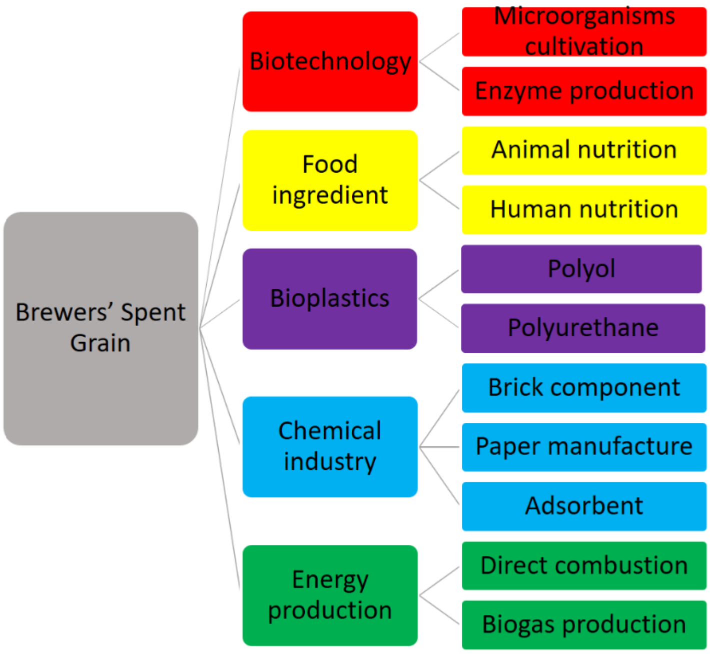

***Fig. 3** The potential application of Brewers' Spent Grain (BSG)*

In order to ensure food safety in the feed/food supply chain and be able to utilize food waste products as either feed or food ingredients, the European Union has implemented specific regulations that impact the by-products from any food production process [6]. Due to the fact that the BSG is intended for farming purposes, it must undergo periodic laboratory tests, which will confirm that it does not endanger the animals [7]. It requires time and financial resources. Moreover, it has to be dried which requires energy and machines. At this moment, BSG is not a very profitable by-product.

Brewers' Spent Grain is generated in large amounts. Every 100 liters of beer produced in the brewery generates about 20 kg of BSG [4]. Assuming annual beer production at the level of 40 million hectoliters [2], in Poland, 800 000 tonnes of BSG is available for development every year.

2. Regional market situation

There is a lack of data about beer production or BSG amounts in every voivodeship. Nevertheless, there is some information about the breweries in every region. The map of Poland, divided into voivodeships with the number of breweries in each of them is shown in Fig. 4 [1,8]. The light blue color shows regions that are the part of the South Baltic Area (SBA). Analyzing the distribution of breweries in Poland in October 2016, it should be noted that it is uneven. The majority of brewing plants - 35, comes from the Mazowieckie Voivodeship. A similar amount of companies operates in the Śląskie Voivodeship (34), while the third place in terms of the number of breweries is occupied by the Małopolskie Voivodeship - 29 registered entrepreneurs. The smallest number operates in the following regions: Świętokrzyskie (2), Warmia and Mazury (4), Opolskie (4) and Lubuskie (5) [1].

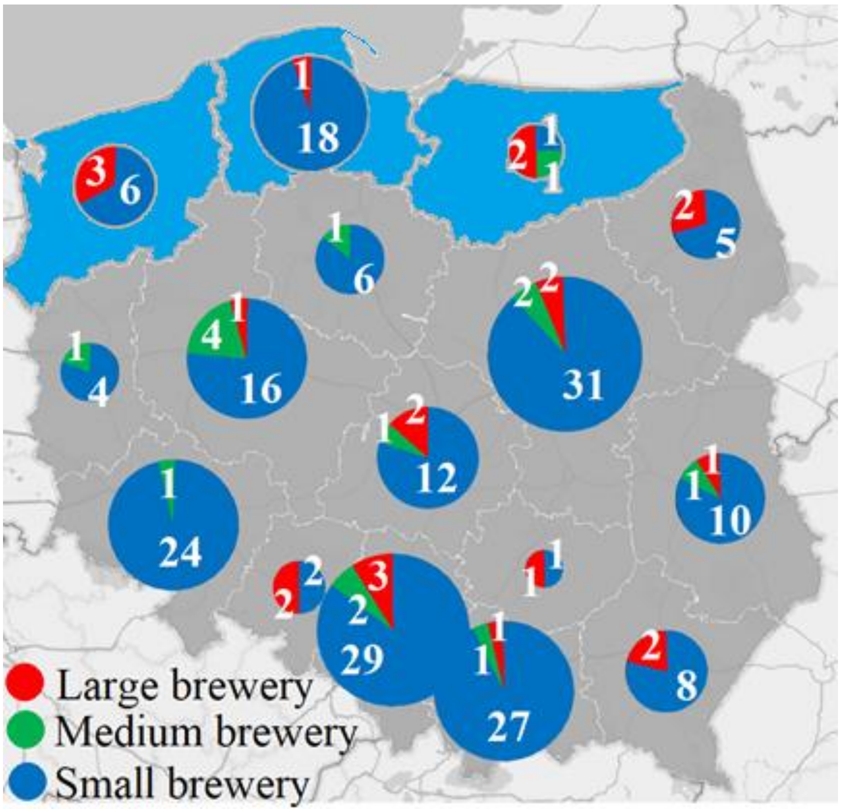

Fig. 4 *Breweries in Poland according to voivodeships and breweries' size. Voivodeships colored in blue are part of the South Baltic Area (SBA)*

It shows that in the SBA region the most breweries are situated in Pomorskie Voivodeship. On the other hand, there are 18 small breweries that produce up to 20 000 hectoliters per year and only 1 large brewery which annual production is greater than 200 000 hectoliters. In comparison to the Zachodnio-pomorskie Voivodeship and Warmia and Mazury region, the annual generation of Brewer's Spent Grain in those 2 regions can be much bigger than in Pomorskie Voivodship. However, large breweries that are the part of the big, international companies are much different from the local, small breweries and their view on the problem of a waste (or by-product) utilization is also different.

As can be seen in Fig. 5, the largest cluster of breweries that produce up to 20 000 hectoliters of beer (marked with a red pin) per year is located in so-called Tricity (Gdańsk – 6 breweries, Gdynia – 1 brewery and Sopot – 1 brewery). Moreover, about 20 km from Gdańsk there is a large brewery (marked with a blue pin) – Browar Amber in Bielkówko which produces annually 200 000 hectoliters of beer. It can be estimated, that more than 4 000 tonnes of BSG can be obtained annually in an area with a radius of 30 km. At the same time, when taking into account only small breweries, the potential of BSG is up to 24 tonnes per year, which is much less but, small breweries may be much more willing to look for new opportunities of development, as mentioned earlier.

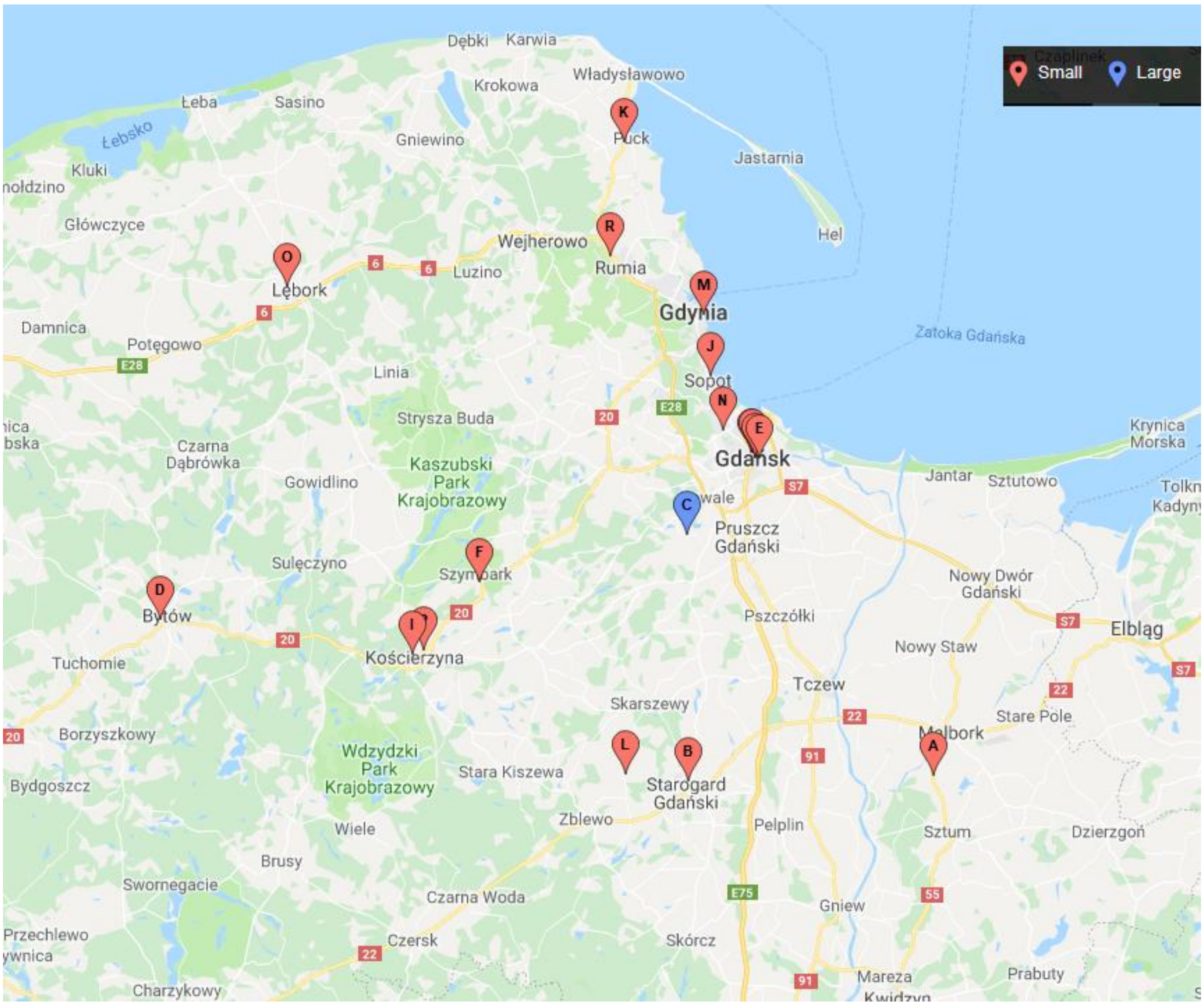

Fig. 5 Geographical distribution of breweries in the Pomorskie region. The red pins show small breweries and the blue pin shows a large brewery

Big entrepreneurs are focused on their main production and they often do not want to think about value chain elongation. On the other hand, small, independent in the sense of the owner's, brewery brewing beer on a smaller scale, usually emphasizing the quality of the beer, a wide selection of ingredients, brewing technique and wanting to be associated with its product. This kind of breweries is often so-called “eco-friendly”. The owners want to emphasize that they are buying local, high-value products from small and organic crops. It is a matter of good marketing to be able to show that wastes or by-products are used in a good way and they do not contribute to environmental pollution or do use substrate in the maximum possible economic and ecological way. Moreover, making production in a small-scale profitable or even almost-profitable is hard so giving a chance to produce a new high-value product from wastes or by-products could make entrepreneurship feasible.

3. Project technology concept in regards to TRL-scale

During the production of beer, there are three main mechanical, chemical and biochemical stages: mashing, boiling, and fermentation. In the mashing stage, malt starch is converted to fermentable sugars, non-fermentable sugars. Proteins are partially degraded to polypeptides and amino acids. This enzymatic conversion stage produces a sweet liquid called wort and a residual solid fraction called Brewers’ Spent Grains (BSG) which is separated during the filtration process. After filtration, the wort is transferred to the brewing kettle where it is boiled with the addition of hops. At the boiling end, the liquid extract is separated from the spent hops to be further processed. A fraction of the hop components ends up in the trub (a precipitation product of the wort boiling process that may include insoluble hop materials, condensation products of hop polyphenols and wort proteins, and isomerised hop acids). During fermentation, the yeast cells will convert the fermentable sugars to ethanol and carbon dioxide. At the end of this stage, most of the cells are collected as spent yeast. According to the technological process shown schematically in Fig. 6, the main by-products generated in the brewing process are BSG, spent hops and spent yeast [9].
Brewers’ Spent Grain is a very promising residue or as it should be called “by-product” for Circular Bioeconomy and Cascading approach. Recent research on the evaluation of the BSG biomass showed results both in terms of the variety of classes of compounds and the quantity of the functional part. Even if BSG chemical composition is dependent on the intrinsic and extrinsic factors such as the barley variety and harvest time, malting and mashing conditions, type and quality of secondary raw materials added in the brewing process, it contains appreciable amounts of valuable compounds (proteins, lipids, carbohydrates, polyphenols, minerals) that remain unexploited in the brewing process [9–13].
It is an ideal situation for thinking of BSG as a substrate for nutrient beverages. Moreover, due to the composition rich in sugars and nutritional factors, hydrolysates produced from BSG can be used in fermentative processes to produce several compounds. Some examples include the use of the sugar-rich hydrolysate as fermentation medium for the production of ethanol by *Saccharomyces cerevisiae*, xylitol by *Candida guilliermondii*, xylitol, arabitol, ethanol and glycerol by *Debaryomyces hansenii*, and lactic acid by *Lactobacillus delbrueckii*, *Lactobacillus pentosus* or *Lactobacillus rhamnosus.* [9].

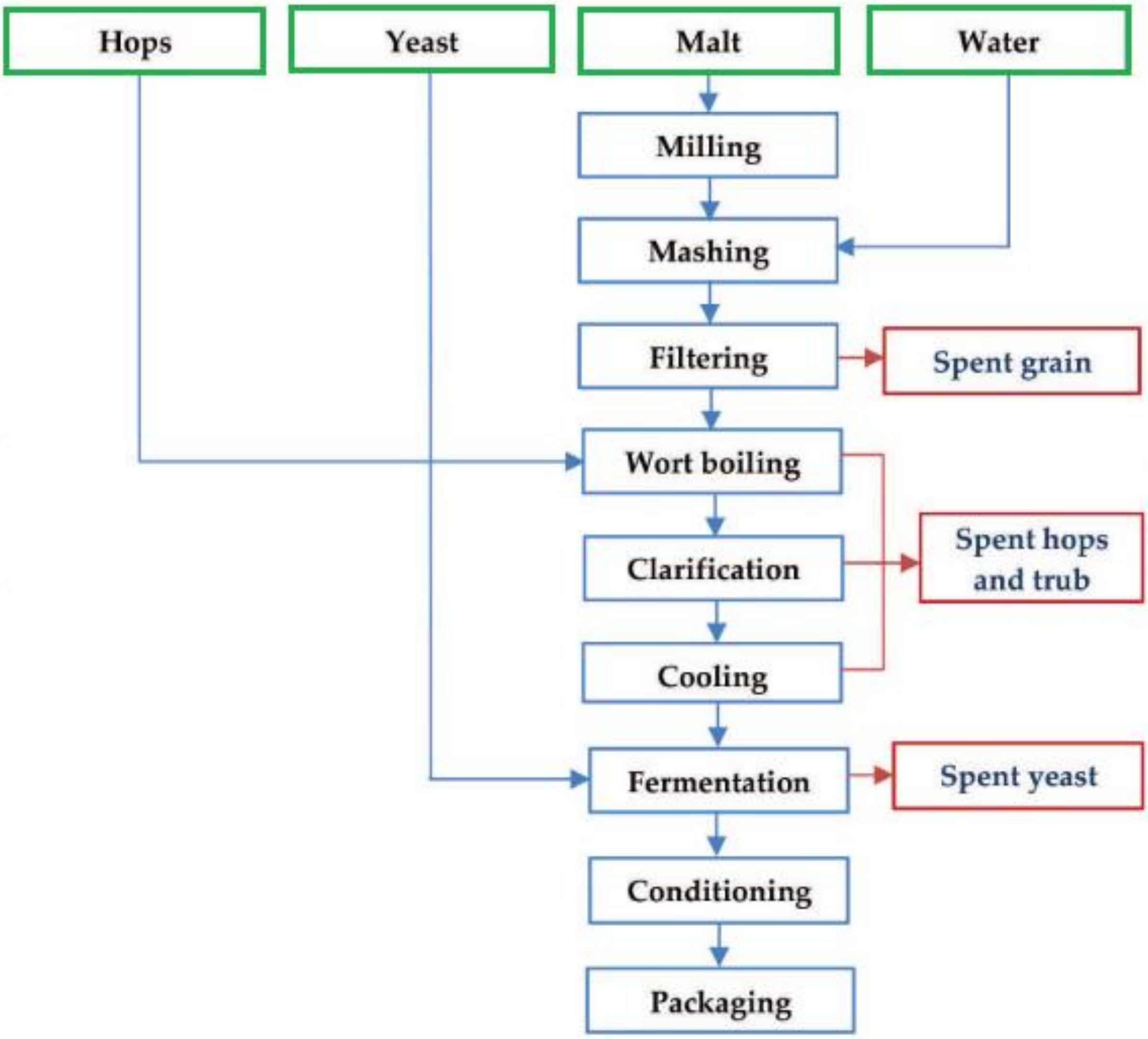

Fig. 6 *Schematic representation of the brewing process (blue color) with main substrates (green color) and places where the main by-products (red color) are generated* [9]

The amount of BSG produced in breweries is significant. The material flow in the brewery is shown in Fig. 7. The numbers were assumed as a sum of 8 small breweries located in Tricity, as mentioned before. The amount of liquid components (e.g. beer or water) is given in kilograms, assuming the density of 1 000 kg/m^3. The amount of BSG is approximately 20% of the main brewery's product - beer. That amount of biomass should not be neglected, especially if it can provide some earnings and give the society a valuable product. As worth to notice here, the amount of water used in the whole process of beer production is relevant. For every liter of beer, there is a need to provide approximately 6 liters of water, most of it is used for washing purposes. In these calculations, only the water in the brewery was taken into account. If use a Life Cycle Assessment (LCA) and include the amount of water required in hops and grain farming etc., the amount of used water would be much, much higher.

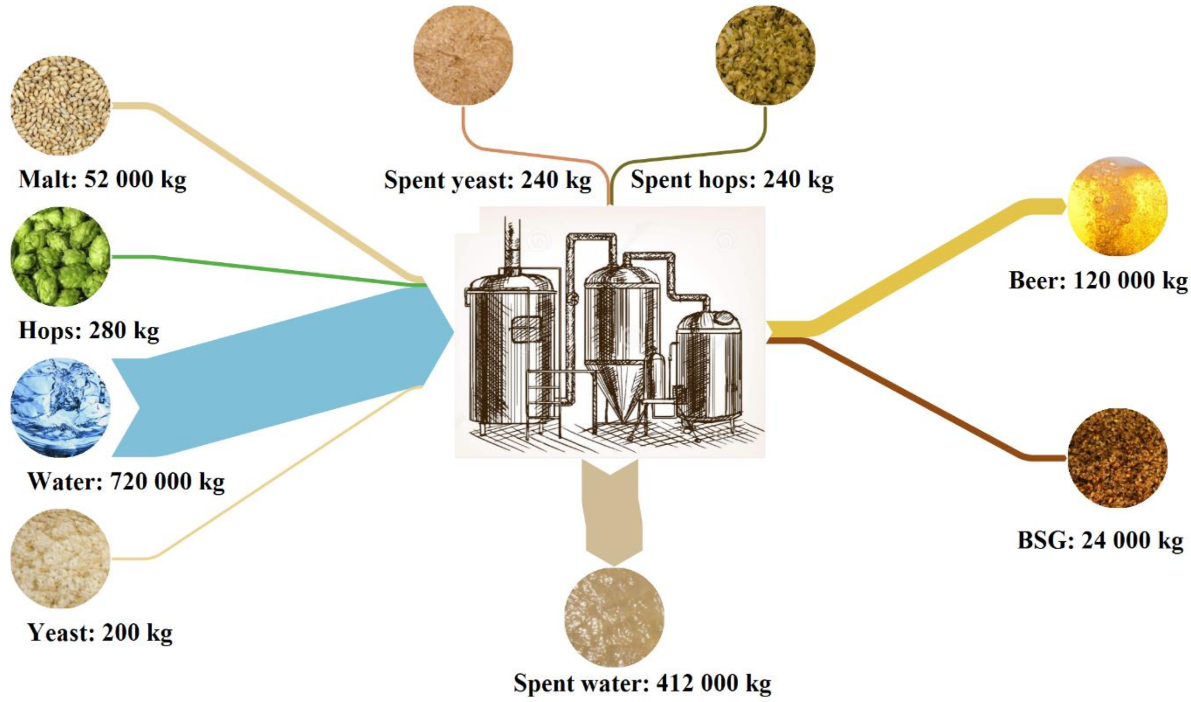

***Fig. 7** Material flow in the brewery*

The idea arises by itself. Small breweries, which produce and sell their beer locally, in small quantities, should expand their offer with their own low-alcohol beverages, rich in nutrients. They already possess the facility for the production of bottled beverages and experience with recipe creating so it would be easier for them to start with a new product.

It would be a very innovative solution which is consistent with the times. Nowadays, people are willing to get local products that are "eco-friendly", made from renewable resources that do not impact the climate so much and are good for their health. The recent worldwide tendency is to avoid or at least decrease the use of synthetic additives. A Brewers' Spent Grain (BSG) is a cheap, renewable, natural and possibly safer alternative with antioxidant and antimicrobial activities.

This low-alcohol beverage would be made out of fruit. Imagination is the only limit what type of fruit could be added and the taste would be created by the brewers. The product would be a rich source of fiber and plant-based proteins which is important because the meat is becoming less justifiable as a source of protein. The quantities of water needed to produce one kilogram of meat alone are insanely high it is sustainable to replace meat-based proteins by plant-based proteins. Moreover, it would be a dairy-free which is significant in terms of ubiquitous lactose intolerance.

The additional circularity in the brewery would be the idea of the neutralized acid extract of BSG addition to the wort. That approach would enhance yeast performance and produced beer of quality equal to that of beer fermented without BSG [3].

As shown before, there are a lot of studies that are dealing with BSG potential application, chemical composition and ways of utilization. The results of experimental research are very promising, and yet the main application for BSG is to use it as food for cattle. The idea to use a BSG for beverages is not totally new and unknown to anyone. There is one start-up company that has started to collect money on a crowdfunding platform in July 2017 for an alcohol-free beverage made of BSG. It calls Canvas [14]. At the end of 2017, a limited amount of this drink was for sale in the United States as a pilot project. It is a kind of protein shake or smoothie,

in which cereals are fermented in very similar way milk is fermented to produce yogurt, and then supplemented with other vegetable products such as fruits, nuts and spices [15].
All the above make the described idea at the Technology Readiness Level (TRL) of 4 according to the following nomenclature:

- PILOT level
  - TRL 1 – basic principles observed
  - TRL 2 – technology concept formulated
  - TRL 3 – experimental proof of concept
  - TRL 4 – technology validated in lab
- DEMO level
  - TRL 5 – technology validated in a relevant environment
  - TRL 6 – technology demonstrated in a relevant environment
- PROVEN level
  - TRL 7 – system prototype demonstration in an operational environment
  - TRL 8 – complete and qualified system
  - TRL 9 – actual system is proven in an operational environment

Although there is a similar product on a market, it can be assumed that it has not been very successful and is not yet fully developed. This can be inferred from the fact that it is not possible to buy the product on the manufacturer's website. All drinks have the status "sold out" and the latest reports about the company are from the beginning of 2018. Moreover, the mentioned Canvas drink [14] is an alcohol-free product and the biomass management proposal described here is based on a low-alcohol beverage, which was not found on the existing market. That is the reason to give the TRL 3. There is a need to develop lab-validated technology simulating a relevant environment.

4. Feasibility of concept

Any idea for a project, especially the one with a low TRL (at the pilot level) has many weaknesses, causes difficulties, problems, challenges, has some barriers. Similarly with the idea described here i.e. a new way to manage the Brewers' Spent Grain (BSG) by small local breweries by producing a low-alcohol nourishing beverage with a high amount of fiber and plant-based protein. This kind of beverage is not produced by any company nor available on the market. There are only reports from the scientific literature stating that BSG is a very promising material rich in nutrients, containing ingredients that can be fermented to produce alcohol. For that reason, there is a need for developing a new technology that would be feasible in an economic and ecologic point of view. To do so, it is necessary to identify and localize all the barriers and challenges in the present concept, providing new knowledge on what research and innovation should be done to implement the concept.
Although there are a number of uses for BSG, the biggest impediment to its use is the cost of transport (due to the high moisture content) and/or drying. Wet BSG contains 77–81% (w/w) water. Due to its high moisture and fermentable sugar contents, BSG is a very unstable material and is liable to deteriorate rapidly due to microbial activity. To preserve the BSG from rotting it can be dried with the advantage that it also reduces the product mass and volume, and therefore, decreases transport and storage costs. The traditional process for drying BSG is based on the use of direct rotary-drum driers, which is very energy-intensive. More efforts

must be directed to finding alternative economically sustainable drying methods. Three methods for preserving spent grain: freeze-drying, oven drying, and freezing were evaluated but they do not meet all the requirements [3].

Freezing is inappropriate because large volumes must be stored and alterations in the arabinose content may occur. Preservation by oven drying or freeze-drying reduces the volume of the product and does not alter its composition. However, freeze-drying is economically unacceptable. Oven drying of BSG must be conducted at temperatures below approx. 60°C, because at higher temperatures unpleasant flavors are generated. In oven drying, there is a risk that the grain temperature near the dryer exit may rise leading to toasting or burning of the dried grains. In addition, smoke emerging from dryer stacks causes odor pollution problems. An alternative drying method which could save energy is to use superheated steam with claimed additional advantages including reduction in environmental impact, improved drying efficiency, elimination of fire or explosion risk, and enhanced recovery of valuable organic compounds [3].

From the above reasons, the best idea is to use a wet BSG on-site (in the company that has produced it) but it is not always possible. The also good solution would be drying the BSG on-site using waste heat (e.g. technological steam) and then transport a dry BSG to the local processing plant that would be built in a brewery cluster, as mentioned before.

The next barrier or challenge connected with the BSG is a taste and color of the products that have BSG in their composition. Brewers' Spent Grain (BSG) is brownish in color when moist and thus can only be used in off-white products or in such products that brown color would not affect. Moreover, because of alterations in the flavor only relatively small quantities of BSG can be incorporated [3]. This negative taste-effect is associated with high quantities of compounds such as 2-butyl-1-octanol, 3-methyl-butanal, 2-heptane, butanal, benzene and 2, 3-butanedione, responsible for its characteristic unpleasant odor. But there are studies that use supercritical CO_2 to mask the unpleasant and bitter taste and simultaneously to preserve the stability of polyphenols or other bioactive compounds. The tests with microencapsulated polyphenols extracted by supercritical CO_2 showed to have about 30% of phenolic and about 50% of flavonoid content more than the control sample and a better antioxidant activity with unchanging flavor properties [9].

Considering that carbohydrates are the significant components of BSG, more attention should be paid to its conversion into soluble and fermentable sugars. Currently, a number of added-value bioproducts such as organic acids, amino acids, vitamins, ethanol, butanediol are produced by fermentation using glucose or xylose as substrates. The cellulosic and non-cellulosic fractions of lignocellulosic materials in BSG are a rich source of these monosaccharides [3].

Another challenge is legislation. In order to ensure food safety in the feed/food supply chain and be able to utilize food waste products as either feed or food ingredients, the European Union has implemented specific regulations that impact the by-products from any food production process, including those from the brewing process (re)entering the food chain, either directly or via animal feed. Regulation (EC) No. 183/2005 [7] requires businesses who deal with animal feed intended for the food chain to register with their local authority and implement a dedicated HACCP plan, which includes the requirement for traceability. Brewers are required to register if they carry out the activity of selling brewery co-products as feed materials. There are currently no regulations with the preservation of brewers' spent grain for applications in human food, but various countries have guidelines for best practice preservation for spent grain used for animal feed [6].

5. Conclusion

Increasing efforts are being directed towards the reuse of agro-industrial by-products, from both economic and environmental standpoints. Brewers' Spent Grain is very promising by-product characterized by good chemical composition, rich in nutrients and giving extensive opportunities for development. However, ways of utilization are affected by limitations due to the size and location of the breweries, which influence the availability and applicability of options. Nowadays, BSG is still sold primarily as a low-value feed for cattle making it not a very profitable by-product. Moreover, small breweries opt to use sewage and landfill disposal methods for BSG, possibly because of the small volume of by-products which they produce.

Numerous attempts have been made to recycle the constituents of spent grain into the brewing process. Due to the large continuous supply, relatively low cost and potential nutritional value, BSG can be considered as an attractive adjunct for human food. Although, there are still challenges and barriers for feasible ways of BSG utilization that need to be faced and overcome to make this valuable biomass more attractive.

A new concept of using the BSG for production of low-alcohol nourishing beverage with a high amount of fiber and plant-based protein is shown in this work. It seems to be a good solution for small breweries to introduce into their offers a new product that would contain their own biomass by-product. Still, the idea carries some barriers and threats. The SWOT analysis was carried out (Table 1) to sum up the pre-feasibility study.

A consequential benefit of the use of industrial by-products such as BSG as raw materials in addition to the advantages described earlier is the generation of more jobs. Moreover, from an environmental point of view, the elimination of industrial by-products represents a solution to pollution problems.

Table 1 *SWOT analysis*

STRENGTH	WEAKNESSES
• the possibility of producing a short series of seasonal and experimental beverages • high-quality products; product-oriented production, the use of good, local products that customers know and appreciate • a growing number of customers and people interested in bioproducts, increasing consumer awareness in the bioeconomy	• difficulties with maintaining the repeatable quality of products constituting a company's permanent offer • high production costs and thus the final product • the high cost of entering the market in the case of the construction of a brewery as a production plant
OPPORTUNITIES	**THREATS**
• development of fashion for craft products • increase in consumer awareness, searching for new custom products • a negative image of mass group products in comparison with local products made according to a new bio-standards	• more restrictive regulations on products made from residues • the appearance of products of dubious quality on the market, "impersonating" for known craft products • difficulties with obtaining the right taste, smell and color of products containing BSG

Bibliography

1. Wojtyra, B.; Grudzień, Ł. Rozwój przemysłu piwowarskiego w Polsce w okresie tzw . piwnej rewolucji w latach 2011 – 2016. *Pr. Geogr. Przem. Pol. Tow. Geogr.* **2017**, *31*, 52–67.
2. Warsaw Statistical Yearbook of Industry - Poland. *Main Stat. Off.* **2018**.
3. Mussatto, S.I.; Dragone, G.; Roberto, I.C. Brewers' spent grain: Generation, characteristics and potential applications. *J. Cereal Sci.* **2006**, *43*, 1–14.
4. Pinheiro, T.; Coelho, E.; Romaní, A.; Domingues, L. Intensifying ethanol production from brewer's spent grain waste: Use of whole slurry at high solid loadings. *N. Biotechnol.* **2019**, *53*, 1–8.
5. Ibbett, R.; White, R.; Tucker, G.; Foster, T. Hydro-mechanical processing of brewer's spent grain as a novel route for separation of protein products with differentiated techno-functional properties. *Innov. Food Sci. Emerg. Technol.* **2019**, *56*, 102184.
6. Kerby, K.; Vriesekoop, F. An Overview of the Utilisation of Brewery By-Products as Generated by British Craft Breweries. *Beverages* **2017**, *3*, 24.
7. Food Standards Agency Feed Hygiene Regulation Available online: https://www.food.gov.uk/sites/default/files/media/document/EU Feed Hygiene Regulation %28183-2005%29 -- Approval and registration activities.pdf (accessed on Jul 22, 2019).
8. Piwna Mapa Polski Available online: https://www.mapotic.com/piwna-mapa-polski/places?attr7896=b8s1,vj7c,c64q&fbclid=IwAR3KjkgBRDrQQmPyI4t07wfQAjxcaa1vpqDMezxUtXQmgQWRjG6v-8NiHB4&lat=53.59902495724183&lng=19.9127197265625&zoom=7&fcat=6398,6399,6400,6401,6402 (accessed on Jul 22, 2019).
9. Fărcaş, A.C.; Socaci, S.A.; Mudura, E.; Dulf, F.V.; Vodnar, D.C.; Tofană, M.; Salanță, L.C. Exploitation of Brewing Industry Wastes to Produce Functional Ingredients. *IntechOpen* **2016**, 13.
10. Lynch, K.M.; Steffen, E.J.; Arendt, E.K. Brewers' spent grain: a review with an emphasis on food and health. *J. Inst. Brew.* **2016**, *122*, 553–568.
11. Fărcaş, A.C.; Socaci, S.A.; Dulf, F. V; Tofană, M.; Mudura, E.; Diaconeasa, Z. Volatile profile, fatty acids composition and total phenolics content of brewers' spent grain by-product with potential use in the development of new functional foods. *J. Cereal Sci.* **2015**, *64*, 34–42.
12. Mussatto, S. Brewer's spent grain: A valuable feedstock for industrial applications. *J. Sci. Food Agric.* **2014**, *94*.
13. del Río, J.C.; Prinsen, P.; Gutiérrez, A. Chemical composition of lipids in brewer's spent grain: A promising source of valuable phytochemicals. *J. Cereal Sci.* **2013**, *58*, 248–254.
14. Drink Canvas Available online: https://drinkcanvas.com/ (accessed on Jul 22, 2019).
15. ABInBev: A nutritional drink based on saved grains Available online: https://ab-inbev.eu/what-we-believe/blogitem/71-a-nutritional-drink-based-on-saved-grains.html (accessed on Jul 22, 2019).

PROCESSING AND PREPARATION OF ORGANIC APPLE WASTE TO PRODUCE HIGH-QUALITY PROTEINS

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Pre-Feasibility Study: Processing and preparation of organic apple waste to produce high-quality proteins

1 Introduction

The steady growth of the world population leads, among other things, to increasing demand for food and thus also for proteins. The projected demand for animal derived-protein will double by 2050[1], which is a significant challenge to overcome sustainably. Thus, the need for alternative protein sources, which are expected to play an essential role in the food sector, gets clear[2]. This increasing demand for protein is not only expected to be followed by severe adverse environmental effects of a growing animal processing sector but also by a global protein deficiency. In order to mitigate these risks, alternative and new protein sources needs to be utilized effectively as supplements (vegetarian products) or even substitutes (emulating existing meat-based products) to animal derived proteins. However, wasted or lost food nowadays accounts for roughly a third of the global food production[3], with industrial processing wastes being a significant part of it. It does not come as a surprise that the United Nations advises to lower the amount of wasted food globally through the Sustainable Development Goal (SDG) specified under Indicator 12.3.1. (Global food and waste)[4]. Per definition, food waste is "any food, and inedible parts of food, removed from (lost to or diverted from) the food supply chain

[1] Mike J. Boland et al., "The future supply of animal-derived protein for human consumption," *Trends in Food Science & Technology* 29, no. 1 (2013).
[2] Maeve Henchion et al., "Future Protein Supply and Demand: Strategies and Factors Influencing a Sustainable Equilibrium," *Foods (Basel, Switzerland)* 6, no. 7 (2017).
[3] Miranda J. Nicholes et al., "Surely you don't eat parsnip skins? Categorising the edibility of food waste," *Resources, Conservation and Recycling* 147 (2019).
[4] United Nations, *The Sustainable Development Goals Report 2019* (2019).

to be recovered or disposed”[5]. As a solution to meet the aforementioned rising demand and to fulfill the SDG, the use of food waste from industrial value chains to process high-quality proteins is proclaimed by various authors[6].

2 Goal

This pre-feasibility study, therefore, discusses the potential generation of a high-quality protein source from previously unused by-products of the regional production of organic dried apple products. The general development of a platform strategy for the production of an innovative prototype and a prototype process for the food industry can be regarded as the ultimate goal to achieve a long-term regional impact. By that, a resource-effective, bioeconomic restructuring in the region is made possible, which can be regarded as the vision of this study.

3 Theoretical Foundation

The need for alternative protein sources due to a growing population, and thus an emerging global protein deficit was already stated. However, especially in industrial countries, the development of a particular demand and interest in alternative protein sources can be observed.[7] These can be seen as not only necessary as a replacement for meat, but rather as an additional source of protein. Drivers for the demand mentioned above can be found mainly in socio-economic factors: rising incomes, increased urbanization, and a general acknowledgment of plant-based food and proteins as part of a healthy diet are seen as such[8]. Ethical and environmental concerns regarding the consumption of meat amplified a rapid expansion of the meat substitute market[9]; multiple players in the alternative protein field are already developing new technologies and ingredients, and others are seeking to solidify their position on the market.

[5] K. Östergren et al., “FUSIONS Definitional Framework for Food Waste,” (2014), https://www.eu-fusions.org/phocadownload/Publications/FUSIONS%20Definitional%20Framework%20for%20Food%20Waste%202014.pdf.
[6] Francesca Girotto, Luca Alibardi, and Raffaello Cossu, “Food waste generation and industrial uses: A review,” *Waste management (New York, N.Y.)* 45 (2015).
[7] Sergiy Smetana et al., “Meat alternatives: life cycle assessment of most known meat substitutes,” *The International Journal of Life Cycle Assessment* 20, no. 9 (2015).
[8] Maeve Henchion et al., “Future Protein Supply and Demand: Strategies and Factors Influencing a Sustainable Equilibrium,” *Foods (Basel, Switzerland)* 6, no. 7 (2017).
[9] Pedro F. Souza Filho et al., “Mycoprotein: environmental impact and health aspects,” *World journal of microbiology & biotechnology* 35, no. 10 (2019).

Numerous fast-food chains are already cooperating with alternative protein producers[10], and thus it is not surprising that dollar sales of plant-based foods, which account for the largest source of alternative protein, grew 11 % last year and 29 % over the past two years[11]. Due to this development, the production of meat analogs and supplements based on vegetable proteins has increasingly become subject of research in the past 20 years[12].

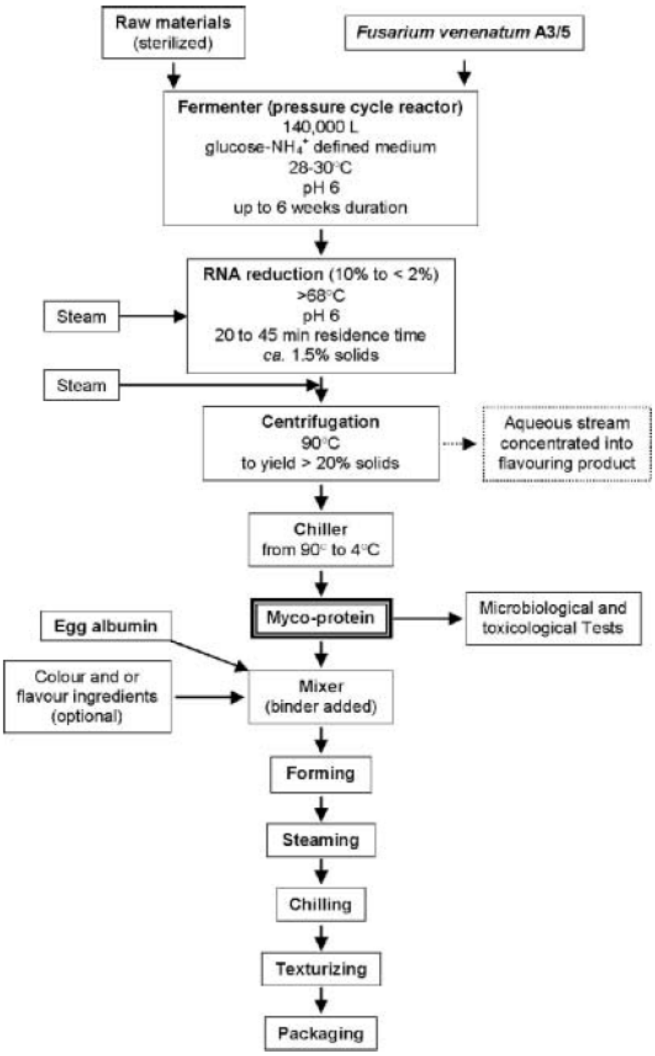

Fig. 2
Diagrammatic representation of the process for producing *myco-protein from* Fusarium venenatum *A3/5* (Wiebe 2002)

Mycoprotein is one of the lesser-known protein sources. The term refers to the proteinaceous food obtained from filamentous fungal biomass and is usable for human consumption[13]. It is furthermore designated as "Generally Recognized As Safe" (GRAS) by the Food and Drug Administration in the US[14]. Generally, the history of mushrooms as an edible goes back to the Egyptians and Romans. While the first believed that they were a godly gift, the latter directly called them a "divine food", created by Jupiter's lightning during storms[15]. They are healthy foods, rich in vegetable proteins, chitin, vitamins, and minerals, but deficient in calories and fat and can be saprophytes, symbionts, and

[10] Zafer Bashi et al., "Alternative proteins: The race for market share is on: Consumer interest in non-meat-based protein options is increasing globally. Food industry players that want to capture the opportunity must understand the evolving market dynamics and where to place their bets.," 2019.
[11] The Good Food Institute, "Plant-Based Market Overview," https://www.gfi.org/marketresearch, accessed April 2020.
[12] Alexander Stephan et al., "Edible mushroom mycelia of Pleurotus sapidus as novel protein sources in a vegan boiled sausage analog system: functionality and sensory tests in comparison to commercial proteins and meat sausages," *European Food Research and Technology* 244, no. 5 (2018).
[13] Pedro F. Souza Filho et al., "Mycoprotein: environmental impact and health aspects," *World journal of microbiology & biotechnology* 35, no. 10 (2019).
[14] Ibid.
[15] Pamela Manzi et al., "Nutrients in edible mushrooms: an inter-species comparative study," *Food chemistry* 65, no. 4 (1999).

parasites of different plants[16]. However, fungal proteins in an industrial setting are far younger. The first use was the production of yeast single-cell proteins during the First and Second World War[17]. During the 1960s, the ascomycete *Fusarium venenatum A3/5* was discovered by the British company Rank Hovis McDougall as another potential protein source for human consumption. The company wanted to develop a cheap and easy to produce microbial protein from a starch- or glucose-based media[18]. They screened approximately 3 000 different fungi and invested 12 years in researching the safety of the organism and final mycoprotein product[19]. Today, *F. venenatum A3/5* is commercialized by one company (Quorn®, Marlow Foods, UK) in supermarkets of 19 countries[20]. The production process, as shown in Fig. 2, however, is seen as costly; hence the market prices for mycoprotein are in the ranges of those of regular meat[21]. Thus, due to high production costs and the cost inefficiency of a UK production, mycoprotein at the moment serve a narrow, premium, vegetarian market[22], and its actual market scope is limited by price. While RITCHIE, LAIRD AND RITCHIE suggest a patented technology using a zero-waste, integrated fermentation process to overcome this hurdle, PETRE AND PETRE suggest the entirely different *submerged cultivation method* (SCM) to reduce costs.

In comparison with the natural environment where all native mushrooms grow on the ground, the submerged cultivation of mushrooms (SCM) follows an entirely different route. Since the field cultivation of mushrooms takes several months and has low productivity of bioactive compounds, the submerged cultivation is seen as a promising alternative[23]. SCM refers to a "biotechnological process of mushroom growth inside an artificial environment represented by the volume of a liquid medium in which all physical and chemical factors needed for optimal development of mycelium are provided without any risk of chemical or biological

[16] Pamela Manzi et al., "Nutrients in edible mushrooms: an inter-species comparative study," *Food chemistry* 65, no. 4 (1999).
[17] Alexander Stephan et al., "Edible mushroom mycelia of Pleurotus sapidus as novel protein sources in a vegan boiled sausage analog system: functionality and sensory tests in comparison to commercial proteins and meat sausages," *European Food Research and Technology* 244, no. 5 (2018).
[18] M. G. Wiebe, "Myco-protein from Fusarium venenatum: a well-established product for human consumption," *Applied microbiology and biotechnology* 58, no. 4 (2002).
[19] Ibid.
[20] Pedro F. Souza Filho et al., "Mycoprotein: environmental impact and health aspects," *World journal of microbiology & biotechnology* 35, no. 10 (2019).
[21] Hannah Ritchie, Jim Laird, and David Ritchie, "3f bio : Halving the Cost of Mycoprotein Through Integrated Fermentation Processes," *Industrial Biotechnology* 13, no. 1 (2017).
[22] Ibid.
[23] Xian-Bing Mao et al., "Optimization of carbon source and carbon/nitrogen ratio for cordycepin production by submerged cultivation of medicinal mushroom Cordyceps militaris," *Process Biochemistry* 40, no. 5 (2005).

contamination"[24]. Now, no known mushroom species is able to grow in natural aquatic habitats due to their requirement of permanent oxygen intake in appropriate concentrations; none is adapted to form fruiting bodies inside a liquid medium. The only way to achieve artificial cultivation is by continually providing the required levels of dissolved oxygen concentrations to maintain metabolic activities. This is done by using individual devices to force oxygen penetration inside the liquid volume[25]. It is no surprise that SCM has relatively high energy costs, which are required for the agitation, oxygen supply, and constant measurements. On the contrary, a "significant industrial potential due to the possibility of process upscaling and operation of large-scale bioreactors"[26] is proclaimed. The process for the submerged mushroom cultivation to get high nutritive mycelial biomass traverses five steps[27]:

1) Preparation of the culture substrates
2) Steam sterilization of the bioreactor culture vessel
3) Aseptic inoculation of the sterilized culture media with the pure cultures of selected mushroom strains
4) Running the submerged cultivation cycles under controlled conditions
5) Collecting, washing, and filtering of the fungal pellets

The culture substrate is of great importance to the yield, and carbon, as well as nitrogen sources, play a significant role because these nutrients are directly linked with cell proliferation and metabolite biosynthesis[28]. At best, the carbon sources are easily accessible and have a competitive manufacturing cost[29]. The vision of this pre-feasibility study is to use local residues from dried apple production. Both of these requirements are believed to be easily met by using this by-product. Apple pomace, generally, is considered a good substrate for edible mushroom production, due to its richness in carbohydrate polymers (lignin), as well as minerals including nitrogen[30]. Furthermore, due to the high content of soluble sugars in the apple cores and the

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[24] Marian Petre, ed., *Mushroom biotechnology: Developments and applications* (London Wall, San Diego, CA: Academic Press is an imprint of Elsevier, 2016). http://www.sciencedirect.com/science/book/9780128027943.
[25] Ibid.
[26] Ibid.
[27] Ibid.
[28] Xian-Bing Mao et al., "Optimization of carbon source and carbon/nitrogen ratio for cordycepin production by submerged cultivation of medicinal mushroom Cordyceps militaris," *Process Biochemistry* 40, no. 5 (2005).
[29] Marian Petre, ed., *Mushroom biotechnology: Developments and applications* (London Wall, San Diego, CA: Academic Press is an imprint of Elsevier, 2016). http://www.sciencedirect.com/science/book/9780128027943.
[30] Fengzhi Lyu et al., "Apple Pomace as a Functional and Healthy Ingredient in Food Products: A Review," *Processes* 8, no. 3 (2020).

high content of sugar polymers such as cellulose and hemicellulose, the material is regarded as well suited as a base for the culture substrate[31]. Concretely, apple pomace is a heterogeneous mix of skin and flesh (95%), seeds (2%-4%) and stems (1%)[32]. Table 1 gives an overview over the physical-chemical composition from various studies.

Table 1 *- Different physical-chemical compositions of apple pomace*[33]

Composition (%; dry weight basis)	**Wang et al. (2019)**	**Jin et al. (2002)**	**Jannati et al. (2018)**	**Ktenioudaki et al. (2013)**
Moisture	4.4	5.8	10.5	7.1
Protein	3.8	4.7	1.2	2.4
Lipids	3.8	4.2	0.6	2.7
Total Dieteray Fiber	26.5	not reported	14.5	42.5
Ash	1.8	1.5	2.5	1.7
Carbohydrates	45.1	83.8	not reported	not reported

The differences in content get apparent. However, there is a great variety of nutrients in apple pomace, making it a good source of minerals, proteins and vitamins. The carbohydrates consist of[34]:

- insoluble sugars including cellulose (127.9 g/kg DW)
- hemicellulose (7.2 to 43.6 g/kg DW)´
- lignin (15.3 to 23.5 g/kg DW)
- glucose (22.7%)
- fructose (23.6%)
- galactose (6% to 15%)

[31] Andrea K. Bosse, Marco A. Fraatz, and Holger Zorn, “Formation of complex natural flavours by biotransformation of apple pomace with basidiomycetes,” *Food chemistry* 141, no. 3 (2013); Roberto Rodríguez Madrera, Rosa Pando Bedriñana, and Belén Suárez Valles, “Production and characterization of aroma compounds from apple pomace by solid-state fermentation with selected yeasts,” *LWT - Food Science and Technology* 64, no. 2 (2015).
[32] Fengzhi Lyu et al., “Apple Pomace as a Functional and Healthy Ingredient in Food Products: A Review,” *Processes* 8, no. 3 (2020).
[33] Ibid.
[34] Camila A. Perussello et al., “Valorization of Apple Pomace by Extraction of Valuable Compounds,” *Comprehensive Reviews in Food Science and Food Safety* 16, no. 5 (2017).

In addition to carbohydrates, some minerals were also determined in apple pomace, such as[35]

- P (0.07% to 0.076%)
- Ca (0.06% to 0.1%)
- Mg (0.02% to 0.36%)
- Fe (31.8 to 38.3 mg/kg, dry weight basis)

Apple pomace is also characterized by a high proportion of polyphenols (31% to 51%), especially cinnamate esters, dihydrochalcones and flavonols[36]. Apple pomace is also readily available. The world production of apples was more than 70 million metric tons in 2015, of which the European Union contributed with more than 15%, with 75% of the apple used and 25%, the pomace, commonly used as animal feed or compost[37].

Besides specific requirements for the culture substrate, the process inside the bioreactor must pinpoint various other factors[38]:

- pH index; varying depending on the mushroom species used
- oxygen intake/aeration rate; to supply the mycelial biomass while submerse
- temperature; approximately between 23°C and 25°C[39]
- stirring rate; to achieve a uniform dispersion of nutrient compounds in the cultivation liquid substrate (60-90 rpm)[40]

The most promising mushroom for the process is *Pleurotus ostreatus*, better known as "oyster mushroom". It is the second most cultivated mushroom globally[41]. In comparison to other

[35] Fengzhi Lyu et al., "Apple Pomace as a Functional and Healthy Ingredient in Food Products: A Review," *Processes* 8, no. 3 (2020).
[36] Ibid.
[37] Malcolm Yates et al., "Multivalorization of apple pomace towards materials and chemicals. Waste to wealth," *Journal of Cleaner Production* 143 (2017).
[38] Marian Petre, ed., *Mushroom biotechnology: Developments and applications* (London Wall, San Diego, CA: Academic Press is an imprint of Elsevier, 2016). http://www.sciencedirect.com/science/book/9780128027943.
[39] Ibid.
[40] Ibid.
[41] Carmen Sánchez, "Cultivation of Pleurotus ostreatus and other edible mushrooms," *Applied microbiology and biotechnology* 85, no. 5 (2010).

edible fungi, it inhibits a shorter growth time[42], does not require sophisticated ingredients in the cultivation substrate[43] and convert lignocellulosic materials to a high percentage into fruiting bodies[44]. The cultivation is thus less pricey, and the initial framework suggests profitability[45]. Finally, as WANG & NG reported, a protein potentially able to have positive effects in the treatment of HIV-positive patients can also be isolated from the fruiting bodies of *Pleurotus ostreatus*[46], showcasing a potential medical application. However, from a scientific point of view, the most valuable and best researched product opportunity is created by using the mycoprotein as a food supplement. Other possible options may emerge in the future, building upon an already established basis.

4 pre-feasibility Assessment

Various potentially conflicting factors need to be considered for the implementation of this concept. First, the technological requirements are on a comparatively high level, which is the case when looking at the theory. Then, the apple cores are somewhat of a black box. Research on apple pomace in general has already been done and thus a lot of information can be found. Apple core housings, or apple cores, are much less researched, because they appear in quite a niche (by-products from dried apple production). It is assumed, that they cannot, due to their high wet-weight, be transported over long distances, which means the production facility needs to be located near the source of the by-product. Before being able to act as a growth substrate in the growth medium, the apple cores need to be separated from the appleseed and dried, to receive a clean primary material. Not only is the cultivation in a bioreactor by itself assumed as a highly-energetic process, but the drying as a previous step does not necessarily contribute to a low-energy profile of the whole process. Furthermore, additional and ongoing research for this exact case is needed, because apple cores were, in comparison to apple pomace[47], never

[42] Vladimir Elisashvili et al., "Lentinus edodes and Pleurotus species lignocellulolytic enzymes activity in submerged and solid-state fermentation of lignocellulosic wastes of different composition," *Bioresource technology* 99, no. 3 (2008).
[43] P. Rani, N. Kalyani, and K. Prathiba, "Evaluation of lignocellulosic wastes for production of edible mushrooms," *Applied biochemistry and biotechnology* 151, 2-3 (2008).
[44] George G. Songulashvili et al., "Bioconversion of Plant Raw Materials in Value-Added Products by Lentinus edodes (Berk.) Singer and Pleurotus spp," *International Journal of Medicinal Mushrooms* 7, no. 3 (2005).
[45] Marian Petre, ed., *Mushroom biotechnology: Developments and applications* (London Wall, San Diego, CA: Academic Press is an imprint of Elsevier, 2016). http://www.sciencedirect.com/science/book/9780128027943.
[46] H. X. Wang and T. B. Ng, "Isolation of a novel ubiquitin-like protein from Pleurotus ostreatus mushroom with anti-human immunodeficiency virus, translation-inhibitory, and ribonuclease activities," *Biochemical and biophysical research communications* 276, no. 2 (2000).
[47] Andrea K. Bosse, Marco A. Fraatz, and Holger Zorn, "Formation of complex natural flavours by biotransformation of apple pomace with basidiomycetes," *Food chemistry* 141, no. 3 (2013).

used before for the cultivation of basidiomycetes (pole mushrooms). The Technology readiness level (TRL) for the process of receiving mycroprotein from a growth substrate based on apple core housings can thus be seen at Level 2: the technology is not yet validated in a laboratory environment, but is promising and expected to do so. This is based on the assumption that apple cores have roughly the same physical and chemical composition as apple pomace. As a next step, a system prototype demonstration in an operational environment should be created.

The initial assessment of the sustainability and ecological scope is positive. The process is a prime example of the circular economy and combines the production of proteins to reduce environmental pollution. While the non-submerse cultivation method of mycoprotein has a similar environmental impact to the production of chicken meat[48], SCM is connected to the responsible use of water, space, and CO_2-footprint. Energy, however, is a factor that needs to be evaluated over the entire implementation process because of its potential impact. Social acceptance can be another hurdle to overcome. Consumers are unfamiliar with mycoprotein, and a recent legal settlement required food labels to include the terminology "mold"[49]. As a counterargument, the rising interest in alternative protein sources can be invoked, especially in vegan or vegetarian markets. Acceptance may be a key driver towards mycoprotein, because protein from insects as well as in-vitro meat performs very poorly in consumer acceptance studies[50]. Proven positive impacts in cholesterol, sugar and insulin blood levels are able to bolster this argument even further. If the determined platform process is successful and a market launch is in prospect, the next step is to expand it to any number of other regional sources of raw materials from waste in order to achieve a positive regional impact in the long term. Lastly, climate-smart food systems, like this, can help to reduce the negative impacts of this sector[51].

Regarding the market situation, a very positive outline can be drawn. To this date, no other company produces mycoprotein in Germany, and the sole producing competitor is Quorn, owned by the Monde Nissin Corporation. The rising demand for alternative proteins was also already expressed, and thus a projected annual growth of the mycoprotein market of 12%

[48] Enrico Benetto, Kilian Gericke, and Mélanie Guiton, *Designing Sustainable Technologies, Products and Policies* (Cham: Springer International Publishing, 2018).
[49] Zafer Bashi et al., "Alternative proteins: The race for market share is on: Consumer interest in non-meat-based protein options is increasing globally. Food industry players that want to capture the opportunity must understand the evolving market dynamics and where to place their bets.," 2019.
[50] Pedro F. Souza Filho et al., "Mycoprotein: environmental impact and health aspects," *World journal of microbiology & biotechnology* 35, no. 10 (2019).
[51] Ibid.

between 2019 to 2027 is not surprising[52]. While Quorn still has a monopoly in the market and is believed to hold a significant amount of market share[53], the rising demand inevitably evokes competitors. The Scottish Biotechnology firm 3F Bio, for example, announced a new, large scale mycoprotein project ("Plenitude") last year, while Swedish start-up "Mycorena" recently opened a new facility, hoping for successful market launch later this year[54]. However, a Germany-based company needs yet to be found. Especially in Germany, the market for alternative proteins is believed to be huge. Compared to its European neighbors, Germany has the highest rate of vegetarianism: 1.3 million people are vegans, while 8 million follow a vegetarian diet[55]. This number further increases every year, thus amplifying demand. Veganism is often a lifestyle choice, which means that the acceptance for a product that is based on waste material is also believed to be high. Then, according to the IFH in Cologne, one of the three top-selling product groups are vegetarian-vegan meat and milk alternatives[56], which results in the fact that meat substitutes being the most popular processed vegan products in Germany, reaching 200 million $ in sales in 2019[57]. The market is therefore considered suitable, especially in Germany.

5 Conclusion

In total, this initial assessment based on a literature review leads to a positive outlook. Through the biotechnological refinement of a rapidly perishable by-product, which up to now has been disposed of at great expense, a protein alternative in great demand can be produced. The depth of added value is continuously increased through accompanying research into the individual processing steps, and the final developed prototypes result in cost savings and the possibility of recycling other waste materials as well.

[52] Bridge2Food.com, „New Scientific Paper Reviews Mycoprotein as Highly Sustainable Meat Substitute as producers Increasingly Turn to Fungi Alternatives" (2019, online: https://bridge2food.com/new-scientific-paper-reviews-mycoprotein-as-highly-sustainable-meat-substitute-as-producers-increasingly-turn-to-fungi-alternatives/)
[53] Quorn last reported their finances in 2017, when sales totalled 205 million pounds – a 16% increase in comparison to last year, totalling in an annual growth rate of 8%
[54] foodnavigator.com, „A new competitor to the Quorn category? Start-up brings mycoprotein product 'one step closer to market'" (2020, online: https://www.foodnavigator.com/Article/2020/02/13/Mycorena-Swedish-start-up-brings-Promyc-one-step-closer-to-market)
[55] Kseniya Bielinska, Leif Rehder, and William Trautmann, "Germany is Leading a Vegalution - Vegan Revolution - in Europe," 2020.
[56] Ibid.
[57] Ibid.

Bibliography

Bashi, Zafer, McCullough, Ryan, Ong, Liane, and Ramirez, Miguel. "Alternative proteins: The race for market share is on: Consumer interest in non-meat-based protein options is increasing globally. Food industry players that want to capture the opportunity must understand the evolving market dynamics and where to place their bets." 2019.

Benetto, Enrico, Gericke, Kilian, and Guiton, Mélanie. *Designing Sustainable Technologies, Products and Policies*. Cham: Springer International Publishing, 2018.

Bielinska, Kseniya, Rehder, Leif, and Trautmann, William. "Germany is Leading a Vegalution - Vegan Revolution - in Europe." 2020.

Boland, Mike J., Rae, Allan N., Vereijken, Johan M., Meuwissen, Miranda P.M., Fischer, Arnout R.H., van Boekel, Martinus A.J.S., Rutherfurd, Shane M., Gruppen, Harry, Moughan, Paul J., and Hendriks, Wouter H. "The future supply of animal-derived protein for human consumption." *Trends in Food Science & Technology* 29, no. 1 (2013): 62–73.

Bosse, Andrea K., Fraatz, Marco A., and Zorn, Holger. "Formation of complex natural flavours by biotransformation of apple pomace with basidiomycetes." *Food chemistry* 141, no. 3 (2013): 2952–2959.

Elisashvili, Vladimir, Penninckx, Michel, Kachlishvili, Eva, Tsiklauri, Nino, Metreveli, Eka, Kharziani, Tamar, and Kvesitadze, Giorgi. "Lentinus edodes and Pleurotus species lignocellulolytic enzymes activity in submerged and solid-state fermentation of lignocellulosic wastes of different composition." *Bioresource technology* 99, no. 3 (2008): 457–462.

Girotto, Francesca, Alibardi, Luca, and Cossu, Raffaello. "Food waste generation and industrial uses: A review." *Waste management (New York, N.Y.)* 45 (2015): 32–41.

Henchion, Maeve, Hayes, Maria, Mullen, Anne Maria, Fenelon, Mark, and Tiwari, Brijesh. "Future Protein Supply and Demand: Strategies and Factors Influencing a Sustainable Equilibrium." *Foods (Basel, Switzerland)* 6, no. 7 (2017).

Lyu, Fengzhi, Luiz, Selma F., Azeredo, Denise Rosane Perdomo, Cruz, Adriano G., Ajlouni, Said, and Ranadheera, Chaminda Senaka. "Apple Pomace as a Functional and Healthy Ingredient in Food Products: A Review." *Processes* 8, no. 3 (2020): 319.

Manzi, Pamela, Gambelli, Loretta, Marconi, Stefania, Vivanti, Vittorio, and Pizzoferrato, Laura. "Nutrients in edible mushrooms: an inter-species comparative study." *Food chemistry* 65, no. 4 (1999): 477–482.

Mao, Xian-Bing, Eksriwong, Titiporn, Chauvatcharin, Somchai, and Zhong, Jian-Jiang. “Optimization of carbon source and carbon/nitrogen ratio for cordycepin production by submerged cultivation of medicinal mushroom Cordyceps militaris.” *Process Biochemistry* 40, no. 5 (2005): 1667–1672.

Nicholes, Miranda J., Quested, Tom E., Reynolds, Christian, Gillick, Sam, and Parry, Andrew D. “Surely you don’t eat parsnip skins? Categorising the edibility of food waste.” *Resources, Conservation and Recycling* 147 (2019): 179–188.

Östergren, K., Gustavsson, J., Bos-Brouwers, H., Timmermans, T., and Hansen, O-J. “FUSIONS Definitional Framework for Food Waste.” (2014). https://www.eu-fusions.org/phocadownload/Publications/FUSIONS%20Definitional%20Framework%20for%20Food%20Waste%202014.pdf.

Perussello, Camila A., Zhang, Zhihang, Marzocchella, Antonio, and Tiwari, Brijesh K. “Valorization of Apple Pomace by Extraction of Valuable Compounds.” *Comprehensive Reviews in Food Science and Food Safety* 16, no. 5 (2017): 776–796.

Petre, Marian, ed. *Mushroom biotechnology: Developments and applications*. London Wall, San Diego, CA: Academic Press is an imprint of Elsevier, 2016. http://www.sciencedirect.com/science/book/9780128027943.

Rani, P., Kalyani, N., and Prathiba, K. “Evaluation of lignocellulosic wastes for production of edible mushrooms.” *Applied biochemistry and biotechnology* 151, 2-3 (2008): 151–159.

Ritchie, Hannah, Laird, Jim, and Ritchie, David. “3f bio : Halving the Cost of Mycoprotein Through Integrated Fermentation Processes.” *Industrial Biotechnology* 13, no. 1 (2017): 29–31.

Rodríguez Madrera, Roberto, Pando Bedriñana, Rosa, and Suárez Valles, Belén. “Production and characterization of aroma compounds from apple pomace by solid-state fermentation with selected yeasts.” *LWT - Food Science and Technology* 64, no. 2 (2015): 1342–1353.

Sánchez, Carmen. “Cultivation of Pleurotus ostreatus and other edible mushrooms.” *Applied microbiology and biotechnology* 85, no. 5 (2010): 1321–1337.

Smetana, Sergiy, Mathys, Alexander, Knoch, Achim, and Heinz, Volker. “Meat alternatives: life cycle assessment of most known meat substitutes.” *The International Journal of Life Cycle Assessment* 20, no. 9 (2015): 1254–1267.

Songulashvili, George G., Elisashvili, Vladimir, Penninckx, Michel, Metreveli, Eka, Hadar, Yitzhak, Aladashvili, Nana, and Asatiani, Mikheil D. “Bioconversion of Plant Raw

Materials in Value-Added Products by Lentinus edodes (Berk.) Singer and Pleurotus spp." *International Journal of Medicinal Mushrooms* 7, no. 3 (2005): 467–468.

Souza Filho, Pedro F., Andersson, Dan, Ferreira, Jorge A., and Taherzadeh, Mohammad J. "Mycoprotein: environmental impact and health aspects." *World journal of microbiology & biotechnology* 35, no. 10 (2019): 147.

Stephan, Alexander, Ahlborn, Jenny, Zajul, Martina, and Zorn, Holger. "Edible mushroom mycelia of Pleurotus sapidus as novel protein sources in a vegan boiled sausage analog system: functionality and sensory tests in comparison to commercial proteins and meat sausages." *European Food Research and Technology* 244, no. 5 (2018): 913–924.

The Good Food Institute. "Plant-Based Market Overview." https://www.gfi.org/marketresearch, accessed April 2020.

United Nations. *The Sustainable Development Goals Report 2019*, 2019.

Wang, H. X., and Ng, T. B. "Isolation of a novel ubiquitin-like protein from Pleurotus ostreatus mushroom with anti-human immunodeficiency virus, translation-inhibitory, and ribonuclease activities." *Biochemical and biophysical research communications* 276, no. 2 (2000): 587–593.

Wiebe, M. G. "Myco-protein from Fusarium venenatum: a well-established product for human consumption." *Applied microbiology and biotechnology* 58, no. 4 (2002): 421–427.

Yates, Malcolm, Gomez, Milagros Ramos, Martin-Luengo, Maria A., Ibañez, Violeta Zurdo, and Martinez Serrano, Ana Maria. "Multivalorization of apple pomace towards materials and chemicals. Waste to wealth." *Journal of Cleaner Production* 143 (2017): 847–853.

Household sector

SOURCE-SORTED ORGANIC HOUSEHOLD WASTE TO BIOPULP FOR BIOGAS - A CASCADING EXAMPLE

COLOURBOX52212928

Prefeasibility study

Source-sorted organic household waste to biopulp for biogas

a cascading example for organic waste

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Tyge Kjær

1. Introduction

Supply of resources to the bioeconomy activities will typically be based on local resources. If the bioeconomy is developed ideally, then the biological raw materials will be based on side-streams and residues from local production and consumption - for instance residues from food production (agriculture and food industry), from the wood industry (forestry, sawmills and wood industry), waste from households (organic house-hold waste), etc.

Bioeconomy can create the basis for new traces of development, which can be characterized as some kind of reindustrialization of the communities in Region Zealand, implying use of residual products as a basis for a bioeconomic development. What used to be characterized as residuals or waste can be included in new production chains - if - of course - a number of preconditions are met.

It is the general assessment that bioeconomic development - especially in relation to new industrial products - has a long way to go. That means it will be an advantage to focus on products and markets that are immediately available, because they can act as a start-up process. Judging by the international product and market development, it is assessed that there is significant potential for the development of a number of new industrial products, which could be based on the biological resources in Region Zealand.

Where are the potentials? The main point of departure is that the bioeconomic development in Region Zealand must be based on biological side-streams and residual products from especially agriculture, forestry, industry and households - and not new specific produced crops. Put in another way: The purpose of the actual bioeconomic must be to ensure the optimal utilization of the biological resources, side-streams and residual products in the Region for the production of industrial products that replace the fossil-based resources as well as for the production of energy.

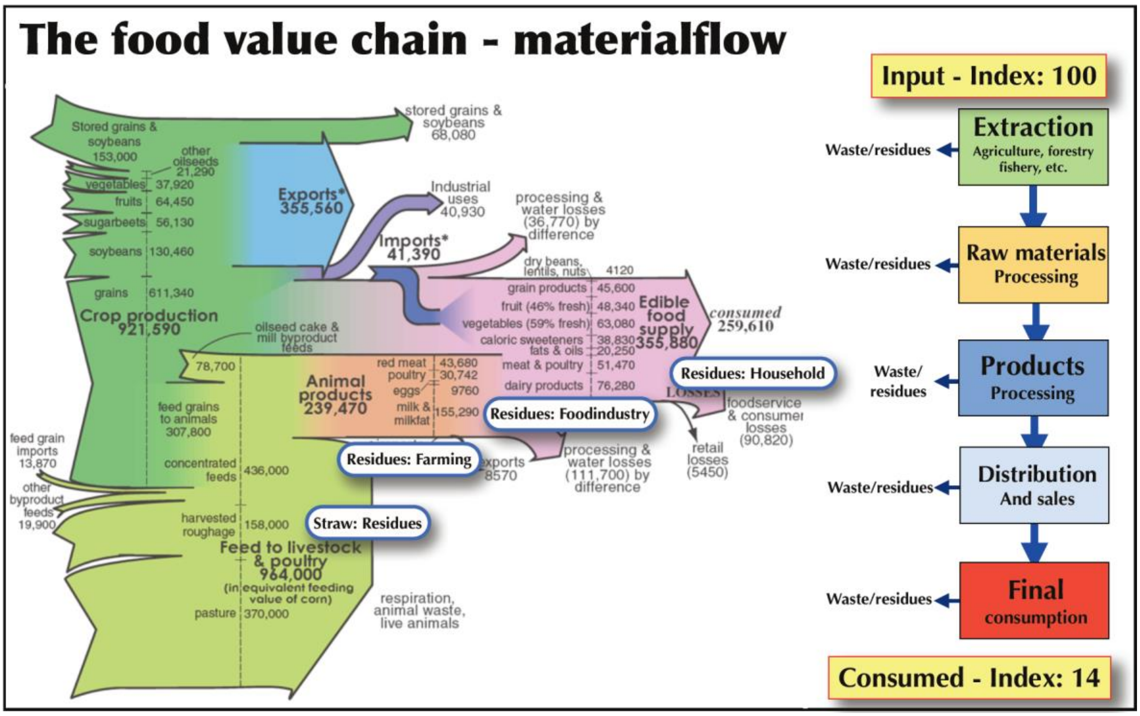
Product and technology development is about finding specific applications for the residual products and biological side-streams that are not currently utilized or are not utilized efficiently. As with all production, it is necessary to be aware of a number of possible negative effects on the environment and nature. These factors must, of course, be included in the utilization of biomass, residual products and biological side-streams.

These considerations lead to three main principles for the development of the bioeconomy, namely (1) the principle of applying and working after the establishment of material ***cascades***, (2) the principle of ensuring that bioeconomic solutions are part of a ***circular*** economy, and (3) the principle of using ***waste streams*** (residual products and side streams), where in particular the first two principles must be mentioned in this introduction.

The cascading principle: The principle of using cascading of products and material / raw materials can best be introduced by showing a material flow where there is no cascading. but where every single station in the life cycle 'throws' waste or residues away

It can be illustrated with an overview of the material flow in the US food industry with the figure below.

Figure 1. The principle of cascading - building a hierarchy in the utilization of the various biomasses.[1]



If the total input in the material flow is set to index 100, as shown in the figure, then only just under ***14% reaches the consumption***. The remaining material represents waste in the form of residues and side-streams which not all are immediately used. The principle of cascading is precisely about enter the material chains and utilizing the residual products and side streams for new and other products. There are in principle two different forms of cascading, where one form can be called product cascading and the other form for material cascading.

Product cascading consists of a product being used for a different or new purpose after use. For example, newsprint, which after use of the newspaper is collected and used as printing paper, which is then used for cardboard after use. In some cases, a cascade will result in a process that can be characterized as down-cycling; in other case the process might create a recycling, and in some - though frequently in much fewer cases - result in material upcycling.

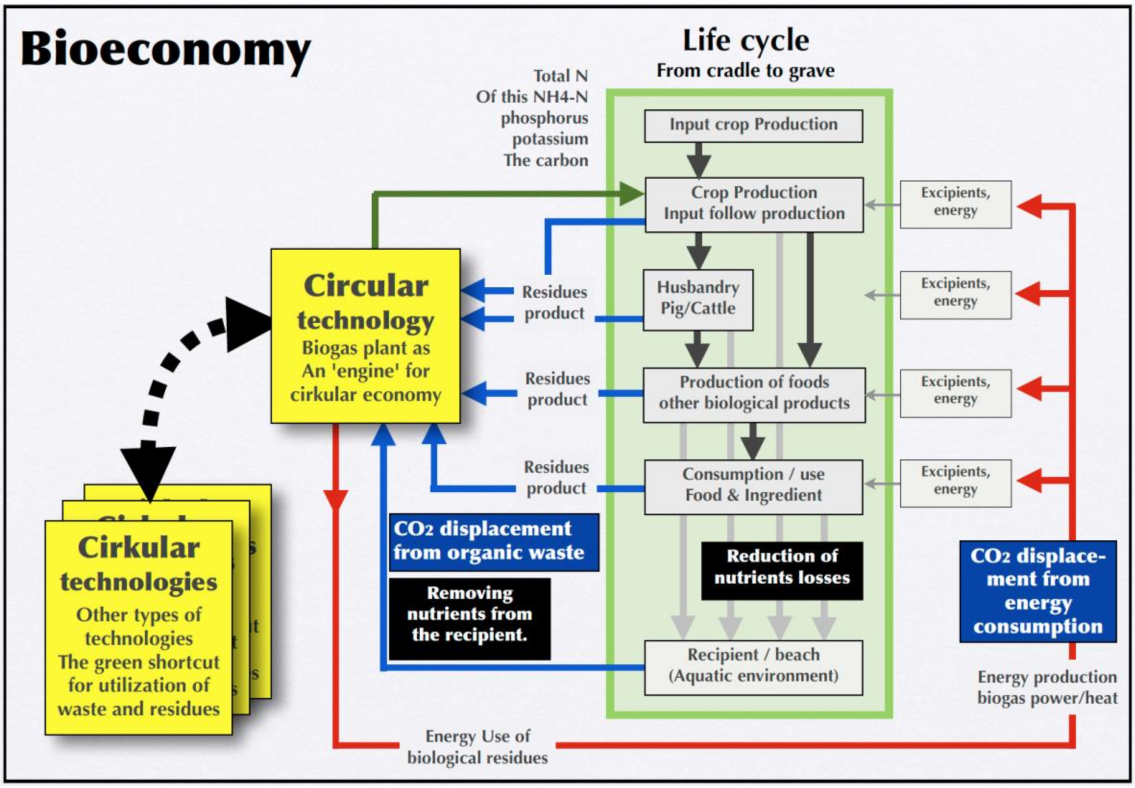
Material cascading consists in the fact that the residual and side streams that arise in a given process constitute the basis for a new material flow, for material cascading. Material cascading is expected to be more effective than product cascading due larger quantities and variations in material types as demonstrated with the figure above.

[1] The source of the figure is: Martin C. Heller and Gregory A. Keoleian: Lifting Cycle-Based Sustainability Indicators for Assessment of the U.S. Food System; Center for Sustainable Systems; University of Michigan; Report No. CSS00-04; December 6, 2000, p. 37.

It is the latter type of cascade - material cascading - which will be used in this report to study the potentials of using organic household waste.

Circular Economy: Circular economy is most often understood as the recycling of residual products or waste from the last station in a given production chain (see for instance the MacArthur butterfly model). It is a very incomplete understanding of circular economy. It appears for instance of the previous figure (figure 1) that the greatest losses of material loss are not in the households, but ***throughout*** the whole life cycle, and especially in the first parts of the total life cycle. The figure below should illustrate types of the residues and side flows:

Figure 2. Material flow in the circular economy, exemplified by wet biomasses in a biogas plant. Circular economy in the biosphere.



The circular economy is - as a concept - an incentive to recycle the materials in a given production life cycle. The figure illustrates that the various waste and side streams can be used for energy production, while at the same time nutrients and carbon are recycled to the agriculture. The important thing about the recycling process is, of course, that one obtains a substitution of other products, for instance fertilizers, based on fossil sources.

The circular economy must - to be preferential - reduce the primary resource pull. A biogas plant is one of many forms of circular technologies, ie technologies that enable the recyle resources and a substitution of primary resources that would otherwise be used without this technology.

The cascade shown in the figure is not the only and final cascade. Residual products and side-streams from the biogas plant can form the basis for new cascades, for example in the shape of surplus heat from the biological biogas process, and CO_2 as residues from upgrading of biogas to methane, where these residues could be used for carbon storage (CCS) or use for industrial purposes (CCU). How-ever, these types of cascades are not included in this report. [2]

2. The feasibility analysis

The purpose is to prepare a feasibility analysis of a biogas plant, which can utilize the organic waste from the domestic waste (household waste) and possibly also organic waste from companies in the area.

The problem is: How can a biogas capacity be created for the treatment of organic household waste? How big should the biogas plant be, and are there benefits associated with size, location, etc.? What measures are needed to ensure that the residual product is of sufficient quality that the residual product and its nutrients can be fully utilized?

The background: The discussion about the use of organic household waste for biogas plants is mainly promoted by the EU Waste Directive, but also promoted by the Danish resource policy.[3] The general Danish problem can be briefly characterized as "Recycle more - burn less". There promotions have created a desire for recycling of a larger part of the household waste reducing the amount for incineration. [4]

These desires have also motivated a large number of municipalities in Region Zealand to initiate the collection of source-sorted biowaste (KOD). A number of municipalities have already implemented collection schemes, while others are on the way. For the municipalities that currently collect source-sorted bio-waste, there have typically been two temporary solutions.

One solution consists of a direct delivery of the biowaste to a small plant at Holbæk, based on digestion in a non-circulating biogas plant with low gas performance. The second solution has consisted of tender schemes, where the waste companies through tenders have entered into a treatment agreement with companies that process the biowaste into biopulp, which is then sold to biogas plants. This solution has become the typical choice for most waste companies and their municipalities on Zealand.

The most important companies for processing source-sorted organic household waste to biopulp are Komtek A / S located in Holsted in South Jutland, HCS A / S with plants lo-

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2 **CCS:** Carbon Capture and Storage, **CCU:** Carbon Capture and Utilization. See for instance: Putting CO2 to Use. Creating value from emissions. IEA (International Energy Agency); September 2019.

3 The Waste Directive (Directive 2008/98 / EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives), and the Danish report »Denmark without waste. Recycle more - burn less«, The Government, October 2013, and »Denmark without waste. Resource plan for waste management 2013-2018«. November 2013.

4 Cf. »Denmark without waste. Recycle more - incinerate less«, op.cit., where the expectation is that 50% of household waste will be recycled as a minimum in 2022 against the current 22%'s recycling and 75% incineration, op.cit., p. 12.

cated in the city Glostrup and NC Miljø, also located in Holsted, near a biogas plant. Furthermore, the company Marius Pedersen should be mentioned, which, however, only collects food waste from shops, producers, canteens, hospitals, etc.[5]

The pre-treatment capacity on Zealand is too small for the total quantities. The capacity throughout Zealand is estimated to be a maximum of 30,000 tonnes. Deliveries to existing biogas plants on Zealand are even smaller. This has meant that a significant part of the pre-treatment takes place in Jutland, and that the majority of the biopulp from the whole Zealand is used at biogas plants in Jutland, while only a small part is delivered to two biogas plants at Zealand (Hashøj and Nysted) or exported to Sweden. This has resulted high transport costs and inappropriate logistics.

The development so far has resulted in the following: Through tenders, pre-treatment has been established at the above-mentioned facilities. In recent years, a number of competing pre-treatment technologies have been developed with an very good environmental profile.[6] Collection systems and pre-treatment technologies have also been under development, where various solutions have been shown to provide high sorting efficiency. There is still a need for a number of experiments and developments in the collection and pre-treatment systems of the source-sorted organic household waste.

What is the problem: The problem is that both the pre-treatment capacity and the biogas capacity are too small in the area of Zealand. It is expected that the pre-treatment capacity (biowaste processed into biopulp) will be automatically expanded as the collection volumes grow. Thus, expansion and establishment plans have been announced at Zealand for both existing pre-treatment companies and new companies. The greatest need is therefore to establish ***sufficient biogas capacity***. It is this issue that needs to be addressed in this report: How can a sufficient capacity be established for the treatment of the biopulp from the pre-treatment plants? of cascades are not included in this report.

3. What are the requirements for biopulp and biogas plant?

The EU provides relatively unambiguous guidance on how to deal with household waste. The first instruction is that 50% of household waste must be recycled (see Article 11), with a call for Member States to collect household bio-waste for composting or biogasification (see Article 22).[7]

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5 The entire process can be described as follows: Households sort food waste (organic household waste - KOD) into special containers. The source-sorted waste is transported to a pre-treatment plant, which through various processes sorts out incorrect sorting, e.g. metal, plastic, cardboard, etc. The result of this pre-treatment process is called biopulp, which is delivered to biogas plants. In the pre-treatment process, water is added to varying degrees. KOD typically has a dry matter content of 30-35%; while the biopulp due to the water addition will be somewhat ‘thinner’ with a dry matter content of 15-19%. The residual product from the biogas plant is typically called biofertilizer.

6 See the study of i.a. the pre-treatment plants in the report by Ida Køster and Mette Sofie Mortensen: The future treatment of KOD (report in Danish); Special report; January 2017.

7 Cf. Waste Directive, op.cit., Official Journal of the European Union, 22.11.2008, Article 11, L312 / 13; Article 22, L312 / 16.

Household waste will typically consist of three main fractions, namely packaging of almost 40%, organic waste (food waste) of also almost 40% and residual waste of 20%, where the latter can typically only be recovered by waste incineration. As a result of this fraction composition, it is generally believed that the achievement of the target of 50% recycling of household waste can only be done by composting or using the organic fractions in a biogas plant.

In a subsequent interpretation of the rules, the Commission has formulated rules which implies that household waste is considered recycled if the organic part of the household waste is composted or treated at a biogas plant and the residual products from the composting or biogasification may be used in the fields for the benefit of agriculture and the environment. Waste incineration is only considered as energy recovery and not recycling. [8]

The residual product must be able to be used in the fields for the benefit of agriculture and the environment, as stated in EU rules. This means that unwanted substances, e.g. heavy metals, plastic fractions, must be below the limit values or even lower. It places strict demands on the pre-treatment; but it also imposes strict requirements on the other input materials for the biogas plants.

The residual product from the biogas plant - the biofertilizer - may contain source-sorted organic household waste, and can be used by Arlagården (milk-producing agriculture) and by organic agriculture. If sludge is included in the biogas plant, Arlagården, the organic farms and most farms ***must not or will not receive*** the residual product. If for instance source-sorted organic household waste is fed to the digestion tank at a wastewater treatment plant, energy will be produced, but the residual product will not be able to »… be used in the fields for the benefit of agriculture and the environment. Then it only will be a matter of energy recovery and not recycling.

4. The raw materials - the source-sorted household waste

It will be an advantage that a biogas plant on household waste is established close to the city and that the pre-treatment plants are located nearby a waste incineration plant, so that sorted material from the pre-treatment can be fed directly to an incineration plant.[9]

Appendix 1 shows that the total amount of organic household waste is around 194,000 to 205,000 tonnes in the whole area of Zealand. However, it is expected that only between 136,000 and 148,000 tonnes will be collected. This assessment is based on previous experience with different collection systems and housing types. In the following,

[8] Cf. Rules and calculation methods; Commission Decision (draft), November 2011, see here Article 2, section 6.

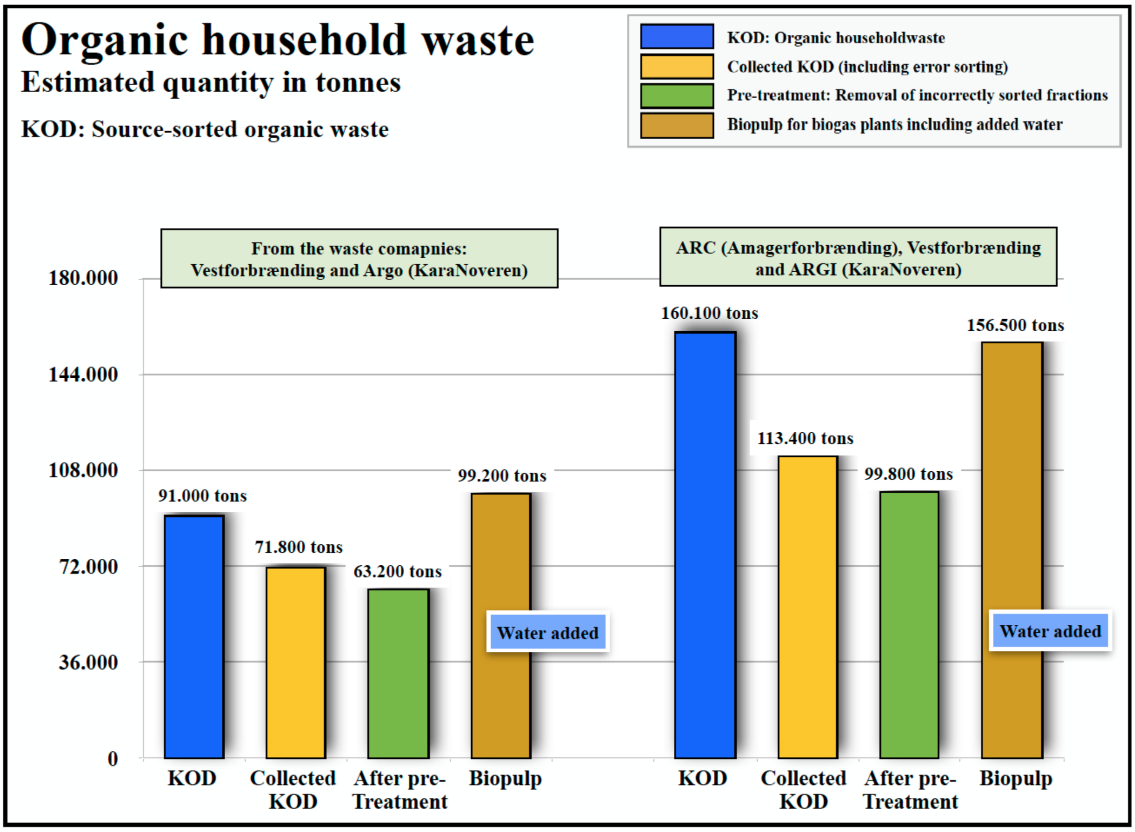
[9] When establishing both pre-treatment plants and biogas plants, the risk of odors and nuisances from heavy traffic, and the distance requirements associated with these conditions, must be taken into account. The organic household waste comes from the cities, which may make it desirable to place the plant as close to the city as possible in order to reduce the transport distance, increase the collection frequency, and the like.

the focus is only on source-sorted organic waste in the following collection areas: Amagerforbrændingen (ARC), Vestforbrænding, KaraNoveren (ARGO).

In accordance with the figures in ***Appendix 1***: A total amount of source-sorted organic household waste of 113,000 tonnes is expected. For Vestforbrænding and ARGO (KaraNoveren), the quantities are expected to be a total of 71,800 tonnes, distributed with 44,200 tonnes for Vestforbrænding and 27,600 tonnes by ARGO's municipalities.

During the pre-treatment, the so-called reject is sorted out, ie. incorrectly sorted material, for instance metal, plastic, etc., which households have mistakenly sorted as organic household waste. During the pre-treatment, some organic material is also lost, the amount of which varies with the different technologies. The benefits of the various pre-treatment technologies are illustrated in more detail in ***Appendix 4*** and are illustrated in more detail with the following overview:

Figure 3 Estimate of the amount of available source-sorted organic household waste (KOD), divided according to the treatment process and divided into the main areas [1] Vestforbrænding and KaraNoveren and [2] Amagerforbrændingen, Vestforbrænding and KaraNoveren, respectively.



There are various biogas catchment options. ***The first option***: There will be 99,200 tonnes of biopulp available, if a pre-treatment and biogas facility is established, covering the catchment areas for Vestforbrænding and Kara-Noveren. ***The second option:*** There will be a total of 156,000 tonnes of biopulp available from the three catchments - the Amager incineration, Vestforbrænding and KaraNoveren. Note that these quantities include the water added in the pre-treatment, which means that the dry matter level in the finished biopulp drops to approx. 15-19%.

Other combinations of the collection catchments area are of course possible. In this context, one must keep in mind that the biopulp collection catchments areas are determined by the two steps, namely collection catchments areas for the pre-treatment plant, and then the delivery from the pre-treatment plants to the biogas plant. [10]

The dry matter content can be a problem. Organic household waste typically has a dry matter content of 30-35%. Water is added at most pre-treatment plants, so that the dry matter content of the biopulp drops to approx. 15-19%. However, this dry matter percentage is still too high for a biogas plant. It is necessary to add liquid/water to bring the dry matter content down to the maximum level for gas-efficient biogas plants, namely 10-12%.

The most obvious liquid/water will be manure, but other liquids can of course not be excluded. The advantage of using manure is, firstly, that the biogas plant is supplied with more NPK (nitrogen, phosphorus and potassium), which is an important prerequisite for the residual product. As previously mentioned, the fertilizer value of the degassed biomass is a prerequisite for being able to call the use in a biogas plant recycling. The second advantage is that use of manure could establish a partnership with farms that both supply manure and receive the biofertilizer from the biogas plant.

Appendix 5 describes the amount of manure that is expected to be available at a location for the plant in the Roskilde area, near Argo (KaraNoveren). Within a distance of up to 20 km, almost 70,000 tonnes of manure are expected to be available with an average transport distance of 15.9 km. At a distance of up to 25 km, around 103,000 tonnes manure will be available with an average transport distance of 18.1 km.

In Appendices 6 and 7, a raw material composition has been calculated. An ideal raw material composition with a maximum dry matter content of approx. 12% leads to two options, where one option is a biogas plant of 160,000 tonnes, based on cattle, pig and mink manure of 60,800 tonnes and 99,200 tonnes of biopulp from Argo (KaraNoveren) and Vestforbrændingen.

The second option consists of a plant of 250,000 tonnes with 156,500 tonnes of biopulp from all three mentioned catchments and 93,500 tonnes of manure. According to the analysis in ***Appendix 5***, the manure for a plant of 160,000 tonnes can be found within a

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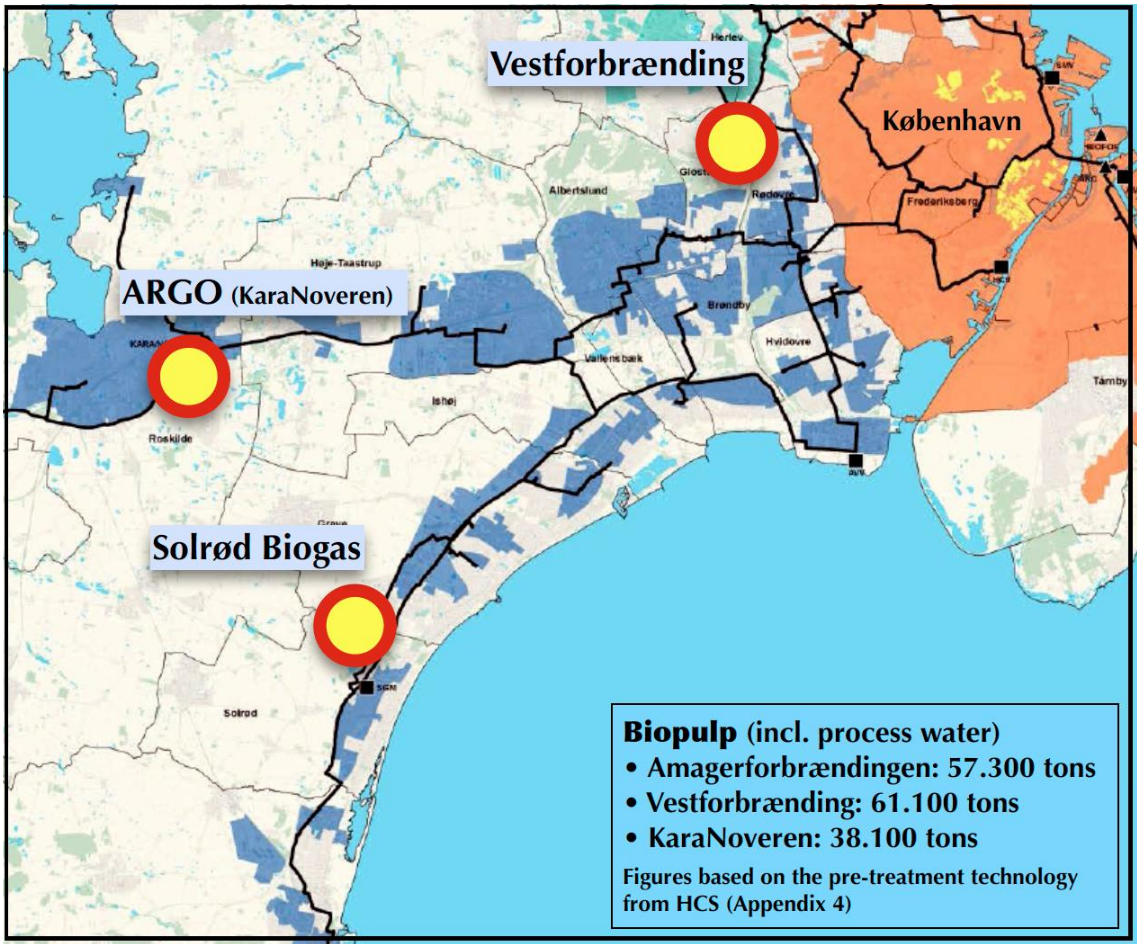
[10] In total, these are the following waste companies, and the number of municipalities and citizens that belong to the individual companies.
- REFA: 2 municipalities with a population of 105,617 people
- Waste plus: 6 municipalities with a population of 305,476 people
- ARC (Amagerforbrænding): 5 municipalities with a population of 805,795 people
- West incineration: 18 municipalities with a population of 735,898 people
- ARGO (Kara / Noveren): 9 municipalities with a population of 418,406 people

Total: 40 municipalities with a total population of 1,541,693 people. This report focuses in particular on Vestforbrænding and Argo, but Affaldplus and ARC are also involved.

distance of 20 km, while the plant of 250,000 tonnes presupposes that the manure is collected at a distance of up to 25 km.

Different placement options can be considered where there is a need to include a number of criteria in the assessments. The starting point here is locations near the two incineration plants, locations in relation to the district heating network and / or the existing natural gas network, transport of manure to the plants and the sale of the plant's residual products. The placement options are illustrated with the figure below:

Figure 4 Possible locations: At Vestforbrænding, at AGRO (KaraNoveren) or at Solrød Biogas.



The figure shows three placement options, each of which has advantages and disadvantages:

- ***A location by Argo (KaraNoveren).*** The advantage of this location is that residual products from the pre-treatment can be fed directly to the incineration plant. If a biogas plant is to be economically feasible, a certain size is required, typically with a capacity of 160,000-250,000 tonnes. It requires a larger investment and a more comprehensive planning of raw material supply and construction of the biogas plant.
- ***A location at Vestforbrændingen*** has the same advantages as a location at Argo, namely that residual products from the pre-treatment can be fed directly into the in-

cineration plant. If the plant is to be feasible, it is also necessary to add liquid / water to the process to reduce the dry matter content of the biopulp. Due to the proximity of a potential facility, it will hardly be able to be based on pig and cattle manure. If necessary, other solutions to this problem must be sought.

- ***A location at Solrød Biogas*** contains several immediately advantages. A third reactor can be added to the existing plant, which means a significantly smaller need for investment, because the technical infrastructure of the existing plant can be used. The plant will be able to be realized with a significantly shorter time horizon. The disadvantage may be that sorted residual waste will not be able to be brought directly to an incineration plant. This must be solved by not placing the pre-treatment plants on the biogas plant, but locating them around the catchment area near waste incineration plants.

The three placement options are the most obvious, but not the only options. Two smaller plants, for instance a plant in connection with a local wastewater treatment plant in Avedøre together with for instance a smaller plant at ARGO (KaraNoveren) might also be a solution.

5. Biogas or waste incineration?

The source-sorted organic household waste is taken out of the incineration. This of course raises the question of whether it is an energy and an environmental advantage to do so.

The question is examined in more detail in ***Appendix 9***. When two technologies are to be compared, there are of course always a number of data problems and comparison difficulties. What calorific value should be used in the calculations of the energy yield in the waste incineration and how large a biogas yield can be estimated, if the same material was used in a biogas plant? In order to be able to compare, the starting point is some expected *standard values* for calorific value and standard values for gas yield. As mentioned, the comparison is examined in more detail in Appendix 9. The main points can be summarized in the following, where the calculations are based on the plant with a yearly capacity of 160,000 tonnes:

Energy:

- ***Biogas production:*** The biopulp of 99,186 tonnes (dry matter 19.1%) gives a gross production of 53,700 MWh. The plant's own consumption of heat in particular reduces net production to 50,400 MWh.
- ***Waste incineration***: The raw material of 62,200 tonnes of organic household waste (equal to the above-mentioned amount of biopulp) gives a gross production of 50,300 MWh, which minus the own consumption of energy gives a net production of 45,900 MWh. This is under the assumption of an efficiency of 85%, which is typical of an incineration plant without flue gas condensation. With flue gas condensation, the efficiency of the plant can be increased to 95%, which will give a net energy produc-

tion of 51,800 MWh. It should be noted, however, that the mentioned efficiencies presuppose the use of auxiliary fuel (natural gas), which in principle must be included in the calculations. It will not be possible to achieve the mentioned efficiencies, if only organic household waste was fired.

Conclusion: In the field of energy, it can be concluded that there is no significant difference between a biogas plant and an incineration plant, especially not if high efficiencies can be assumed for the incineration plant. Waste incineration is from 9% below to 3% above the production at the biogas plant.

Environment and resource performance

- ***Biogas production:*** The biopulp together with the added manure provides a residual product which can be fully utilized. Thus, no waste. Furthermore, the used biopulp contributes 327 tonnes of nutrients (NPK), where the total contribution (including manure raw material input) is 815 tonnes of nutrients. The nutrients of the organic source-sorted household waste have a value of 2.2 mill. DKK with a total value for the entire residual product of DKK 5.9 million. kr.
- ***Waste incineration:*** The residual products cannot be used, but must be disposed. The nutrients are lost. Proportionally calculated, a non-usable residual product of a total of 25,100 tonnes must be expected, where wastewater amounts to 12,400 tonnes and slag, fly ash and sludge amounts to 12,700 tonnes (approx. 20%). Disposal and disposal costs and charges are expected to amount to between DKK 5-8 million. kr.

Climate action

- ***Biogas production:*** Contributes in total to a reduction of a total of 42,200 tonnes CO_2 equivalent (see ***Appendix 13***), where the displacement of fossil energy amounts to 29,500 tonnes.
- ***Waste incineration:*** The contribution will in principle be the same as regards the displacement of fossil energy. Since the electrical efficiency is lower on a thermal cogeneration plant compared to an engine plant, the reduction of greenhouse gases is somewhat smaller; furthermore, there is no effect in relation to reduction of the methane losses from not treated manure. The contribution is expected to be between 23,400-25,100 tonnes (cf. ***Appendix 13*** and ***Appendix 16).***

Conclusion: In the area of environment and resources, there is a significant difference between the utilization of the organic household waste at a biogas plant in compareson with a waste incineration plant. Application of organic household waste to biogas plants represents a circular economic thinking. There are environmental, resource, climate and economic benefits of sending the biological household waste through a biogas plant.

Appendices 11-12 and ***Appendices 14-15*** contain an analysis of investments and operating economics. It is assessed that there is no significant risk associated with the investments. The greatest risk is associated with the gas yield, where a relatively conservative estimate has been assumed with a gas yield of 350 m3 methane per tons of dry matter.

There is also a risk associated with possible changes to existing support schemes. This risk can be covered through a shortest possible depreciation period, where the budget analysis in ***Appendix 12*** and ***Appendix 15*** shows the possibility of a depreciation period of 10 years.

6. Summary

The feasibility analysis can be summarized as follows:

- There is a need in Zealand for the establishment of a biogas capacity for the treatment of source-sorted organic household waste (KOD) with a capacity on 100,000 tonnes to 156,000 tons (see ***Appendix 6 and 7***)
- The capacity need can be solved through the establishment of one or more biogas plants, based on biopulp from established or new pre-treatment plants. If the plant size requires it, the biopulp can be supplemented with other raw materials, for instance pig and cattle manure from agriculture in the catchment areas. A high quality in pre-treatment and in the chossen raw material for the biogas plant can help to ensure the delivery of the high quality biofertilizer to the farmers.
- Several localization options can be pointed out, where the priority is location at Argo (KaraNoveren), Solrød Biogas or at the location of Vestforbrændingen.
- There are a number of environmental and climate benefits from the establishment of a biogas plant, based on source-sorted organic household waste. Such a biogas plant should not be seen as a competitor to waste incineration, but as a symbiotic supplement that can contribute to optimal utilization of waste, resources, recycling with a good economic profit.

The appendices

During the project period, two waste companies changed their name. Both names - the new and old names appear in the report. Here is an overview of new and old names:

- KaraNoveren. New name: ARGO (waste, resources, recycling, profits).
- The Amagerforbrænding (Amager incineration plant). New name: ARC (Amager Resource Center).
- The Vestforbrændingen (West incineration plant)

The appendices, which contain a number of calculations, are only included here in a Danish version. The contents of the individual appendices (table header and table contents) are described in more detail in the following overview, so that you can request translated tables.

Appendix 1: Expected amount of source-sorted organic household waste (KOD)
Total quantities divided into the waste catchments for Amagerforbrænding, Vestforbrænding and KaraNoveren.

Appendix 2: KOD distributed by municipality in Region Zealand
KOD quantities divided into municipalities in the waste catchments to the waste companies REFA, Affaldfaldplus and KaraNoveren.

Appendix 3: KOD distributed by municipality in the Capital Region
KOD quantities divided into municipalities in the waste catchments for Amagerforbrændingen and Vestforbrændingen. The other waste cineration plants in the Capital Region are not included in this overview.

Appendix 4: Biopulp - pre-treatment of KOD
Analysis of input and output of three pre-treatment plants: KomTek in Holsted, HCS in Glostrup and NC Miljø in Holsted. The three technologies have different levels of reject and biomass loss in the pre-treatment process, as well as varying amounts of water added to the produced biopulp.

Appendix 5: Pig- og cattle manure potential at location at Argo (KaraNoveren
The amount of manure, distributed on pig, cattle and mink manure in a catchment area at a distance of 20 km and 25 km, respectively, in relation to the location of the biogas plant near Argo (KaraNoveren).

Appendix 6: Gas yield for a biogas plant of 160,000 tonnes
Plant of 160,000 tonnes capacity will be able to cover the treatment of biopulp from the municipal catchments to Vestforbrænding and KaraNoveren.

Appendix 7: Gas yield for a biogas plant of 250,000 tonnes
Plants of 250,000 tonnes capacity will be able to cover the treatment of biopulp from the municipal catchments to Vestforbrænding, Amagerforbrændingen and KaraNoveren

Appendix 8: Nutrients in the residual product
The expected amount of NPK (nitrogen, phosphorus and potassium) in the residual products from a plant of 160,000 tonnes and from a plant of 250,000 tonnes, as well as cal-‘ culation of the market value of the nutrients.

Appendix 9: Biogas or combustion

Comparison of energy yield by combustion of KOD and by application of KOD in a biogas plant based on the residual products from a plant of 160,000 tonnes. Furthermore, comparison of the environmental effects of the residual products during incineration and during treatment in biogas plants.

Appendix 10: Gas prices and electricity billing prices

In order to calculate the operating economy of the biogas plants, an estimate has been prepared of the expected future subsidies for biogas production. The plant assessments are based on a motor plant, and thus on the basis of electricity billing prices according to current schemes projected for 10 years, corresponding to the expected depreciation period.

Appendix 11: Investment - estimate for a plant for 160,000 tonnes of raw materials

On the basis of unit sums for plant costs for biogas plants with engine plants and / or upgrading plants, the expected investment for the plant is calculated, which is used to estimate the operating economy in Appendix 12.

Appendix 12: Operating economy for a biogas plant of 160,000 tonnes

The operating economy of the plant is calculated on the basis of expected gas production, calculated settlement prices, expected costs for biopulp, transport costs for the supply of manure and application of residual products (biofertilizer) to farmers, as well supply of depreciation and return on plant capital.

Appendix 13: Reduction of greenhouse gases at plants of 160,000 tonnes

Reduction in greenhouse gas emissions includes three main groups of calculations: reduction by displacing fossil energy in electricity and heat production, reduction of methane formation from discarded organic material, and offsetting of greenhouse gas emissions by electricity consumption and transport.

Appendix 14: Investment - estimate for a plant for 250,000 tonnes of raw materials

On the basis of unit sums for plant costs for biogas plants with engine plants and/or upgrading plants, the expected investment for the plant is calculated, which is used to estimate the operating economy in Appendix 15.

Appendix 15: Operating economy for a biogas plant of 250,000 tonnes

The operating economy of the plant is calculated on the basis of expected gas production, calculated settlement prices, expected costs for biopulp, transport costs for the supply of manure and application of residual products (biofertilizer) to farmers, as well as depreciation and return on plant capital.

Appendix 16: Reduction of greenhouse gases at plants of 250,000 tonnes

Reduction in greenhouse gas emissions includes three main groups of calculations: reduction by displacing fossil energy in electricity and heat production, reduction of methane formation from discarded organic material, and offsetting of greenhouse gas emissions by electricity consumption and transport.

Bilag 1: **Forventet mængde organisk husholdningsaffald**

Beregningerne af den samlede mængde husholdningsaffald beregnes gennem følgende trin:

- Antal husholdningerne, opdelt på etageboliger og enfamilieboliger
- Beregning af mængde af organisk husholdningsaffald, baseret på enhedsangivelser, hvor der er anvendt to forskellige metoder (se beregningsforudsætninger i fodnoten).
- Efterfølgende estimeres, hvor stor en mængde der forventes indsamlet (se beregningsforudsætningerne i fodnoten).
- Til brug for de videre beregninger tages der et genmnemsnit af mængderne fra de to forskellige metoder, som er anvendt i beregningerne.

Alle mængder er angivet i tons.

KOD til biogasanlæg på Sjælland

Materiale input Forventet	Befolkning antal indb. [1]	KOD Metode 1 [2]	KOD Metode 2 [3]	Indsamlet Metode 1 [4]	Indsamlet Metode 2 [4]	**Mængde anvendt her søgelsen Se bilag 3**
Affaldsoplandene						
REFA indsamling	103.617	8.821	10.341	6.826	8.129	7.478
Affaldsplus	305.476	25.779	29.643	19.581	22.959	21.270
Amagerforbrænding	805.795	69.032	64.117	42.692	40.327	**41.510**
Vestforbrænding	735.898	57.963	63.137	41.786	46.756	**44.271**
Kara/Noveren	418.406	33.112	38.355	25.329	29.876	**27.603**
Samlet:	2.369.192	194.707	205.593	136.214	148.047	**142.131**
Mængden af KOD - kg pr. År:						
• Mængdde pr. husholdning i kg:		178,8	188,8	125,1	135,9	130,5
• Mængde pr. indbygger i kg:		82,2	86,8	57,5	62,5	60,0

Opland 1: Amagerforbrænding, Vestforbrænding, KaraNoveren

Amagerforbrænding	805.795	69.032	64.117	42.692	40.327	**41.510**
Vestforbrænding	735.898	57.963	63.137	41.786	46.756	**44.271**
Kara/Noveren	418.406	33.112	38.355	25.329	29.876	**27.603**
Samlet:	1.960.099	160.107	165.609	109.807	116.959	**113.383**

Opland 2: Vestforbrænding og KaraNoveren

Vestforbrænding	735.898	57.963	63.137	41.786	46.756	**44.271**
Kara/Noveren	418.406	33.112	38.355	25.329	29.876	**27.603**
Samlet:	1.154.304	91.075	101.492	67.115	76.632	**71.874**

Note:

[1] Befolkningstal efter Danmarks Statistik.

[2] ***Metode 1*** er baseret på materiale fra Miljøstyrelsen: Kortlægning af dagrenovation i Danmark - med fokus på etageboliger og madspild; Miljøstyrelsen, 2014, s. 10, tabel 1.2. De oplyste nøgletal for KOD er: 3,60 kg pr. husstand pr. uge for enfamilieboliger og 3,36 kg pr. husstand pr.uge for etageboliger. Det bemærkes, at miljøstyrelsens tal for dagrenovation i enfamilieboliger stammer fra en undersøgelse fra 2011 (Miljøprojekt nr. 1414.); medens tal for etageboliger er fra 2001.

[3] ***Metode 2*** er baseret på en undersøgelse udført af Affaldplus: Henrik Wejdling, Affaldplus. Nøgletal: 4,5 kg pr. husstand pr. uge for enfamilieboliger og 2,96 kg pr. husstand pr. uge for etageboliger, opgjort i 2014.

[4] Opgørelserne af estimerede mængder reduceres med en forventet indsamlingseffektivitet på 70% hos enfamilieboliger og 50% i etageboliger. Endvidere forventes de indsamlede mængder øget med fejlsorteringer, hvor der antages en fejlsortering på 15%. Kilder til disse opgørelser er vedrørende indsamlingseffektivitet Henrik Wejdling, op.cit. Vedrørende fejlsortering er oplysningerne hentet i talværdien, som stammer fra affaldsanalyser af KOD fra 2.919 enfamilieboliger og 1.626 etagebolige i kommunerne Egedal, Frederikssund, Rødovre, Hillerød, Gribskov, Brøndby og Halsnæs. Analyserne blev udført i 2012 - 2015 af ECONET.

Bilag 2: **KOD kommunefordelt - Region Sjælland**

Samme beregninger som i tabel 1, men opdelt på oplandskommunerne til de enkelte affaldsselskaber i Region Sjælland.

KOD til biogasanlæg

Materiale input Forventet	Befolkning antal indb. [1]	KOD Metode 1 [2]	KOD Metode 2 [3]	Indsamlet Metode 1 [4]	Indsamlet Metode 2 [4]	**Mængde anvendt her søgelsen Se bilag 3**
REFA (2 kommuner)						
Guldborgsund	60.979	5.482	6.416	4.235	5.038	4.636
Lolland	42.638	3.339	3.925	2.591	3.092	2.841
Samlet:	103.617	8.821	10.341	6.826	8.129	**7.478**
Affaldplus (6 kommuner)						
Faxe	35.614	2.921	3.504	2.312	2.802	2.557
Næstved	82.342	6.973	8.037	5.308	6.236	5.772
Ringsted	34.031	2.732	3.059	2.022	2.318	2.170
Slagelse	78.140	6.698	7.456	4.931	5.625	5.278
Sorø	29.543	2.426	2.893	1.909	2.305	2.107
Vordingborg	45.806	4.029	4.694	3.099	3.673	3.386
Samlet:	305.476	25.779	29.643	19.581	22.959	**21.270**
KaraNoveren (9 kommuner)						
Greve	49.518	3.797	4.382	2.894	3.404	3.149
Holbæk	69.972	5.640	6.491	4.288	5.031	4.659
Kalundborg	48.660	4.049	4.814	3.176	3.825	3.501
Køge	59.868	4.684	5.339	3.528	4.106	3.817
Lejre	27.317	1.919	2.376	1.566	1.945	1.755
Odsherred	32.816	2.648	3.194	2.106	2.565	2.335
Roskilde	86.207	7.008	7.733	5.115	5.791	5.453
Solrød	21.788	1.641	1.911	1.261	1.494	1.378
Stevns	22.260	1.726	2.115	1.394	1.718	1.556
Samlet:	418.406	33.112	38.355	25.329	29.876	**27.603**
I alt Region Sjælland	827.499	67.712	78.339	51.736	60.965	**56.351**

Note:

[1] Befolkningstal efter Danmarks Statistik.

[2] ***Metode 1*** er baseret på materiale fra Miljøstyrelsen: Kortlægning af dagrenovation i Danmark - med fokus på etageboliger og madspild; Miljøstyrelsen, 2014, s. 10, tabel 1.2. De oplyste nøgletal for KOD er: 3,60 kg pr. husstand pr. uge for enfamilieboliger og 3,36 kg pr. husstand pr.uge for etageboliger. Det bemærkes, at miljøstyrelsens tal for dagrenovation i enfamilieboliger stammer fra en undersøgelse fra 2011 (Miljøprojekt nr. 1414.); medens tal for etageboliger er fra 2001.

[3] ***Metode 2*** er baseret på en undersøgelse udført af Affaldplus: Henrik Wejdling, Affaldplus. Nøgletal: 4,5 kg pr. husstand pr. uge for enfamilieboliger og 2,96 kg pr. husstand pr. uge for etageboliger, opgjort i 2014.

[4] Opgørelserne af estimerede mængder reduceres med en forventet indsamlingseffektivitet på 70% hos enfamilieboliger og 50% i etageboliger. Endvidere forventes de indsamlede mængder øget med fejlsorteringer, hvor der antages en fejlsortering på 15%. Kilder til disse opgørelser er vedrørende indsamlingseffektivitet Henrik Wejdling, op.cit. Vedrørende fejlsortering er oplysningerne hentet i talværdien, som stammer fra affaldsanalyser af KOD fra 2.919 enfamilieboliger og 1.626 etagebolige i kommunerne Egedal, Frederikssund, Rødovre, Hillerød, Gribskov, Brøndby og Halsnæs. Analyserne blev udført i 2012 - 2015 af ECONET.

Bilag 3: **KOD kommunefordelt - Region Hovedstaden**

Samme beregninger som i tabel 1, men opdelt på oplandskommunerne til de enkelte affaldsselskaber i Region Hovedstaden, dog kun kommunerne til Amagerforbrændingen (Arc) og Vestforbrændingen.

KOD til biogasanlæg

Materiale input Forventet	Befolkning antal indb. [1]	KOD Metode 1 [2]	KOD Metode 2 [3]	Indsamlet Metode 1 [4]	Indsamlet Metode 2 [4]	**Mængde anvendt her søgelsen Se bilag 3**
Amagerforbrændingen (5 kommuner)						
København	591.481	51.070	46.585	31.041	28.653	29.848
Hvidovre	52.831	4.293	4.469	2.962	3.176	3.069
Dragør	14.142	1.071	1.256	829	987	908
Tårnby	42.860	3.362	3.564	2.361	2.575	2.468
Frederiksberg	104.481	9.227	8.243	5.498	4.935	5.216
Samlet:	805.795	69.023	64.117	42.692	40.327	**41.510**
Vestforbrænding (18 kommuner)						
Albertslund	27.880	2.282	2.497	1.653	1.856	1.755
Ballerup	48.224	3.982	4.180	2.769	2.994	2.882
Brøndby	35.322	2.820	2.882	1.912	2.011	1.961
Egedal	42.773	3.060	3.726	2.456	3.013	2.735
Furesø	40.156	3.045	3.470	2.293	2.668	2.481
Frederikssund	44.725	3.364	3.955	2.611	3.116	2.864
Gentofte	75.350	5.930	6.087	4.039	4.268	4.154
Gladsaxe	67.914	5.600	5.838	3.869	4.154	4.012
Glostrup	22.461	1.933	1.993	1.321	1.404	1.362
Gribskov	41.107	2.815	3.440	2.268	2.789	2.529
Halsnæs	31.049	2.379	2.809	1.854	2.220	2.037
Herlev	28.429	2.357	2.562	1.695	1.894	1.795
Hillerød	49.672	3.818	4.263	2.819	3.224	3.021
Høje-Taastrup	49.960	3.832	4.152	2.748	3.060	2.904
Ishøj	22.358	1.679	1.747	1.158	1.241	1.199
Lyngby-Taarbæk	55.097	4.725	4.927	3.266	3.507	3.386
Rødovre	38.002	3.215	3.366	2.231	2.405	2.318
Vallensbæk	15.419	1.127	1.243	824	932	878
Samlet:	735.898	57.963	63.137	41.786	46.756	**44.271**
I alt Region Hovedstaden	1.541.693	126.986	127.254	84.478	87.084	**85.781**

Note:

[1] Befolkningstal efter Danmarks Statistik.

[2] ***Metode 1*** er baseret på materiale fra Miljøstyrelsen: Kortlægning af dagrenovation i Danmark - med fokus på etageboliger og madspild; Miljøstyrelsen, 2014, s. 10, tabel 1.2. De oplyste nøgletal for KOD er: 3,60 kg pr. husstand pr. uge for enfamilieboliger og 3,36 kg pr. husstand pr.uge for etageboliger. Det bemærkes, at miljøstyrelsens tal for dagrenovation i enfamilieboliger stammer fra en undersøgelse fra 2011 (Miljøprojekt nr. 1414.); medens tal for etageboliger er fra 2001.

[3] ***Metode 2*** er baseret på en undersøgelse udført af Affaldplus: Henrik Wejdling, Affaldplus. Nøgletal: 4,5 kg pr. husstand pr. uge for enfamilieboliger og 2,96 kg pr. husstand pr. uge for etageboliger, opgjort i 2014.

[4] Opgørelserne af estimerede mængder reduceres med en forventet indsamlingseffektivitet på 70% hos enfamilieboliger og 50% i etageboliger. Endvidere forventes de indsamlede mængder øget med fejlsorteringer, hvor der antages en fejlsortering på 15%. Kilder til disse opgørelser er vedrørende indsamlingseffektivitet Henrik Wejdling, op.cit. Vedrørende fejlsortering er oplysningerne hentet i talværdien, som stammer fra affaldsanalyser af KOD fra 2.919 enfamilieboliger og 1.626 etagebolige i kommunerne Egedal, Frederikssund, Rødovre, Hillerød, Gribskov, Brøndby og Halsnæs. Analyserne blev udført i 2012 - 2015 af ECONET.

Bilag 4: **Biopulp - Forbehandling af KOD**

Nedenstående oversigt viser input og output på tre forskellige forbehandlingsanlæg. Anlæggene har forskellige virkningsgrader, effektivitet og output. Især bemærkes, at der tilsættes vand - i forskellig omfang; det har betydning for den mængde væske (gylle), der i øvrigt skal tilføres i biogsanlægget. De valgte forbehandlingsanlæg er følgende:

- **KomTek**, baseret på en pulper- og separatorteknologi.
- **HCS**, Glostrup, som er baseret på en kombination af en vaskeproces, en luftstrøm, som frasorter eventuel plast, samt en hammermølle.
- **NC Miljø**, Holsted, hvor forbehandlingen frasorterer de uorganiske fraktioner af glas, metal og plastik, hvorefter en hammermølle fremstiller biopulpen.

Input mængden er baseret på Bilag 1. Det tilførte materiale reduceres med reject (fejlsorteret emner fra kildesorteringen) samt reduceret med et forventet biomasse spild i forbehandlingen. Endvidere forøges mængderne med det vand, der tilsættes i processen

Forbehandling af KOD - input og udbytte samt tørstofindhold
Mængder angivet i tons

Forbehandlings-teknologier	Input til forbe-handling	Reject Frasortret materiale	Tab af biomasse i forbehand.	Biomasse output, eks-klusiv vand	Angivet output i procent af bioinput	**Mængde an-Input ma-triale til biogasanlæg**
Komtek A/S:						
1) Mængden fra Vestforbrænding og KaraNoveren:						
• Input af KOD i tons:	71.874	6.109	3.594	62.171	160,00%	**118.017**
• Input vand i tons:	55.846				***Tørstofindhold biopulp:***	**15,8%**
• Output i tons, angivet i tørstof:						**18.651**
2) Mængden fra Amagerforbrænding, Vestforbrænding og KaraNoveren:						
• Input af KOD i tons:	113.383	9.638	5.669	98.076	160,00%	**186.175**
• Input vand i tons:	88.099				***Tørstofindhold biopulp:***	**15,8%**
• Output i tons, angivet i tørstof:						**29.423**
HCS - (H.C.Svendsen)						
1) Mængden fra Vestforbrænding og KaraNoveren:						
• Input af KOD i tons:	71.874	5.031	3.594	63.249	166,67%	**99.186**
• Input vand i tons:	35.937	-	-		***Tørstofindhold biopulp:***	**19,1%**
• Output i tons, angivet i tørstof:						**18.975**
2) Mængden fra Amagerforbrænding, Vestforbrænding og KaraNoveren:						
• Input af KOD i tons:	113.383	7.937	5.669	99.777	166,67%	**156.469**
• Input vand i tons:	56.692	-	-		***Tørstofindhold biopulp:***	**19,1%**
• Output i tons, angivet i tørstof:						**29.933**
NC Miljø						
1) Mængden fra Vestforbrænding og KaraNoveren:						
• Input af KOD i tons:	71.874	2.875	11.500	57.499	131,25%	**89.843**
• Input vand i tons:	32.343	-	-		***Tørstofindhold biopulp:***	**19,2%**
• Output i tons, angivet i tørstof:						**17.250**
2) Mængden fra Amagerforbrænding, Vestforbrænding og KaraNoveren:						
• Input af KOD i tons:	113.383	4.535	18.141	90.706	131,25%	**141.729**
• Input vand i tons:	51.022	-	-		***Tørstofindhold biopulp:***	**19,2%**
• Output i tons, angivet i tørstof:						**27.212**

Kilde: Egne beregninger på basis af Ida Køster & Mette Sofie Mortensen: Fremtidens behandling af KOD; Speciale, Januar 2017, Roskilde Universitet, s. 39-43. Beregningerne er baseret på det materialeflow, som er oplyst af de pågældende forbehandlingsvirksomheder.

Bilag 5. **Gyllepotentiale ved placering ved KaraNoveren**

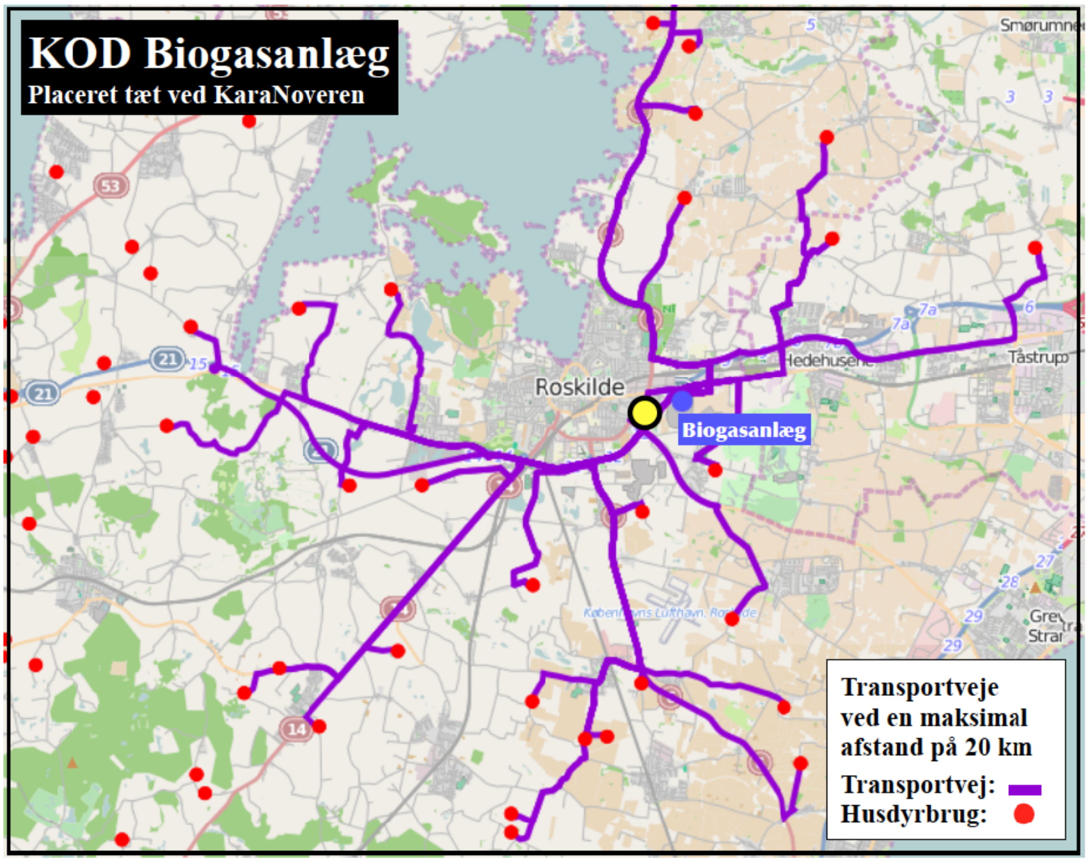
Opgørelserne tager udgangspunkt i et forslag til placering af biogasanlægget tæt ved Kara-Noveren. Gylle råvaregrundlaget er opgjort på følgende måde:

- Gylle ressourcerne, baseret på det CentraleHusdyrRegister's for husdyrbesætninger, opdelt på svine-, kvæg- og minkgylle.
- Gylle ressourcerne i forhold til et opland for biogasanlæggets placering, hvor der er regnet med to muligheder: 1) leverance af alle gylle, 2) leverance af 75% af gyllen

Gylle fra svine-, kvæg- og minkbrug

Opdelt efter gylletype	Alle brug Afstand 20 km i tons	Alle brug Afstand 25 km i tons	Brug med 1.000 tons+ Afstand 20 km i tons	Brug med 1.000 tons+ Afstand 25 km i tons
Svinegylle i tons:	89.029	119.792	87.972	118.723
Kvæggylle i tons:	996	15.495	0	14.090
;imkgylle i tons:	7.769	9.462	5.029	5.029
I alt:	97.795	144.749	93.001	137.842
Forslag til anlægdsimensionering:				
Udgangspunkt for beregningerne - svine- og kvæggylle:			93.001	137.842
Skøn - 25% af gyllen forventes ikke at være tilgængelig:			23.250	34.460
I alt - forventet minimum - maksimum:			**69.750**	**103.381**

Udgangspunkt: Gylleforsyning på 70.000-103.000 tons ved følgende gennemsnitlige transportafstande ved 70.000 tons: 15,9 km; ved 103.000 tons: 18,1 km.



Bilag 6. **Biogasanlæg på 160.000 tons**

Forudsætningen for et anlæg med en samlet råvaremængde på 160.000 tons er følgende:

- Biopulp: 99.186 tons med tørstofindhold på 19,1% (se bilag 4 - HCS-teknologien). Biopulp fra følgende oplande: Vestforbrændingen og KaraNoveren.
- 58.850 tons svinegylle indenfor en kørselsafstand på max. 20 km (se bilag 5).
- 2.000 tons dybstrøelse.
- andre råvarer er naturligvis ikke udelukket, men sammensætningen bør sike, at tørstofindholdet ikke er meget højere end de anførte ca. 12%.

Det bemærkes, at biopulpen er for tør til at kunne omrøres i biogasanlægget. Der er behov for at tilføre væske. Det opnås mest ideelt ved gyllen, fordi det samtidig betyder, at restproduktet opnår et højere indhold af næringsstoffer, især kvælstof.

Biogasanlæg på KOD

Materiale input:	Mængde tons	Tørstof indhold i procent	Organisk tørstof i procent	Tørstof mængde tons	Methan potentiale m3/tons	Forventet bidrag til gasproduktion Ren metan m3
Gylle:						
Svinegylle	48.590	5,5%	80,0%	2.138	290,0	620.008
Kvæggylle	5.510	7,5%	80,0%	331	190,0	62.814
Minkgylle	3.750	6,5%	75,0%	183	350,0	63.984
Dybstrøelse kvæg	3.000	25,0%	80,0%	600	180,0	108.000
Dybstrøelse fjerkræ	0	57,5%	76,0%	0	180,0	0
Hestegødning	0	47,9%	80,0%	0	350,0	0
Energiafgrøder:						
Energiafgrøder (majs)	0	33,0%	97,0%	0	352,0	0
Roer	0	20,0%	92,0%	0	435,0	0
Græs	0	33,0%	90,0%	0	307,0	0
Efterafgrøder						
Olieræddike	0	14,9%	87,2%	0	253,0	0
Gul sennep	0	15,9%	87,2%	0	253,0	0
Andre afgrøder	0	0,0%	0,0%	0	253,0	0
Andre råvarer						
Halm 11%	0	85,0%	97,0%	0	245,0	0
Roetoppe	0	11,6%	85,0%	0	370,0	0
Grødeskær	0	27,0%	98,0%	0	405,4	0
Tang	0	11,7%	98,0%	0	54,0	0
Affaldsfraktioner						
Restprodukter/affald	0	90,0%	97,0%	0	405,4	0
KOD Biopulp (HCS):	**99.186**	**19,1%**	**86,0%**	**16.292**	**350,0**	**5.702.302**
Andre fraktioner	0	0,0%	0,0%	0	0,0	0
Sum	160.036	-	-	19.544	335,5	6.557.109

Tørstofprocent i tilført materiale:	12,2%
Restprodukt - mængder i tons:	148.435 tons
Tørstofprocent i restproduktet:	8,1%
Biogasudbytte - m3 pr tilført tons:	41,0 m3 pr. Tons

Kilde til enhedsfaktorer: Thorkil Birkmose, Kurt Hjort-Gregersen & Kasper Stefanek: Biomasser til biogasanlæg i Danmark - på kort og lang sigt; AgroTek, 2013, og Søren Ugilt Larsen: Energiafgrøder til biogasproduktion; Seminar om biomasse til biogas; Skejby, 25. november 2010. M.V.

Energiproduktion:

Gas - brutto	234.640 GJ	Brændværdi (nedre) metan:	35,784 MJ/m^3
Gas - brutto	65.178 MWh	Brændværdi (nedre) metan:	9,940 KWh/m^3

Omregnet til biogas:

Ren methan:	6,6 Mio. m^3
Biogas (65% metan):	10,1 Mio m^3

Bilag 7. **Biogasanlæg på 250.000 tons**

Forudsætningen for et anlæg med en samlet råvaremængde på 250.000 tons er følgende:

- Biopulp: 156.469 tons med tørstofindhold på 19,1% (se bilag 4 - HCS-teknologien). Biopulp fra føgende oplande: Amagerforbrændingen, Vestforbrændingen og KaraNoveren.
- 90.500 tons svinegylle indenfor en kørselsafstand påmellem 20-25 km (se bilag 5).
- 3.000 tons dybstrøelse.
- andre råvarer er naturligvis ikke udelukket, men sammensætningen bør sike, at tørstofindholdet ikke er meget højere end de anførte ca. 12%.

Det bemærkes, at biopulpen er for tør til at kunne omrøres i biogasanlægget. Der er behov for at tilføre væske. Det opnås mest ideelt ved gyllen, fordi det samtidig betyder, at restproduktet opnår et højere indhold af næringsstoffer, især kvælstof.

Biogasanlæg på KOD

Materiale input:	Mængde tons	Tørstof indhold i procent	Organisk tørstof i procent	Tørstof mængde tons	Methan potentiale m3/tons	Forventet bidrag til gasproduktion Ren metan m3
Gylle:						
Svinegylle	78.102	5,5%	80,0%	3.437	290,0	996.588
Kvæggylle	8.678	7,5%	80,0%	521	190,0	98.930
Minkgylle	3.750	6,5%	75,0%	183	350,0	63.984
Dybstrøelse kvæg	3.000	25,0%	80,0%	600	180,0	108.000
Dybstrøelse fjerkræ	0	57,5%	76,0%	0	180,0	0
Hestegødning	0	47,9%	80,0%	0	350,0	0
Energiafgrøder:						
Energiafgrøder (majs)	0	33,0%	97,0%	0	352,0	0
Roer	0	20,0%	92,0%	0	435,0	0
Græs	0	33,0%	90,0%	0	307,0	0
Efterafgrøder						
Olieræddike	0	14,9%	87,2%	0	253,0	0
Gul sennep	0	15,9%	87,2%	0	253,0	0
Andre afgrøder	0	0,0%	0,0%	0	253,0	0
Andre råvarer						
Halm 11%	0	85,0%	97,0%	0	245,0	0
Roetoppe	0	11,6%	85,0%	0	370,0	0
Grødeskær	0	27,0%	98,0%	0	405,4	0
Tang	0	11,7%	98,0%	0	54,0	0
Affaldsfraktioner						
Restprodukter/affald	0	90,0%	97,0%	0	405,4	0
KOD Biopulp (HCS):	156.469	19,1%	86,0%	25.702	350,0	8.995.559
Andre fraktioner	0	0,0%	0,0%	0	0,0	0
Sum	250.000	-	-	30.442	337,1	10.263.061

Tørstofprocent i tilført materiale:	12,2%
Restprodukt - mængder i tons:	231.842 tons
Tørstofprocent i restproduktet:	8,0%
Biogasudbytte - m3 pr tilført tons:	41,1 m3 pr. Tons

Kilde til enhedsfaktorer: Thorkil Birkmose, Kurt Hjort-Gregersen & Kasper Stefanek: Biomasser til biogasanlæg i Danmark - på kort og lang sigt; AgroTek, 2013, og Søren Ugilt Larsen: Energiafgrøder til biogasproduktion; Seminar om biomasse til biogas; Skejby, 25. november 2010. M.V.

Energiproduktion:

Gas - brutto	367.253 GJ	Brændværdi (nedre) metan:	35,784 MJ/m^3
Gas - brutto	102.015 MWh	Brændværdi (nedre) metan:	9,940 KWh/m^3

Omregnet til biogas:

Ren methan:	10,3 Mio. m^3
Biogas (65% metan):	15,8 Mio m^3

Bilag 8. **Næringsstoffer i restproduktet.**

På grundlag af forskellige nøgletal estimeres der følgende sammensætning af kvælstof, fosfor og kalium i restproduktet fra biogasanlægget med de to forskellige anlægsstørrelser.

Sammensætning af NPK ved anlæg på 160.000 tons og 250.000 tons

Baseret på råvaresammensætningen i Bilag 5 og Bilag 6.

Input	Råvare i tons	Total N kg/tons	**Total N i tons**	NH4-N kg/tons*	**NH4-N i tons**	Fosfor kg/tons	**Fosfor i tons**	Kalium kg/tons	**Kalium i tons**
Anlæg på 160.000 tons									
Svinegylle	48.590	4,15	**201,6**	3,12	**151,4**	1,00	**48,6**	2,15	**104,5**
Kvæggylle	5.510	3,50	**19,3**	2,63	**14,5**	0,80	**4,4**	3,20	**17,6**
Minkgylle	3.750	8,52	**32,0**	2,63	**9,9**	2,00	**7,5**	1,09	**4,1**
Dybstrøelse kvæg	3.000	8,50	**25,5**	2,00	**6,0**	2,50	**7,5**	5,00	**15,0**
Husholdningsaffald	99.186	1,49	**147,8**	1,12	**111,1**	0,22	**21,8**	1,59	**157,7**
I alt input:	160.036	2,66	**426,2**	1,83	293	0,56	90	-	299
Output i tons:*	**149.004**	**2,86**	**426,2**	**2,15**	**319,6**	**0,60**	**89,8**	**2,01**	**298,9**
Hvis KOD alene/output:	89.626	1,65	**147,8**	1,24	**111,1**	0,24	**21,8**	1,76	**157,7**
Lavere nærringstofindhold i %:		58%		58%		40%		88%	
Anlæg på 250.000 tons									
Svinegylle	78.103	4,15	**324,1**	3,12	**243,3**	1,00	**78,1**	2,15	**167,9**
Kvæggylle	8.678	3,50	**30,4**	2,63	**22,8**	0,80	**6,9**	3,20	**27,8**
Minkgylle	3.750	8,52	**32,0**	2,63	**9,9**	2,00	**7,5**	1,09	**4,1**
Dybstrøelse kvæg	3.000	8,50	**25,5**	2,00	**6,0**	2,50	**7,5**	5,00	**15,0**
Husholdningsaffald	156.469	1,49	**233,1**	1,12	**175,2**	0,22	**34,4**	1,59	**248,8**
I alt input:	250.000	2,58	**645,1**	1,83	457	0,54	134	-	464
Output i tons:*	**232.675**	**2,77**	**645,1**	**2,08**	**483,8**	**0,58**	**134,5**	**1,99**	**463,6**

Værdien af næringsstofferne - dagens priser

Anlæg på 160.000 tons	**NPK-mængder**	**Enheds-pris**	**Samlet værdi i millioner kr.**
Kvælstof	426,2 tons	6,94 kr	3,0 mio. Kr
Fosfor	89,8 tons	12,30 kr	1,1 mio. Kr
Kalium	298,9 tons	6,00 kr	1,8 mio. Kr
I alt	814,9 tons	—	**5,9** mio. Kr

Anlæg på 250.000 tons	**NPK-mængder**	**Enheds-pris**	**Samlet værdi i millioner kr.**
Kvælstof	645,1 tons	6,94 kr	4,5 mio. Kr
Fosfor	134,5 tons	12,30 kr	1,7 mio. Kr
Kalium	463,6 tons	6,00 kr	2,8 mio. Kr
I alt	1.243,1 tons	—	**8,9** mio. Kr

Bilag 9: **Biogas eller forbrænding**

Nedenstående analyse skal belyse, hvor effektiv biogasanlægget er i sammenligning med forbrændingsanlæg. Der er to aspekter i sammenligningen af de to anlægstyper, dels sammenligning af energiproduktionen, og dels sammenligning med anlæggenes miljøeffekter.

Forbehandling af KOD - vurdering af energi- og miljøeffektiviteter

Forbehandlingsteknologier Beregnet på anlæg på 160.000 tons	Biogasanlæg udnyttelse af KOD	Forbrændingsanlæg udnyttelse af KOD **Ældre anlæg**	Forbrændingsanlæg udnyttelse af KOD **Nyere anlæg**	
Råvarerne:				
Tilførte mængder i tons:	71.874	71.874	71.874	[1]
Frasorteret - tilført forbrændingsanlæg i tons:	9.703	9.703	9.703	[1]
Råvarer tilført anlæggene (TS på 30%) i tons:	62.171	62.171	62.171	[1]
• Råvarer omregnet til 19,1% tørstof:	99.186	—	—	[2]
• Råvarer omregnet til 35% tørstof:	—	53.289	53.289	[3]
Brændværdi til forbrændingen - GJ/tons:	—	4,0 GJ/tons	4,0 GJ/tons	[3]
• Brændværdi omregnet - kWh/tons	—	1.111,1	1.111,1	
• Anlæggets virkningsgrad (Lov 461):	—	85%	95%	[4]
Energiproduktionen:				
Energiproduktion på biogasanlæg i MWh:	53.713	—	—	[5]
Energiproduktion i alt i MWh:	—	50.329	56.250	[6]
Egetforbrug af energi i MWh:				
• Varme: enhedsfaktor/kWh pr. tons råvarer:	24,0	4,0	4,0	[7]
• El: Enhedsfaktor/kWh pr. tons råvarer:	7,0	83,0	83,0	[7]
• El: Forbehandling kWh pr. tons råvare:	2,8	—	—	[8]
Varmeforbruget anlægget:	2.380	214	214	[9]
Elforbruget på anlægget:	694	4.423	4.423	[9]
Elforbruget i forbehandlingen:	201	—	—	[9]
Netto energiproduktion:	**50.437**	**45.906**	**51.827**	**[10]**
Miljøeffekter - enhedsfaktorer:				
• Anvendelse til gødning (NPK) i tons:	1,4	0,0	0,0	[10]
• Næringsstoffer i anvendt KOD i kg/tons:	5,3	0,0	0,0	[10]
• Spildevand kg/tons	0,0	200,0	200,0	[11]
• Slagger kg/tons:	0,0	171,0	171,0	[11]
• Flyveaske og slam kg/tons:	0,0	33,0	33,0	[11]
Mængderne:				
• Anvendelse til gødning (NPK) i tons:	**99.186**	0	0	[10]
• Næringsstoffer i anvendt KOD i tons:	**327**	0	0	[10]
• Spildevand i tons:	0	**12.434**	**12.434**	[11]
• Slagger i tons:	0	**10.631**	**10.631**	[11]
• Flyveaske og slam i tons:	0	**2.052**	**2.052**	[11]

[1] Se opgørelsen i Bilag 4: tilført mængde minus reject og biomassespild.
[2] Omregningen som følge af forbehandlingsmetoden. Se bilag 4; her er valgt HCS.
[3] Omregnning til standardforudsætninger - 35% tørstof og brændværdi på 4 GJ/tons.
[4] Standardvirkningsgrad på 85%, men 95% for røggaskondenserende anlæg; jvf. lov nr 461, 2009.
[5] Biogasproduktionen på den tilførte biopulp; jvf. Bilag 6, fremhævet linje, omregnet til MWh.
[6] Produktion på forbrændingsanlæg med forudsat brændværdi og virkningsgrad (85% og 95%).
[7] Enhedsforbrug: Biogas, standard efter teknologikataloger; Forbrændingsanlæg: Efter Grønt Regnskab 2015, Vestforbrændingen, beregnet efter hovedtal og efter tabel s. 12.
[8] Oplysninger fra HCS, fra Ida Køster og Mette Sofie Mortensen: Fremtidens behandling af KOD; Roskilde Universitet, Januar 2017, s. 41.
[9] Enhedsfaktorer: Biogas beregnet efter 99.186 tons. Forbrændingen beregnet i forhold til 53.289 tons.
[10] Faktorer for biogas: Se Bilag 8.
[11] Faktorer for forbrænding, baseret på: Grønt regnskab 2015, Vestforbrændingen.

Bilag 10. **Gaspriser og el-afregningspriser**

Til el-produktion baseret på biogas gives der fast årligt beløb pr. produceret kWh. Tilskuddet er godkendt af EU frem til 2023. Det er ikke på forhånd givet, at den eksisterende ordning videreføres efter 2023. Her tages der udgangspunkt i den gældende ordning. Tilskuddet har nogle faste elementer og nogle elementer, der afhænger af prisen på naturgas. Formålet med dette bilag er at vurdere, hvordan dette tilskudselementer udvikler sig. Prisreguleringen har tre grundeelementer:

- Et hovedstøttebeløb, som årligt pristalreguleres. I dag 81,6 øre pr. kWh. Se ***kolonne 3*** nedenfor.
- Et tillæg reguleret efter naturgaspriserne. Udgangspunktet er 26 øre pr. kWh, som reguleres op eller ned afhængig af naturgasprisen, afhlængig af om den er over eller under en pris på 53,20 pr GJ. Falder naturgasprisen med 1 kr/GJ, stiger tilskuddet med 1 øre, og omvendt. ***Kolonne 4***.
- Et midlertidigt tillæg på 10 øre, som aftrappes frem mod 2020. I år 6 øre pr. kWh. ***Kolonne 5.***

Til fremskrivningen af forventet prisudvikling anvendes der følgende fremgangsmåde: Tilskuddet på de 26 øre reguleres den daglige ahead-slutpris på Nordpool gasmarkedet, omregnet til et årligt gennemsnit. Der findes ikke fremskrivninger på denne gaspris. I stedet anvendes den fremskrivning, som Energistyrelsen har udarbejdet frem til 2035, hvor naturgas priserne her er de såkaldte CIF-priser, som er priser, hvor sælger betaler omkostninger fragt og forsikringer. Disse priser er højere end daily ahead-slutpriser; men disse prisers udviklingsmønster bruges her til at forudsige den forventede udvikling i de regulerende gaspriser; se kolonne 2. Årets priser, f.eks. 2016-priserne, anvendes til regulering af 2017-priserne, osv. - således forskudt ét år.

Det bemærkes, at de nedenstående priserne ikke er inflationsreguleret. Priser fra 2014-2017 er løbende priser. Priserne for perioden 2018-2035 er faste priser (priser i årets prisniveau - 2017-priser).

År	Gaspriser CIF-priser kr/GJ [1]	Gaspriser Daily ahead årsgen.snit kr/GJ [2]	Basispris pristals-reguleret øre/kWh [3]	Tillæg 1 Regulering Tillæg øre/kWh [4]	Tillæg 2 10 øres tillægget aftrappes [5]	Biogas el-produktion Samlet pris øre/kWh [6]
2014	-	48,5	-	-	-	
2015	55,3	45,6	80,6	30,7	10,0	121,3
2016	37,7	31,1	81,4	33,6	8,0	123,0
2017	37,9	31,3	81,6	48,1	6,0	135,7
2018	37,5	30,9	81,6	47,9	4,0	133,5
2019	37,2	30,7	81,6	48,3	2,0	131,9
2020	37,0	30,5	81,6	48,5	0,0	130,1
2021	39,4	32,5	81,6	48,7	0,0	130,3
2022	42,7	35,2	81,6	46,7	0,0	128,3
2023	45,0	37,1	81,6	44,0	0,0	125,6
2024	47,2	38,9	81,6	42,1	0,0	123,7
2025	49,3	40,7	81,6	40,3	0,0	121,9
2026	51,3	42,3	81,6	38,5	0,0	120,1
2027	53,2	43,9	81,6	36,9	0,0	118,5
2028	55,0	45,4	81,6	35,3	0,0	116,9
2029	56,7	46,8	81,6	33,8	0,0	115,4
2030	58,3	48,1	81,6	32,4	0,0	114,0
2031	59,3	48,9	81,6	31,1	0,0	112,7
2032	60,2	49,7	81,6	30,3	0,0	111,9
2033	61,0	50,3	81,6	29,5	0,0	111,1
2034	61,8	51,0	81,6	28,9	0,0	110,5
2035	62,8	51,8	81,6	28,2	0,0	109,8

Gennemsnitlige afregningspriser for perioden 2018-2029 - øre pr kWH: 124,680

[1] Forventede naturgaspriser (CIF), Energistyrelsen. Det er de priser, som skal anvendes i de samfundsøkonomiske beregninger i forbindelse med etablering af kollektive forsyningssystemer.
[2] Beregning af daily ahead-priser 2014-16 og forventede daily ahead-priser i periode 2018-2035.
[3] Takster - fast tilskud, pristalsreguleret. Vi regner i faste priser; derfor ingen regulering her.
[4] Tillæg på 26 øre, reguleret efter prisafvigelser (kolonne 1) i forhold til udgangspunktet på en gaspris på 53,2 kr pr. GJ og et tilskud på 26 øre pr. kWh.
[5] Tillæg 2: Tillæg på 10 øre, som aftrappes og bortfalder med udgangen af 2019.
[6] Forventet afregningspris for elproduktion baseret på biogas for periode 2018-2035.

Bilag 11. **Anlægsoverslag: For 160.000 tons råvarer**

Anlægsberegningerne er baseret på bilag 6 med 160.036 tons med KOD som hovedråvarer suppleret med gylle for at sikre, at tørstofindholdetbikke ikke overstiger et niveau på ca. 12%.

Tabellen giver et overslag over anlægsomkostningerne for et biogasanlæg med en behandlingskapacitet på 160.000 tons. Der anvendes en beregningsmetode, der er baseret på enhedsomkostninger. Der beregnes både en anlægssum for et biogasanlæg med opgradering og et anlæg med motoranlæg.

Enhedsomkostningerne er hentet fra Energistyrelsens Teknologikatalog.*) Erfaringsmæssigt hører overslagene fra Teknologikataloget til i den højere ende. Der er anvendt følgende enhedsomkostninger:

Opgraderingsanlæg:

- Enhedsomkostning for alle anlægsomkostninger til selve biogasanlægget: 380 kr/tons råvarer. Mindre prisregulering i forghold til Teknologikataloget.
- Enhedsomkostninger til opgraderingsanlæg: 18,0 kr/m3 rågas.

Biogasanlæg med motoranlæg:

- Dimensionering fra el-siden: Hvor stort et kapacitetsbehov vil der være på motorsiden, hvis anlægget skal producere med en rådighedsfaktor på 98%, dvs. skal producere i alt i 8.585 timer pr år.
- Enhedsomkostning for biogasanlæg inklusiv motoranlæg: 30,0 mio kr pr MW.

Anlægsomkostninger biogasanlægget til 160.000 tons

	Biogasanlæg u.motor med opgradering	Enhed	**Biogasanlæg med motor Kraftvarme**	Enhed
Råvare i tons	160.036	tons	160.036	tons
Gasproduktion i kubikmeter metan:	6.557.109	m3	6.557.109	m3
Gasproduktion i kubikmeter biogas (m3):	10.087.860	m3	-	-
Gasproduktion i MWh:	-	-	65.178	MWh
Rådighedsfaktor:	95	%	98	%
Antal driftstimer årligt:	8.322	timer/år	8.585	timer/år
Gasproduktion pr time:	1.212	m3/time	-	-
Energiindhold	-	-	65.178	MWh
El-produktion. Virkningsraden for el-produktion: 41%		-	26.723	MWh
El-produktion - nødvendig kapacitet:	-	-	3,1	MW
Enhedsomkostning anlæg uden motor:	380	kr/tons RV	-	-
Enhedsomkostning opgraderingsanlæg:	18,0	kr/m3 rågas	-	-
Enhedsomkostning biogasanlæg m. motor:	-	-	30,0	mio/MW
Anlægssum biogasanlæg uden motor:	60,8	Mio.kr	-	-
Opgraderingsanlæg:	31,8	Mio.kr	-	-
Anlægssum for biogasanlæg med motor	-	-	93,4	Mio.kr
Anlægssum i alt:	**92,6**	**Mio.kr**	**93,4**	**Mio.kr**

Oplysningerne er som nævnt aseret på tallene i Energistyrelsens teknologikatalog. Erfaringer fra de seneste år viser, at man kan regne med lavere anlægsomkostninger end ovenstående tal.

*) Technology Data for Energy Plants, Energinet.dk og Energistyrelsen, Maj 2012, s. 185-197.

Bilag 12. **Driftsøkonomi på 160.000 tons**

Beregningerne skal give et overblik over økonomien i anlægget. Det forudsættes, at anlægget ikke har opgraderings- eller motoranlæg. Beløbet er gennemsnitstal for anlæggets udgifter og driftsresultater over de første 10 år.

	Forudsat	Enheder	**Beregning**	Enheder	**Note**
Samlet råvaremængde	160.036	tons			[1]
Gasudbytte - ren metan	6.557.109	m3			[1]
Gasudbytte - biogas	10.087.860	m3	Omregnet til 65% metan		[1]
Gasudbytte i MWh:	65.178	MWh	Efter nedre brændværdi		[2]
Metan, forventet tab:	0,5%	MWh			
Biogas til motoranlæg:	**64.852**	**MWh**			
Eget forbrug varme	3.841	MWh	24	kWh/tons	[3]
Omsætning/Indtægter					
Afregningspris:	524,30	kr/MWh	34,002	Mio. D.kr	[4]
Indtægter i alt:			**34,002**	**Mio. D.kr**	
Drift og vedligeholdelse					
Biopulp - leveret ab anlæg:	180	kr/tons	11,385	Mio. D.kr	
Biogas - drift og vedligehold:	36,75	kr/tons RV	5,881	Mio. D.kr	[5]
Transport - tur/retur, lager:	0,95	kr/tonkm	3,161	Mio. D.kr	
Elforbrug på anlægget:	0,80	kr/kWh	0,896	Mio. D.kr	[6]
Variable udgifter i alt:			**21,324**	**Mio. D.kr**	
Anlægsinvesteringer					
- Biogas anlæg - kun anlæg:			60,800	Mio. D.kr	[7]
- Motoranlæg:			32,600	Mio. D.kr	[7]
Total Investering:			93,400	Mio. D.kr	
Afskrivning og forretning:			10,782	Mio. D.kr	
- Afskrivningsperiode:	10	år			[8]
- Forrentning:	2,7%	p.a.			[8]
Kapitalomkostninger i alt:			**10,782**	**Mio. D.kr**	
Samlede udgifter på biogasanlægget:			**32,106**	**Mio. D.kr**	
Resultat før skat:			**1,896**	**Mio. D.kr**	

[1] Se Bilag 6.
[2] Gasudbyttet i MWh er angivet med den nedre brændværdi på 9,940 kWh/m3 metan.
[3] Egetforbruget af varme (opvarmning af biogasreaktor) baseres på dels varmeveksling med restproduktet og dels anvendelse af overskudsvarme fra anlæggets motoranlæg. Se også her note 4.
[4] Den anvendte afregningspris er baseret på opgørelserne baseret på følgende principper: Anlægget modtager en forventet el-pris, beregnet i bilag 10 (elvirkningsgrad på 51%). Endvidere sælges varme fra motoranlægget til 25 øre pr. kWh (varmevirkningsgrad på 55%). Ikke hele varmen sælges, idet der bruges 3.841 MWh til opvarmning af biogasreaktoren. Efter afholdte af udgifter til drift og vedligehold af motoranlægget forventes der en gennemsnitlig indtægt på 524,30 kr pr. MWh.
[5] Technology Data, op.cit., s. 191: Drift & vedligeholdelse på 36,75 kr/tons råvare, og transport til/fra anlægget på 0,90 kr/tonkm.
[6] Svarer til anvendelse af 7 kWh elektricitet pr. tons råvarer.
[7] Se beregningerne i bilag 11.
[8] De anvendte forudsætninger i beregningen af kapitalomkostningerne efter annuitetsprincippet. Finansieringen er baseret på Kommunekredit, incl. garantiprovision.

Bilag 13. **Drivhusgasser ved 160.000 tons**

Beregningen af drivhusgasudledningen er opdelt på to typer af udledninger:

- Reduktion af udledninger, som skyldes (a) fortrængning af fossil energi fra produktion af el og varme på biogas; (b) reduktion af den metandannelse, som naturligt vil finde sted fra det organiske materiale (fra gyllen, fra anden generations biomasser, osv.)
- Udledninger fra forbrug af fossil energi: (a) fra elforbruget på anlægget, og (b) fra transporten på lastbil til og fra biogasanlægget.

Beregningerne og grundlaget for beregningerne fremgår af oversigten nedenfor:

• Vedvarende energi - fortrængning af fossil energi's drivhusgasemissioner			
Forventet el-produktion fra motoranlæg:	26.589	MWh	[1]
Udnyttet varme fra de to anlæg:	35.669	MWh	
Fortrængning af el produceret på kulkraft - faktor:	0,835	tos/Wh	
Fortrængning af fossil energi til varmeforbrug (naturgas):	0,204	MWh	
Fortrængning af drivhusgasser:	**29.489**	**tons**	[3]
• Reduktion fra metandannelse fra organisk materiale			
Metandannelse ved anvendelse af rågylle:			
Metan fra gylle (under opbevaring og efter udspredelse):	20%		[4]
Metan fra svine- og kvæggylle (se Bilag 6):	854.806	m3	[5]
Forventet udledning af metan emission fra svin og kvæg:	170.961	m3	[6]
Emission omregnet til tons (0,717 kg/m3):	122,6	tons	[7]
Omregnet til drivhusgas ækvivalent (faktor 25):	3.064	tons	[8]
Metandannelse fra henlagt organisk materiale:			
Metan fra organisk materiale - procenttab i forhold til udrådning:	10%		[4]
Metan fra andre råvarer 2. generation råvarer (se tabel 6):	5.702.302	m3	[5]
Forventet metandannelse som henlagt materiale:	570.230	m3	[6]
Emission omregnet til tons (0,717 kg/m3):	408,9	tons	[7]
Omregnet til drivhusgas ækvivalent (faktor 25):	10.221	tons	[8]
Samlet reduktion ved opsamling af metan i et biogasanlæg:	**13.286**	**tons**	
• Elektricitetsforbrug:			
El-forbrug på anlæg - 7 kWh pr. tons råvare:	1.120,0	MWh	[9]
El-forbrug til andre formål (se note):	0,0	MWh	[10]
Samlet elektricitetsforbrug på anlægget:	1.120,0	MWh	
Forventet udledning af drivhusgasser - emissionsfaktor (d.d.):	205	gram/kWh	[11]
Udledning af drivhusgasser ved elforbrug:	**-230**	**tons**	
• Transport på lastbil af input og output på anlægget):			
Samlet transport, opgjort i tonkm (ind- og udtransport):	3.327.632	tonkm	[12]
Drivhusgas udledning pr. tonkm:	0,095	kg/tonkm	[13]
Udledning af drivhusgasser ved transport:	**-316**	**tons**	
• Samlet drivhusreduktion:			
Samlet reduktion modreget drivhusgasudledninger fra transport og elforbrug:	**42.229**	**tons**	

Noter:
[1] Se opgørelsen i Bilag 6 og Bilag 12.
[2] Emissionsfaktor for gasolie/dieselolie; jvf. Energistyrelsen, Standardfaktorer; Januar 2017.
[3] Den forventede fortrængning, hvis biogas anvendes kraft/varmeproduktion.
[4] Anslåede procenter. Metandannelsen varierer med temperaturen, idet den er størst om sommeren.
[5] Biogasproduktionen fra svine- og kvæggylle, samt dybstrøelse fra kvæg; jvf. Bilag 6.
[6] Metanemission uden biogasanlægget, omregnet på basis af heholdsvis 20% og 20%.
[7] Omregnet baseret på biogassens vægtfylde på 717 gram pr. m3.
[8] Metan's drivhusækvivalent, ansat til faktor 25, jvf. UNFCCC/CP/2013/10/Add.3; 31 January 2014.
[9] Forventet elforbrug pr. tons råvarer. Varierer mellem 7-12 kWh; her er antaget 7 kWh pr. tons.
[10] Der vil være et mindre elforbrug på omrøre i tankanlæg, som ikke er medtaget her.
[11] Udledningen drivhusgasser for el-produktionen i 2016 Energinet.dk, Miljødeklarationer (125%-metoden).
[12] Transportbehovet opgjort som tilførsel på 160.000 tons og frakørsel på 148.435 tons med en gennemsnitlig afstand på 15,9 km.
[13] Forventet drivhusgas udledning pr. tonkm på mellemstor lastbil. Kilde Dataark fra European Environment Agency Term27-2012 Assessmet, hvor der angives en udledning af drivhusgasser for lastbiler på 0,075 kg pr. tonkm. Andre kilder angiver dog højere emissioner, hvorfor der her forsigtigvis anvendes en faktor på 0,095 kg pr. tonkm. Jvf eksempelvis miljøredegørelse 2016 ICT/Logistics.

Bilag 14. **Anlægsoverslag: For 250.000 tons råvarer**

Anlægsberegningerne er baseret på bilag 7 med 250.000 tons med KOD som hovedråvarer suppleret med gylle for at sikre, at tørstofindholdetbikke ikke overstiger et niveau på ca. 12%.

Tabellen giver et overslag over anlægsomkostningerne for et biogasanlæg med en behandlingskapacitet på 250.000 tons. Der anvendes en beregningsmetode, der er baseret på enhedsomkostninger. Der beregnes både en anlægssum for et biogasanlæg med opgradering og et anlæg med motoranlæg.

Enhedsomkostningerne er hentet fra Energistyrelsens Teknologikatalog.*) Erfaringsmæssigt hører overslagene fra Teknologikataloget til i den højere ende. Der er anvendt følgende enhedsomkostninger:

Opgraderingsanlæg:

- Enhedsomkostning for alle anlægsomkostninger til selve biogasanlægget: 380 kr/tons råvarer. Mindre prisregulering i forghold til Teknologikataloget.
- Enhedsomkostninger til opgraderingsanlæg: 18,0 kr/m3 rågas

Biogasanlæg med motoranlæg:

- Dimensionering fra el-siden: Hvor stort et kapacitetsbehov vil der være på motorsiden, hvis anlægget skal producere med en rådighedsfaktor på 98%, dvs. skal producere i alt i 8.585 timer pr år.
- Enhedsomkostning for biogasanlæg inklusiv motoranlæg: 30,0 mio kr pr MW

Anlægsomkostninger biogasanlægget til 250.000 tons

	Biogasanlæg u.motor med opgradering	Enhed	**Biogasanlæg med motor Kraftvarme**	Enhed
Råvare i tons	250.000	tons	250.000	tons
Gasproduktion i kubikmeter metan:	10.263.061	m3	10.263.061	m3
Gasproduktion i kubikmeter biogas (m3):	15.789.325	m3	-	-
Gasproduktion i MWh:	-	-	102.015	MWh
Rådighedsfaktor:	95	%	98	%
Antal driftstimer årligt:	8.322	timer/år	8.585	timer/år
Gasproduktion pr time:	1.897	m3/time	-	-
Energiindhold	-	-	102.015	MWh
El-produktion. Virkningsraden for el-produktion: 41%		-	41.826	MWh
El-produktion - nødvendig kapacitet:	-	-	4,9	MW
Enhedsomkostning anlæg uden motor:	380	kr/tons RV	-	-
Enhedsomkostning opgraderingsanlæg:	18,0	kr/m3 rågas	-	-
Enhedsomkostning biogasanlæg m. motor:	-	-	30,0	mio/MW
Anlægssum biogasanlæg uden motor:	95,0	Mio.kr	-	-
Opgraderingsanlæg:	49,8	Mio.kr	-	-
Anlægssum for biogasanlæg med motor	-	-	146,2	Mio.kr
Anlægssum i alt:	**144,8**	**Mio.kr**	**146,2**	**Mio.kr**

Oplysningerne er som nævnt aseret på tallene i Energistyrelsens teknologikatalog. Erfaringer fra de seneste år viser, at man kan regne med lavere anlægsomkostninger end ovenstående tal.

*) Technology Data for Energy Plants, Energinet.dk og Energistyrelsen, Maj 2012, s. 185-197.

Bilag 15. **Driftsøkonomi på 250.000 tons**

Beregningerne skal give et overblik over økonomien i anlægget. Det forudsættes, at anlægget ikke har opgraderings- eller motoranlæg. Beløbet er gennemsnitstal for anlæggets udgifter og driftsresultater over de første 10 år.

	Forudsat	Enheder	**Beregning**	Enheder	**Note**
Samlet råvaremængde	250.000	tons			[1]
Gasudbytte - ren metan	10.263.061	m3			[1]
Gasudbytte - biogas	15.789.325	m3	Omregnet til 65% metan		[1]
Gasudbytte i MWh:	102.015	MWh	Efter nedre brændværdi		[2]
Metan, forventet tab:	0,5%	MWh			
Biogas til motoranlæg:	**101.505**	**MWh**			
Eget forbrug varme	6.000	MWh	24	kWh/tons	[3]
Omsætning/Indtægter					
Afregningspris:	524,30	kr/MWh	53,219	Mio. D.kr	[4]
Indtægter i alt:			**53,219**	**Mio. D.kr**	
Drift og vedligeholdelse					
Biopulp - leveret ab anlæg:	180	kr/tons	17,960	Mio. D.kr	
Biogas - drift og vedligehold:	36,75	kr/tons RV	9,188	Mio. D.kr	[5]
Transport - tur/retur, lager:	0,95	kr/tonkm	5,595	Mio. D.kr	
Elforbrug på anlægget:	0,80	kr/kWh	1,400	Mio. D.kr	[6]
Variable udgifter i alt:			**34,142**	**Mio. D.kr**	
Anlægsinvesteringer					
- Biogas anlæg - kun anlæg:			95,000	Mio. D.kr	[7]
- Motoranlæg:			51,200	Mio. D.kr	[7]
Total Investering:			146,200	Mio. D.kr	
Afskrivning og forretning:			16,878	Mio. D.kr	
- Afskrivningsperiode:	10	år			[8]
- Forrentning:	2,7%	p.a.			[8]
Kapitalomkostninger i alt:			**16,878**	**Mio. D.kr**	
Samlede udgifter på biogasanlægget:			**51,020**	**Mio. D.kr**	
Resultat før skat:			**2,199**	**Mio. D.kr**	

[1] Se Bilag 7.

[2] Gasudbyttet i MWh er angivet med den nedre brændværdi på 9,940 kWh/m3 metan.

[3] Egetforbruget af varme (opvarmning af biogasreaktor) baseres på dels varmeveksling med restproduktet og dels anvendelse af overskudsvarme fra anlæggets motoranlæg. Se også her note 4.

[4] Den anvendte afregningspris er baseret på opgørelserne baseret på følgende principper: Anlægget modtager en forventet el-pris, beregnet i bilag 10 (elvirkningsgrad på 51%). Endvidere sælges varme fra motoranlægget til 25 øre pr. kWh (varmevirkningsgrad på 55%). Ikke hele varmen sælges, idet der bruges 6.000 MWh til opvarmning af biogasreaktoren. Efter afholdte af udgifter til drift og vedligehold af motoranlægget forventes der en gennemsnitlig indtægt på 524,30 kr pr. MWh.

[5] Technology Data, op.cit., s. 191: Drift & vedligeholdelse på 36,75 kr/tons råvare, og transport til/fra anlægget på 0,95 kr/tonkm.

[6] Svarer til anvendelse af 7 kWh elektricitet pr. tons råvarer.

[7] Se beregningerne i bilag 14.

[8] De anvendte forudsætninger i beregningen af kapitalomkostningerne efter annuitetsprincippet. Finansieringen er baseret på Kommunekredit, incl. garantiporovision.

Bilag 16. **Drivhusgasser ved 250.000 tons**

Beregningen af drivhusgasudledningen er opdelt på to typer af udledninger:

- Reduktion af udledninger, som skyldes (a) fortrængning af fossil energi fra produktion af el og varme på biogas; (b) reduktion af den metandannelse, som naturligt vil finde sted fra det organiske materiale (fra gyllen, fra anden generations biomasser, osv.)
- Udledninger fra forbrug af fossil energi: (a) fra elforbruget på anlægget, og (b) fra transporten på lastbil til og fra biogasanlægget.

Beregningerne og grundlaget for beregningerne fremgår af oversigten nedenfor:

• Vedvarende energi - fortrængning af fossil energi's drivhusgasemissioner			
Forventet el-produktion fra motoranlæg:	41.617	MWh	[1]
Udnyttet varme fra de to anlæg:	55.828	MWh	
Fortrængning af el produceret på kulkraft - faktor:	0,835	tos/Wh	
Fortrængning af fossil energi til varmeforbrug (naturgas):	0,204	MWh	
Fortrængning af drivhusgasser:	**46.156**	**tons**	[3]
• Reduktion fra metandannelse fra organisk materiale			
Metandannelse ved anvendelse af rågylle:			
Metan fra gylle (under opbevaring og efter udspredelse):	20%		[4]
Metan fra svine- og kvæggylle (se Bilag 7):	1.267.502	m3	[5]
Forventet udledning af metan emission fra svin og kvæg:	253.500	m3	[6]
Emission omregnet til tons (0,717 kg/m3):	181,8	tons	[7]
Omregnet til drivhusgas ækvivalent (faktor 25):	4.544	tons	[8]
Metandannelse fra henlagt organisk materiale:			
Metan fra organisk materiale - procenttab i forhold til udrådning:	10%		[4]
Metan fra andre råvarer 2. generation råvarer (se tabel 6):	8.995.559	m3	[5]
Forventet metandannelse som henlagt materiale:	899.556	m3	[6]
Emission omregnet til tons (0,717 kg/m3):	645,0	tons	[7]
Omregnet til drivhusgas ækvivalent (faktor 25):	16.125	tons	[8]
Samlet reduktion ved opsamling af metan i et biogasanlæg:	**20.669**	**tons**	
• Elektricitetsforbrug:			
El-forbrug på anlæg - 7 kWh pr. tons råvare:	1.750,0	MWh	[9]
El-forbrug til andre formål (se note):	0,0	MWh	[10]
Samlet elektricitetsforbrug på anlægget:	1.750,0	MWh	
Forventet udledning af drivhusgasser - emissionsfaktor (d.d.):	205	gram/kWh	[11]
Udledning af drivhusgasser ved elforbrug:	**-359**	**tons**	
• Transport på lastbil af input og output på anlægget):			
Samlet transport, opgjort i tonkm (ind- og udtransport):	5.889.233	tonkm	[12]
Drivhusgas udledning pr. tonkm:	0,095	kg/tonkm	[13]
Udledning af drivhusgasser ved transport:	**-559**	**tons**	
• Samlet drivhusreduktion:			
Samlet reduktion modreget drivhusgasudledninger fra transport og elforbrug:	**65.906**	**tons**	

Noter:
[1] Se opgørelsen i Bilag 6 og Bilag 12.
[2] Emissionsfaktor for gasolie/dieselolie; jvf. Energistyrelsen, Standardfaktorer; Januar 2017.
[3] Den forventede fortrængning, hvis biogas anvendes kraft/varmeproduktion.
[4] Anslåede procenter. Metandannelsen varierer med temperaturen, idet den er størst om sommeren.
[5] Biogasproduktionen fra svine- og kvæggylle, samt dybstrøelse fra kvæg; jvf. Bilag 7.
[6] Metanemission uden biogasanlægget, omregnet på basis af heholdsvis 20% og 20%.
[7] Omregnet baseret på biogassens vægtfylde på 717 gram pr. m3.
[8] Metan's drivhusækvivalent, ansat til faktor 25, jvf. UNFCCC/CP/2013/10/Add.3; 31 January 2014.
[9] Forventet elforbrug pr. tons råvarer. Varierer mellem 7-12 kWh; her er antaget 7 kWh pr. tons.
[10] Der vil være et mindre elforbrug på omrøre i tankanlæg, som ikke er medtaget her.
[11] Udledningen drivhusgasser for el-produktionen i 2016 Energinet.dk, Miljødeklarationer (125%-metoden).
[12] Transportbehovet opgjort som tilførsel på 250.000 tons og frakørsel på 231.842 tons med en gennemsnitlig afstand på 18,1 km.
[13] Forventet drivhusgas udledning pr. tonkm på mellemstor lastbil. Kilde Dataark fra European Environment Agency Term27-2012 Assessmet, hvor der angives en udledning af drivhusgasser for lastbiler på 0,075 kg pr. tonkm. Andre kilder angiver dog højere emissioner, hvorfor der her forsigtigvis anvendes en faktor på 0,095 kg pr. tonkm. Jvf eksempelvis miljøredegørelse 2016 ICT/Logistics.

PYROLYSIS WITH THATCHING MATERIAL COMMON REED (PHRAGMITES AUSTRALIS) IN MECKLENBURG-WESTERN POMERANIA OR MECKLENBURG-VORPOMMERN

COLOURBOX31721058

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Project acronym BioBIGG

Work package Work package 5: Implementation of innovative agro-industrial value-chains and biomass-based production in SME's

Deliverable: Deliverable 5.2: Pre-feasibility and innovation programmes for innovative value chains

Published by: BioBIGG

Abbreviations

BioBIGG	Bioeconomy in the South Baltic Area: Biomass-based Innovation and Green Growth
bld	below limit of detection
ca.	circa
DM	Dry matter
e.g.	Exempli gratia
EPA	Environmental Protection Agency
H.	Heft (English - magazine)
HVRT	Hot vapour residence time
LAGA	Bund/Länder Arbeitsgemeinschaft Abfall - Federal / State Working Group on Waste
RT	Residence time
S.	Seite (English - page)
t/ton	Metric tonne
TRL	Technology Readiness Level
u.	und (English - and)
Wt	Weight
WW	Wet weight
MWP	Mecklenburg West-Pomerania (Mecklenburg Vorpommern/MV)
ha	hectare
°C	Degree Celsius

1 Introduction

Common reed (from this point onwards only 'reed') is a typical wetland plant found all over the with an ancient history of utilisation, mostly for thatching. There are references to the use of roof thatching in northern Europe in the last ice age.[1] And some regions are nowadays still famous for their thatched roofs.

Mecklenburg West-Pomerania (MWP) has a long coast with wide marsh regions and reed beds, the tradition of reed thatching still prevails today. Several thousand houses are roofed with this renewable ressource which has to be renewed every 30-40 years. After its service on the roof, half and half of the material go either into incineration plants or compost plants. In any case, the material is not overly welcome in neither one of them due to some problems in the further processing.

This Pre-feasibility study aims to investigate the afteruse of old thatching reed. Pyrolysis is identified to be a promissing technique for reusing old thatching read, thus was selected to be further investigated.

Pyrolysis

Definition: *Chemical decomposition of compounds caused by high temperatures*. [2]

Three products are always produced during the process: solid char, condensable liquids (bio oil or tar), and permanent gasses. Depending on the mode of pyrolysis and the raw material, the yield of every product varies.

[1] Schaatke, W. (1992): Das Reetdach - Natürliches Wohnen unter sanftem Dach - Von der Uhrzeit bis heute (The Reed Roof - Natural Living Under a Soft Roof - From Primeval Times Until Today). Christians Verlag, Hamburg, 264 pp.

[2] Collins English Dictionary – Complete and Unabridged, 12th Edition,(2014) HarperCollins Publishers

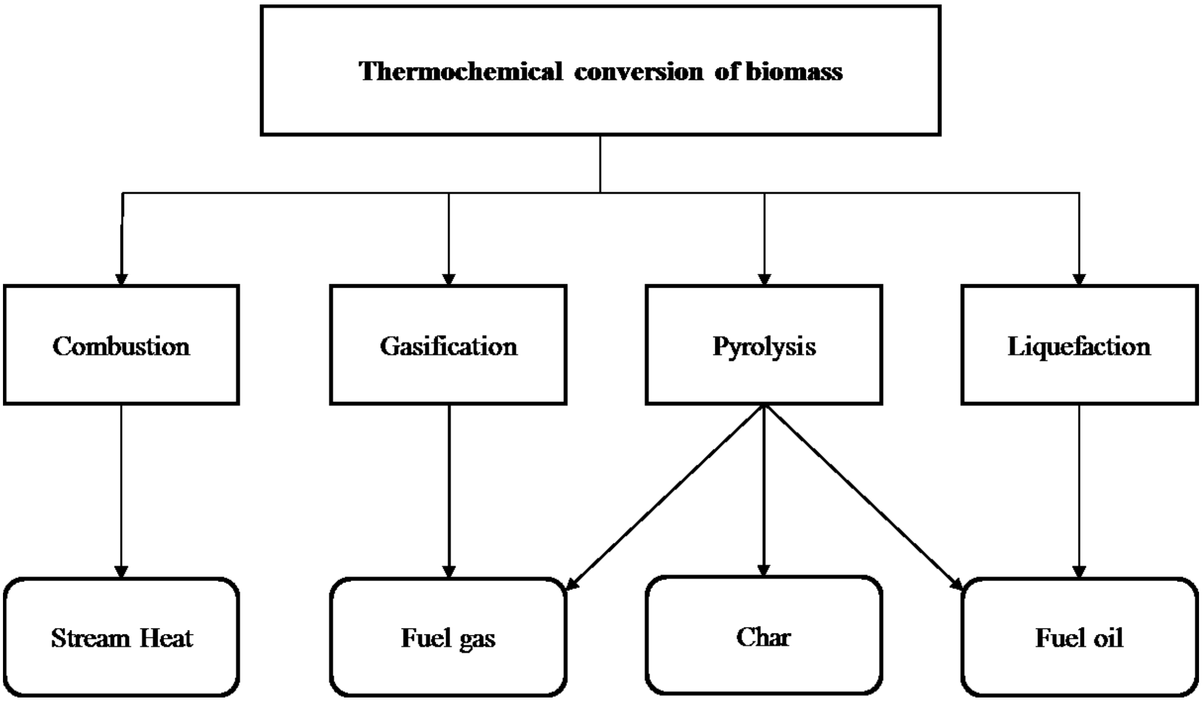

Figure 1: Thermochemical conversion processes of biomass.
Extracted from: Ibrahim, B. (2018): Investigation of the applicability of wetland biomass for producing hydrochar by hydrothermal carbonization and its effectiveness for the adsorption of ammonia (doctoral dissertation).
Original literature: Zhang et al., 2010; Balat et al., 2009

Bio-char and bio-oil and gas are produced when reed undergoes the process of pyrolysis.This PFS will specifically focus on the production of bio-char.

During the research process, one pyrolysis bio-char production plant in MWP was found:

GreenCarbon GmbH [3]
Sülter Weg 1
19077 Uelitz
Deutschland

This company mainly pyrolises wood and other types of biomass in smaller quantities. They have successfully tested the pyrolysation of fresh reed, whilst no tests have been conducted using old thatching reed. Caroline Dräger, the management assistant of the company, expressed an interest in undertaking a larger test series, if interested collaboration partners would lead the necessary activities, for instance providing the test-material and research about possible end products from the charcoal. She pointed out that the tests and research are essential before accepting old thatching reed as pyrolysis material for their plant.[4]

Pyrolysis at GreenCarbon GmbH:

The plant uses eight retorts with a capacity of about four cubic meters. The raw material gets shredded with a mobile shredder in order to fit into theretort. Details depend on the raw material. A crane will

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[3] GreenCarbon GmbH. Impressum page. Last access 18 September 2020. http://www.greencarbon-gmbh.de/impressum.html
[4] Telephone interview with Caroline Dräger 19 May 2020

put the shredded material into the retort which will be left open and heated to 100-105°C. This pre-heat serves to prepare the steel for the process and to vaporise residual moisture from the biomass. For the next step the lid will be closed. Pyrolysis bases on heating in the absence of oxygen. Inside the heating reactor, the material will stay for a minimum of 160 up to 240 minutes at 600-850°C. The temperature and time depend on the material. When all organic materials have decomposed, the retort will be put into a sand bath for 24 hours to cool down.Subsequently, metals will be sorted out by a metal detector. Last step is to sieve the char to different sizes. Liquids vaporise, gases are instantly used for pre-heating the next retort and heating the fresh biomass drying area next to the reactor. [5]

2 Technology Readiness Level (TRL)

Technology Readiness Level (TRL) of this project concept cannot be entirely defined. On the one hand, the before mentioned pyrolysis plant has TRL 9. Most biomass types are proven suitable materials, including fresh reed.[6] On the other hand, without having tried out the process with old thatching reed, success cannot be 100% sure. This lowers the whole project concept TRL of 3-4. Reed tilers state that reed halms laying beneath the first 5cm layer of weathered reed are as good as new[7]. One study about compost properties made from old thatching reed analysed properties of the material and found no precarious components.[8] In case, after a few tests in the pyrolysis plant, old thatching reed proves to be suitable for the company, consequently the project concept would quickly reach TRL 9.

3 Definition of Project Concept

Reed background

Properties of Common reed (*Phragmites australis)*

Scientific Name: *Phragmites australis (Cav.) Trin. ex Steud.*

Common reed is a typical perennial wetland plant spread over the whole world with an ancient history of utilisation, mostly for thatching. It belongs to the botanical family of Poaceae and can grow up to heights of 4m with stems between 0.5 to 1.5 cm in diameter. [9] The plant is very easy to identify.

[5] Telephone interview with Michaela Schuldt 30 July 2020
[6] Telephone interview with Michaela Schuldt 23 April 2020
[7] Telephone interview with Tom Hiss 26 November 2019
[8] Schaecke, B. u. a. (2000): Eignung von Reet alter Rohrdächer als Kompostrohstoff - Schadstoffbelastung und wertgebende Inhaltsstoffe. In: Tagungsband III. Dialog Abfallwirtschaft, Universität Rostock.
[9] Tilley, D.J., and L. St. John. 2012. Plant Guide for common reed (Phragmites australis). USDA-Natural

Figure 2: Common reed in winter, source: Paul Schulze, Humboldt-Universität zu Berlin.

Table 1 shows the Ellenberg indicator values for reed. It is a classification system for ecologic properties and reactions of plants. The scale ranges from 1 to 9 for light, temperature, reaction, nutrients and salinity. Moisture has 12 scaling values. Reed is perfectly flexible to grow in all inland (periodically) wet areas, especially in modern eutrophic environments in Europe.[10]

Indicator	***Value***	***Explanation***
Light	7	half-light plant, mostly occurring at full light, but also in the shade up to about 30% of diffuse radiation incident in an open area
Temperature	5	moderate heat indicator, from lowland to montane belt, mainly in submontane-temperate areas
Moisture	10	aquatic plant that survives long periods without soil flooding
Reaction	7	indicator of slightly acidic to slightly basic conditions, never occurring in very acidic conditions
Nutrients	7	occurring at nutrient-rich sites more often than at average sites and only exceptionally at poor sites
Salinity	0	not salt tolerant, glycophyte
Continentality	x	indifferent
Life form	A	Hydrophyt or Geophyt

Table 1: Ellenberg indicator values (Ellenberg & Leuschner 2010, translated from German)

[10] Ellenberg, Heinz; Leuschner, Christoph (2010): Vegetation Mitteleuropas mit den Alpen: in ökologischer, dynamischer und historischer Sicht

Though Ellenberg claims to have found no salinity tolerance, Tilley et al. state otherwise: 'Common reed is found in highly saline areas including salty tidal marshes and inland saline playas.' [9]

Reed is able to quickly populate large areas due to its extensive system of scaly rhizomes and stolons, which allow the plants to spread into dense monotypic stands.[9] The above ground biomass production varies highly depending on environmental conditions and harvesting periods.

Above ground biomass production	12,5 to 23,8 t DM/ha[11]
Moisture content	Varies through the season, Ø 15 % [12]
Hemicellulose	20.4-28.8% (stems) 29.3-31.1% (leaves) [13]
Neutral detergent fibre	77.8-82.4% (stems) 63.6-64.5% (leaves) [13]
Acid detergent fibre	49.0-60.8% (stems) 32.5-35.8% (leaves) [13]
Acid detergent Lignin	6.5-9.0% (stems) 3.1-6.5.8% (leaves) [13]
Mineral content (ash)	4,1-5,7% [14]

Table 2: Properties of reed

3.1 Harvesting and processing *Phragmites australis*

There are various methods for harvesting reed. In case of thatching material winter is the preferred time for harvest. The plant is dry, nutrients are stored in the roots and, in the best case, the soil is frozen. That makes the best conditions for harvesting with heavy machinery. There are caterpillar vehicles designed especially for grounds with low bearing capacity. Nowadays there even are machines that cut and tie reed completely automatically into ready-to-use thatching reed bundles. Those loose bundles make ventilation desiccation possible when storing.

For higher quality, the shorter and thinner stems have to be sorted out. The leftovers could possibly be gathered and used for pyrolysis as well. This would happen during the winter, when roof thatching is at down-season.

[11] Zerbe, S., Steffenhagen, P., Parakenings, K., Timmermann, T., Frick, A., Gelbrecht, J., Zak, D.: Environmental Management (2013) 51: 1194. Ecosystem Service Restoration after 10 Years of Rewetting Peatlands in NE Germany, p. 1202.

12 Wichmann, S., Wichtmann, W. (2009): Bericht zum Forschungs- und Entwicklungsprojekt. Energiebiomasse aus Niedermooren (ENIM)

[13] Dragoni, Federico & Giannini, Vittoria & Ragaglini, G. & Bonari, Enrico & Silvestri, Nicola. (2017). Effect of Harvest Time and Frequency on Biomass Quality and Biomethane Potential of Common Reed (Phragmites australis) Under Paludiculture Conditions. BioEnergy Research, p. 1069-1071.

[14] Wichtmann, W., Oehmke, C., Bärisch, S., Deschan, F., Malashevich, U., Tanneberger, F.: Combustibility of biomass from wet fens in Belarus and its potential as a substitute for peat in fuel briquettes. In: Mires and Peat, Volume 13 (2013/14), Article 06, 1–10

Figure 3: Presentation of the Paludi-caterpillar at the conference "Reed as a renewable resource" in Greifswald 2013, source: Paul Schulze, Humboldt-Universität zu Berlin

3.2 *Phragmites australis* for roof thatching

Until the late 1800s, reed and straw were the only roofing materials in Europe. [15] Master of MWP Guild of reed thatchers, Rainer Carls, says that a roof up to 100 m² can be thatched with the yield of two hectares.[16] In 1988, the Rural Development Commission stated that with good technical and professional practice, a roof should have a durability of 50-60 years. In best cases, a roof can live up to 100 years[17]. According to the MWP Guild of reed thatchers the times of such long durability are over. Environmental influences and reed quality nowadays lead to a durability of 30-40 years. A new kind of lignolytes, a fungus type that nourishes on lignin, has establishes itself on thatched roofs. As lignin is a major substance of reed, its decaying process proceeds much faster. Another accelerating factor is the higher content of nitrogen, along other nutrients, in the air. Algae that live in the first weathering layer of the reed contribute to its faster decay.[16]

A reed roof needs maintenance and care to achieve a long lifetime. Once a year the company Hiss Reet (www.hiss-reet.de) recommends a cleaning of moss and algae so that it can dry off easier after a rain.[18] The upper weathered layer falls down automatically or can be taken down manually. When the thickness of the roofing is down to half of its primary 30-40 cm, the whole roofing has to be renewed to ensure stability.

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[15] Iital, A.; Klõga, M.; Kask, Ü.; Voronova, V.; Cahill, B. (2012): Reed harvesting. In: Schultz-Zehden, A. & Matczak, M. (eds.) Compendium: An Assessment of Innovative and Sustainable Uses of Baltic Marine Resources, Maritime Institute in Gdansk, Gdansk, 103–124.

[16] Telephone interview with Rainer Carls 20 November 2019

[17] Rural Development Commission, 1988. The Thatcher's Craft. First published 1960. London

[18] Hiss Reet. Maintenance of thatched roofs. https://www.hiss-reet.de/reetdach/wartung-pflege/pflege-wartung/?L=1 . Last access 15 November 2019

3.3 *Phragmites australis* after roof thatching

Rainer Carls explained that when taking down the old thatching, the reed is transported to block heating stations or to composting plants. Thatchers reported to him that some plant operators do not accept the old reed anymore. They had often found residual metal wires in the reed, as the wires were not removed properly when taking down the reed from the roofs. Those metal wires have to be manually removed by the plant operator since being out of stainless steels. These metals do not react to magnetism and cannot be sorted out of the loose material by a magnet, as is common practice with other metals. Using galvanized wires instead of stainless steel wires should solve this problem because they are able to decompose.[19] Gerd Werner from the composting plant 'Produktionsschule Wolgast' has made his thatcher-clients only use compostable wires and reports no problems since then.[20]

The reed may also cause problems for composting plants with its long decomposition time. Better results are achieved by adding decomposing bacteria to the compost. Reed still needs more time to decompose than other green waste due to its woody characteristics.

According to the experience of Tom Hiss, only the upper layer (5cm) is affected by the weather. It would be weathered, wet and covered with moss, lichen and fungus. After visual inspection the under layers still seem as good as new. However additional tests would be necessary to see if the constant changes of humid and dry air have influenced the underlying material as well.

Schaecke and Kape conducted a study about suitability of old thatching reed as resource for composting. They checked on waste load of persistent organic pollutants and heavy metals as well as valuable components. None of the results exceeded the limits of different official German legal regulations.[21] Detailed results can be seen in the following three tables.

To summarize this chapter, in theory, there are no organic or chemical impediments for the pyrolysis of old thatching reed.

[19] Telephone interview with Rainer Carls 28 May 2020

[20] Telephone interview with Gerd Werner 5th June 2020

[21] Schaecke, B. u. a. (2000): Eignung von Reet alter Rohrdächer als Kompostrohstoff - Schadstoffbelastung und wertgebende Inhaltsstoffe. In: Tagungsband III. Dialog Abfallwirtschaft, Universität Rostock.

	Polychlorinated biphenyls (PCB_6 28 – 180) (each component number) mg/kg DM	Polycyclical aromatic hydrocarbons (PAH_{16}, Sum after EPA) mg/kg DM	Dibenzodioxins and furans PCDD/PCDF	selected chlorinated hydrocarbons CHC (21 i.a. lindane, aldrin, dieldrin, endrin) for each CHC-component mg/kg DM	Volatile halogenated hydrocarbons VHH (6 i.a. dichloromethane, trichloromethane, tetrachloroethene) for each VHH-component mg/kg DM
Old thatching reed	bld - 0.002	0.520 – 0.988	1.03 – 5.07	bld - 0.995	bld
Compost from biowaste Communication no. 10 from LAGA in 1995	0.01 – 0.1	0.800 – 4.220	2 - 40	-	-
Limit values from the Biowaste Ordinance for compost Orientation values	0.033	-	17.0	-	-
Sewage sludge ordinance (1992)	0.2	-	100	-	-
Guide value for soil use (BGA 1990)	-	-	<5 (unlimited use in agr./gardening)	-	-

Table 3: Persistent organic pollutants in old thatching reed in comparison to different official German legal regulations. Found in and translated from: Schaecke, B. u. a. (2000): Eignung von Reet alter Rohrdächer als Kompostrohstoff - Schadstoffbelastung und wertgebende Inhaltsstoffe. In: Tagungsband III. Dialog Abfallwirtschaft, Universität Rostock. P. 37
Original literature: LAGA-Merkblatt M 10 (1995) Qualitätskriterien und Anwendungsempfehlungen für Kompost Klärschlammverordnung (AbfKlärV 1992), Bioabfallverordnung (BioAbfV 1998)
Rieß, P. (1993) Entsorgungspraxis-Spezial, H. 9, S. 6-13
Haag, R. u.a. (1994) Wasser, Luft u. Boden, H. 10, S. 86-88
Leifeld, J. u.a. (1996) Wasser u. Boden, H. 11, S. 17-23
Marb, C. u.a. (1997) Müll u. Abfall, H 10, S 609-620
Krauß, P. u.a. (1997) Müll u. Abfall, H. 4, S. 211-221

			Location/object of sample taking of old thatching reed			
fresh reed		**Heavy metal**	**Zirkow *Hallenhaus (traditional building from northern Germany)***	**Elmenhorst Residential building**	**Torgelow Barn**	**Massow Combined barn and residential building**
1.0 -	3.0	lead	4.86	4.32	5.31	6.31
0.01 -	0.08	cadmium	0.10	0.14	0.12	0.11
0.35 -	0.55	chrome	0.89	1.25	1.40	1.26
4.5 -	13.0	copper	4.83	6.18	7.31	5.64
2.0 -	4.0	nickel	5.47	10.56	6.34	9.69
bld -	0.06	mercury	0.05	0.06	0.01	0.05
6.5 -	30.0	zinc	55.80	91.50	140.0	31.2

Table 4: Heavy-metal pollution of old thatching reed in four different samples from MWP. Found in and translated from: Schaecke, B. u. a. (2000): Eignung von Reet alter Rohrdächer als Kompostrohstoff - Schadstoffbelastung und wertgebende Inhaltsstoffe. In: Tagungsband III. Dialog Abfallwirtschaft, Universität Rostock. P. 29

Biowaste	**lead**	**cadmium**	**chrome**	**copper**	**nickel**	**mercury**	**zinc**
Old thatching reed	4.31 - 6.31	0.10 - 0.14	0.89 - 1.40	4.83 - 6.18	5.47 - 9.69	0.01 - 0.06	31.2 - 140
Crop straw	19	0.95	18	32	4	bld	100
Bark	20 - 57	0.6 - 2.1	30 - 63	23 - 60	12 - 20	0.1 - 0.5	150 - 300
Wood chaff	12 - 53	0.1 - 0.2	8 - 40	8 - 16	4 - 13	0.1	58 - 137
Organic waste	24 - 138	0.2 - 0.9	28 - 86	5 - 31	9 - 27	0.1 - 3.5	30 - 138
Compost from biowaste (x 1991 - 1995)	64	0.64	30	43	18	0.22	196
Limit value 20t/ha	150	1.5	100	100	50	1.0	400
Biowaste Ordinance 1998 30 t/ha	100	1.0	70	70	35	0.7	300

Table 5: Heavy-metal pollution of old thatching reed in comparison to other organic materials. Found in and translated from: Schaecke, B. u. a. (2000): Eignung von Reet alter Rohrdächer als Kompostrohstoff - Schadstoffbelastung und wertgebende Inhaltsstoffe. In: Tagungsband III. Dialog Abfallwirtschaft, Universität Rostock. P. 30
Original literature: Thomé-Kozmiensky, K. J. (1994) Abfallwirtschaftsjournal H. //8, S. 477-494
Bioabfallverordnung (BioAbfV) 1998
Zeitschrift Humuswirtschaft u. Kompost 1996 H. 3, S. 8 u. 32
Krauß, P. u. Wilke, M. (1997) Müll u. Abfall H. 4, S. 211-219

Biowaste	Organic matter (ignition loss) % DM	Total N % DM	P (total) % DM	K (total) % DM	Mg (total) % DM	Ca. (total) % DM	pH
Old thatching reed	92 - 95	0.51 - 0.69	0.02 - 0.03	0.10 - 0.13	0.01 - 0.02	0.04 - 0.09	3.2 - 4.4
Crop straw	94	0.4 - 0.8	1.0	1.74	0.12	0.29	-
Bark	92	0.5 - 1.0	0.01 - 0.03	0.02 - 0.05	0.02 - 0.06	0.36 - 0.72	-
Wood chaff	75	0.2 - 0.4	0.44	0.25 - 0.42	0.06 - 0.09	0.36 - 0.72	-
Organic waste	30 - 75	0.6 - 20.	0.04 - 1.0	0.33 - 2.82	0.12 - 0.90	0.29 - 5.0	-
Compost from organic waste	25 - 45	0.8 - 1,7	0.17 - 0.52	0.5 - 1.24	0.20 - 1.24	1.43 - 4.5	7 - 8.3

Table 6: Valuable components of old thatching reed in comparison to other organic materials.
Found in and translated from: Schaecke, B. u. a. (2000): Eignung von Reet alter Rohrdächer als Kompostrohstoff - Schadstoffbelastung und wertgebende Inhaltsstoffe. In: Tagungsband III. Dialog Abfallwirtschaft, Universität Rostock. P. 41
Original literature: LAGA-Merkblatt M 10 (1995) Qualitätskriterien und Anwendungsempfehlungen für Kompost
Thomé-Kozmiensky, K.J. (1994) Abfallwirtschaftsjournal H. 7/8, S 477-494
Autorenkollektiv (1999) UBA-Abschlussbericht/Nr. 1450 638 C8 Nährstofffreisetzung bei der Kompostierung und Vergärung

4 Regional market situation

Mecklenburg-Western Pomerania (MWP) is located in the northeast of Germany. It shares borders with Brandenburg in the south, Lower Saxony in the south-west and Schleswig-Holstein in the west, as well as to the Polish region Pomerania in the east. The north of MWP is the coast to the Baltic Sea. MWP has a total area of 23.213km².[22]

The local demand in Germany exceeds the local supply by far. In 2008, only 15% of the demand for thatch in Germany could be met by regional production. Imported material mainly comes from Eastern Europe, such as Hungary, Rumania, Ukraine, or from China. 10.000ha would be necessary to meet the German demand. A survey in 2016 showed that in Mecklenburg-Western Pomerania there are 10 companies to harvest about 550 ha. Most of it is located near Greifswald University which has expertise in this area, as they support and facilitate new studies and projects. Only 2ha were located in western MWP.[23]

The guild of reed thatching companies of MWP currently has 17 members. The guild estimates that an additional number of 20-40 companies exist who are not members however most of them being very small and consisting of only one person. 17 guild members and 30 non-guild members makes an estimate of **47 reed thatchers** in total.

Each company builds or renovates two to three **(Ø 2,5) roofs every year**. The average roof in MWP has 150-180m² (**Ø 165m²**). As explained earlier, when the old roof has to be renewed, it will be down to half of its initial thickness and weight. That means, one has to calculate with **25kg per m²**.

To form an estimate of how much old thatching reed is available in MWP every year, all the average figures were multiplied with each other.

47 x 2,5 x 165 x 25 = 484687,5 (~485.000) kg

It is very important to keep the relations between the total number and the distribution of reed thatched houses in regard to the location of the existing pyrolysis plants in mind.

The grand majority of reed-thatched houses can be found near the coast and on the islands. Currently, there is no data available to estimate how much old thatching reed per year would exactly be available for the pyrolysis plant near Schwerin. Currently, the old thatching reed is used or in compost plants or in block heating stations. The company aims to keep the distance to biomass suppliers as low as possible to save money for the transportation and personnel. For a renovation of a roof, 4.125kg old reed needs to be transported to the plant. Costs for the deposit vary between 65€/t and 200€/t. By selecting the cheaper destination when it is farther away than the expensive destination, one would still not save on costs. This is due to the high personnel costs of the truck driver and the high rental costs of the truck to reach the destination. 30-50km are the average.[24]

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[22] Webseite MV Land zum Leben Daten und Fakten 31.7.2020, https://www.mecklenburg-vorpommern.de/ueber-das-land-zum-leben/daten-und-fakten/

[23] LM M-V (2017): Umsetzung von Paludikultur auf landwirtschaftlich genutzten Flächen in Mecklenburg-Vorpommern. Fachstrategie zur Umsetzung der nutzungsbezogenen Vorschläge des Moorschutzkonzeptes. Ministerium für Landwirtschaft und Umwelt Mecklenburg-Vorpommern, Schwerin. P.22

[24] Telephone interview with Rainer Carls 28 May 2020

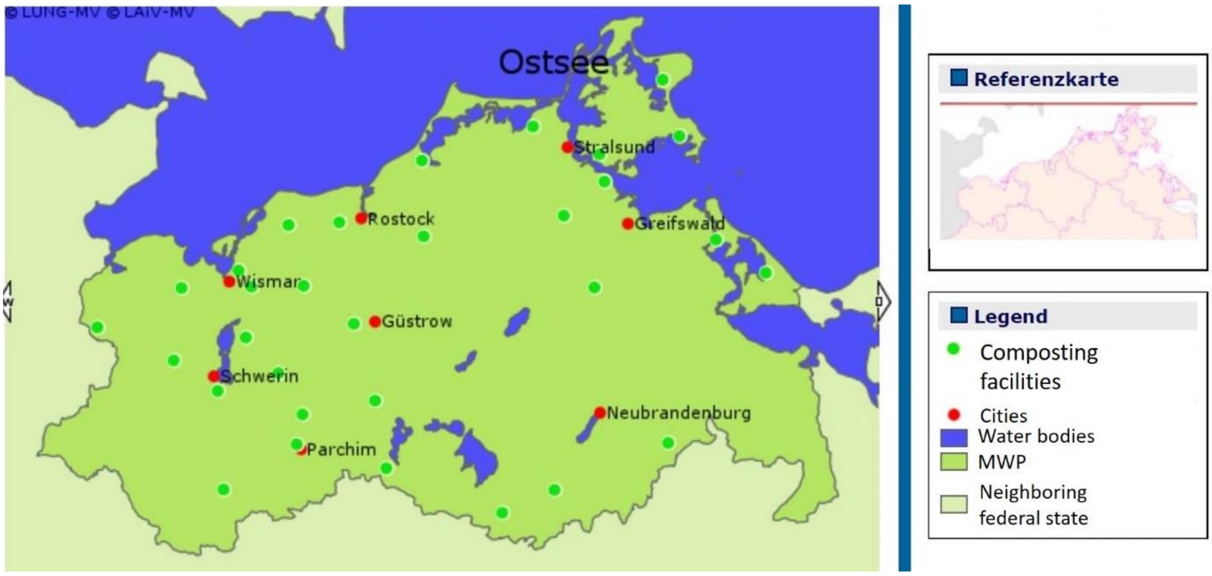

Figure 4: Locations of composting facilities in MWP. https://www.umweltkarten.mv-regierung.de/atlas/script/index.php

The situation might change if the material would be seen as a valuable biomass instead of waste. The pyrolysis plant proposed a system of three categories for the material, depending on its state of decomposition:

1 - low quality - pyrolysis plant receives money for the deposition

2 - middle quality – pyrolysis plant and supplier remain equal

3 – high quality – pyrolysis plant pays the supplier with a certain amount of €

With this new aspect, the profitable transport distance could reach up to 100km. [4]

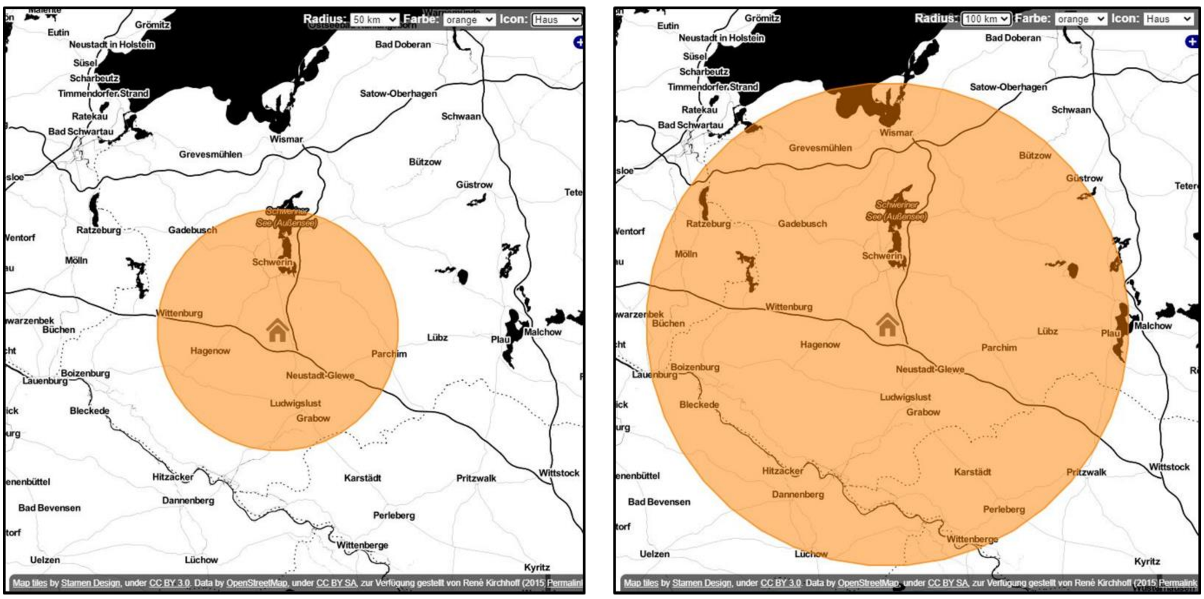

Figure 5: Radius of 50km (left) and of 100 km (right) around the pyrolysis plant. http://www.nozhove.de/osm/umkreis.html

4.1 Bio-Char End-Products

So far, in Germany bio-char has found several applications within the agricultural area. Either as supplement for feeding to animals or as littering, soil conditioner or supplement for biogas plants. [25]

The pyrolysis plant produces Terra Preta with a part of its self-made bio-char. [26] The most conceivable solution for their reed char would be to add it to the same process. At the moment only small amounts of thatching reed can be expected to be transported to the plant. Hence, a separate product line for reed char would be pointless.

Still, alternatives with more economic impact should be investigated. A short desk research about reed bio-char brought forth articles about filtering capacities of the char, for example:

- Yang Z., Chen J., 2017, Preparation, Characterization and Adsorption Performance of Reed Biochar, Chemical Engineering Transactions, 62, 1243-1248.
- Cui, L., Chen, T., Yin, C., Yan, J., Ippolito, J., and Hussain, Q. (2019). "Mechanism of adsorption of cadmium and lead ions by iron-activated biochar," BioRes. 14(1), 842-857.
- Mosley LM, Willson P, Hamilton B, Butler G, Seaman R. The capacity of biochar made from common reeds to neutralise pH and remove dissolved metals in acid drainage. Environ Sci Pollut Res Int. 2015 Oct; 22(19):15113-22.
- Zhao, C., Ma, J., Li, Z., Xia, H., Liu, H., & Yang, Y. (2020). Highly enhanced adsorption performance of tetracycline antibiotics on KOH-activated biochar derived from reed plants. RSC advances, 10, 5066-5076.

4.2 Why go for pyrolysis?

As mentioned in chapter 3, both compost and incineration plants complain about loose metal wires. They have to pick it out manually because the stainless steel wires do not react to magnetism and cannot be sorted out by a magnet. GreenCarbon say that it’s no problem because they sieve the char after the pyrolysis process and would find the wires. [6]

Composting plants complain also about the slow decomposition. Reed is a rather tough material and many composting plants won’t accept the reed. [16]

The thermal use of reed in incineration plants is problematic. This is because of the high chlorine content of the reed. Chlorine reacts in flue gas with sodium and potassium to chlorides, which are highly aggressive and attack the steel of the boilers and pipes, especially at high temperatures. Even the ashes can lead to problems because the softening point compared to other fuels is relatively low. The ashes can then become sticky, which also leads to problems in the boilers. [27] GreenCarbon said that everything they put in their process turns into coal and what doesn’t turn into coal just evaporates.[6]

[25] Fachverband Pflanzenkohle. Produktverzeichnis. (25.11.2020) https://fachverbandpflanzenkohle.org/pflanzenkohle/produktverzeichnis/

[26] GreenCarbon GmbH. Produkte. (25.11.2020) http://www.greencarbon-gmbh.de/holzkohle.html

[27] Schütt, Broder: Grünabfall- und Schnittholzverwertung in Schleswig-Holstein unter Klimaschutzaspekten. Untersucht in den Kreisen Nordfriesland, Rendsburg-Eckernförde, und Segeberg. (2011) Im Auftrag des Ministeriums für Landwirtschaft, Umwelt und ländliche Räume des Landes Schleswig-Holstein.

There are other options of course, other ideas for the after use of old thatching reed. Transforming it into construction material like insulation panels for example, as is done with fresh reed.

Tom Hiss, director of the company 'Hiss Reet' explained that for their reed damming panels only fresh reed stems of a certain thickness meet the required quality standard for the official construction permit because a certain uniformity of the material is needed for this. He couldn't imagine using old thatching reed for that cause. [7]

Biogas is another option. With fresh reed it is done in MV by the biogas plant of GES Biogas GmbH in Neu Kosenow. They use the cutting from nature conservation areas. Their harvesting areas are within a radius of about 20 km around the plant. The biogas plant is a typical wet fermentation. Since 2009, the plant has been on the grid and uses 50% of the landscaping material (grass and reed). Otherwise, feed residues, corn, beets and manure are used. So that could also be an option but probably they would have the same problem like composting plants, with the metal wires. [28]

Another option could be pressing the old reed into pellets for pellet heaters. This idea would be facing the same two problems with metal wires and the problematic ashes for the pellet heaters.

Thy pyrolysis plant seems to be able to avoid all the named problems without restraint of making any deviations from the normal daily process. The small available quantities would not allow such deviations.

5 Feasibility of Concept (pilot concept)

Tests with various charges in different states of decomposition need to be made in the pyrolysis plant. Cooperating thatchers would be needed. Research about the possibilities of selling the bio-char is needed. In the end, the pyrolysis plant has to confirm the 3-category-quality system and define the prices for each category.

A supply throughout all the year could be established when including leftovers from the harvesting process. Importantly, all farmed reed fields in MWP lie to the east, near the city of Greifswald, while the pyrolysis plant lies to the west, near Schwerin. The distance is too big for a profitable transportation of the reed from the fields to the plant.

Another great opportunity could be a cooperation with CARBOnet. This is an international cooperation network researching for the economic and ecological utilisation of biomass and other alternatives through carbonisation. The network is funded by the German Federal Ministry for Economic Affairs and Energy as part of the funding programme Zentrales Innovationsprogramm Mittelstand. Coordination is led by Innovations und Bildungszentrum Hohen Luckow e.V. [29]

Based on the results of the desk research the concept seems feasible. For further progress in the project, applied tests are needed.

[28] Deutscher Verband für Landschaftspflege: Biogasanlage GES Biogas GmbH, Projektbeschreibung. (25.11.2020) https://mulle.lpv.de/praxis-forschung/datenbank/projektdetails/id/biogasanlage-ges-biogas-gmbh.html

[29] CARBOnet. Index page. http://carbonet.ibz-hl.de. Last access 29 September 2020

6 Conclusion

Common reed is a widespread plant in the whole world. Large areas of MWP are covered with this perennial grass and the historical use of traditional house thatching with reed can be seen everywhere along the coast and also often in the inland areas.

This Pre-feasibility study aimed to investigate the afteruse of old thatching reed. Pyrolysis was selected as the focus of this study.

Firstly, a pyrolysis plant near the state capital of Schwerin was found producing bio char out of various raw biomass materials. The plant had tested pyrolysis with fresh reed before this PFS and is willing to carry out tests with old thatching reed. Secondly, desk study was conducted searching for possible impediments for the use of old thatching reed because of its long time on house roofs. None were found. Based on the findings of the desk research the concept seems feasible. For further progress in the study, applied tests at the pyrolysis plant are needed. This will not be possible during the BioBIGG project period. For any interested party to make further progress in this project concept a collaboration with the pyrolysis plant and the is recommended.

References

CARBOnet. Index page. http://carbonet.ibz-hl.de/. Last access 29 September 2020.

Collins English Dictionary – Complete and Unabridged, 12th Edition 2014 © HarperCollins Publishers 1991, 1994, 1998, 2000, 2003, 2006, 2007, 2009, 2011, 2014.

Deutscher Verband für Landschaftspflege: Biogasanlage GES Biogas GmbH, Projektbeschreibung. Source: https://mulle.lpv.de/praxis-forschung/datenbank/projektdetails/id/biogasanlage-ges-biogas-gmbh.html. Last access 25November 2020.

Dragoni, Federico & Giannini, Vittoria & Ragaglini, G. & Bonari, Enrico & Silvestri, Nicola. (2017). Effect of Harvest Time and Frequency on Biomass Quality and Biomethane Potential of Common Reed (Phragmites australis) Under Paludiculture Conditions. BioEnergy Research, p. 1069-1071.

Ellenberg, Heinz; Leuschner, Christoph (2010): Vegetation Mitteleuropas mit den Alpen: in ökologischer, dynamischer und historischer Sicht.

Fachverband Pflanzenkohle. Produktverzeichnis. Source: https://fachverbandpflanzenkohle.org/pflanzenkohle/produktverzeichnis/. Last access 25 November 2020.

GreenCarbon GmbH. Impressum page. Source: http://www.greencarbon-gmbh.de/impressum.html. Last access 18 September 2020.

GreenCarbon GmbH. Produkte. Source: http://www.greencarbon-gmbh.de/holzkohle.html. Last access 25 November 2020.

Hiss Reet. Maintenance of thatched roofs. Source: https://www.hiss-reet.de/reetdach/wartung-pflege/pflege-wartung/?L=1 . Last access 15 November 2019.

Ibrahim, B. (2018): Investigation of the applicability of wetland biomass for producing hydrochar by hydrothermal carbonization and its effectiveness for the adsorption of ammonia (doctoral dissertation).

Iital, A.; Klõga, M.; Kask, Ü.; Voronova, V.; Cahill, B. (2012): Reed harvesting. In: Schultz-Zehden, A. & Matczak, M. (eds.) Compendium: An Assessment of Innovative and Sustainable Uses of Baltic Marine Resources, Maritime Institute in Gdansk, Gdansk, 103–124.

LM M-V (2017): Umsetzung von Paludikultur auf landwirtschaftlich genutzten Flächen in Mecklenburg-Vorpommern. Fachstrategie zur Umsetzung der nutzungsbezogenen Vorschläge des Moorschutzkonzeptes. Ministerium für Landwirtschaft und Umwelt Mecklenburg-Vorpommern, Schwerin.

Rural Development Commission, 1988. The Thatcher's Craft. First published 1960. London.

Schaatke, W. (1992): Das Reetdach - Natürliches Wohnen unter sanftem Dach - Von der Uhrzeit bis heute (The Reed Roof - Natural Living Under a Soft Roof - From Primeval Times Until Today). Christians Verlag, Hamburg, 264 pp.

Schaecke, B. u. a. (2000): Eignung von Reet alter Rohrdächer als Kompostrohstoff - Schadstoffbelastung und wertgebende Inhaltsstoffe. In: Tagungsband III. Dialog A bfallwirtschaft, Universität Rostock.

Schütt, Broder: Grünabfall- und Schnittholzverwertung in Schleswig-Holstein unter Klimaschutzaspekten. Untersucht in den Kreisen Nordfriesland, Rendsburg-Eckernförde, und Segeberg. (2011) Im Auftrag des Ministeriums für Landwirtschaft, Umwelt und ländliche Räume des Landes Schleswig-Holstein. Available online: https://www.schleswig-holstein.de/DE/Fachinhalte/A/abfallwirtschaft/Downloads/Gruenabfall_Studie.pdf?__blob=publicationFile&v=1. Last access 19 May 2020.

Telephone interview with Caroline Dräger 19 May 2020.

Telephone interview with Gerd Werner 5th June 2020.

Telephone interview with Michaela Schuldt 23 April 2020.

Telephone interview with Michaela Schuldt 30 July 2020.

Telephone interview with Rainer Carls 20 November 2019.

Telephone interview with Rainer Carls 28 May 2020.

Telephone interview with Tom Hiss 26 November 2019.

Tilley, D.J., and L. St. John. 2012. Plant Guide for common reed (Phragmites australis). USDA-Natural.

Tony Bridgwater, ‘Pyrolysis of biomass‘, Power Point Presentation, ETIP Bioenergy Webinar, 25 May 202.

Webseite MV Land zum Leben Daten und Fakten 31.7.2020, https://www.mecklenburg-vorpommern.de/ueber-das-land-zum-leben/daten-und-fakten/. Last access 25 November 2020.

Wichmann, S., Wichtmann, W. (2009): Bericht zum Forschungs- und Entwicklungsprojekt. Energiebiomasse aus Niedermooren (ENIM).

Wichtmann, W., Oehmke, C., Bärisch, S., Deschan, F., Malashevich, U., Tanneberger, F.: Combustibility of biomass from wet fens in Belarus and its potential as a substitute for peat in fuel briquettes. In: Mires and Peat, Volume 13 (2013/14), Article 06, 1–10.

Zerbe, S., Steffenhagen, P., Parakenings, K., Timmermann, T., Frick, A., Gelbrecht, J., Zak, D.: Environmental Management (2013) 51: 1194. Ecosystem Service Restoration after 10 Years of Rewetting Peatlands in NE Germany, p. 1202.

SUSTAINABLE BIO-BASED ALTERNATIVES AS A SUBSTITUTE FOR PLASTIC PACKAGING, DISHES AND CUTLERY IN THE CATERING SECTOR ON THE BEACHES OF ROSTOCK

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Deliverable: Deliverable 5.2: Pre-feasibility and innovation programmes for innovative value chains

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1. Introduction

The severe pollution of the marine ecosystem by plastic products worldwide is by far not a new topic. Between 4.8 – 12.7 million tonnes of plastic is entering oceans every year (Jambeck et al., 2015), which has led to predictions that by 2050, more plastic than fish (by weight) will be found in the world's oceans (World Economic Forum et al. 2016). Only around 15 % of our plastic waste worldwide is recycled, while 63 % of our waste is collected and ends up in landfills. The remaining percentage eventually finds its way back into the environment (Bauske et al. 2019). A common method utilised by industrial countries is to ship their plastic waste to other countries (especially countries located in Asia) until Chinas government banned imports of several types of waste -above all plastic waste. Germany stands among 81 countries that has shipped plastic waste to China (McNaughton & Nowakowski, 2019).

In Europe, Germany was ranked as the highest annual packaging waste producer, creating 220.5 kg per capita just in 2016 alone (Umweltbundesamt, 2018). Food packaging is often designed to be used just once before being thrown away. Therefore, it is no surprise that disposable plastic packaging and single-use plastics are the main source of litter found on beaches. According to the UN Environment Programme Report from 2018, "The most common single-use plastics found on beaches are, in order of magnitude: cigarette butts, plastic beverage bottles, plastic bottle caps, food wrappers, plastic grocery bags, plastic lids, straws and stirrers, and foam take-away containers".. This lightweight material is then easily transported into the sea by winds and rain whereas marine animals consume it. Bauske et al. (2019) mentioned in their WWF report, that the amount of plastic recorded to be present on beaches was 30 % higher during the tourist season than in the summer season. Therefore, a well-visited beach is synonymous to an increased amount of waste.

The problem is that conventional plastic waste does not biodegrade; it just breaks down into smaller pieces over time. The so-called microplastics, all plastic particles with a diameter < 5 mm, can be found everywhere -even at the most remote places like the Arctic sea. It is therefore not surprising that microplastics were found in beach sediment along the German Baltic coast (Stolte , Forster, Gerdts, & Schubert, 2015). Microplastic is not only a threat to the environment but also to human health (Gibbens, 2019). Once it enters the food chain, it is only a matter of time until it ends up in the human body. The long-term consequences of plastic particles in the human body have not yet been sufficiently investigated enough to make clear determinations.

However, plastic and microplastic pollution can lead to economic problems; such as the absence of tourists, costly clean-up operations and reduced of fishing income. The problems are likely to increase considerably in the future (UN Environment Programme Report, 2018).

This Pre-Feasibility Study examines the possibility of replacing plastic packaging, dishes and cutlery, with sustainable bio-based products on the beaches of Rostock. This is especially in terms of keeping these beaches and their aquatic environments plastic-free under already in place national and regional policies. The five steps of the so-called waste hierarchy[1] were examined to identify possible ways towards this objective, aiming to select the most promising solution that can be carried out in a sustainable way and at the regional and national levels.

[1] Directive 2008/98 /EC

2. Feasibility concept of a plastic free region

There are many possibilities to achieve the aim of replacing plastic based packaging, tableware and cutlery, with sustainable bio-based products that help in reducing the total amount of plastic waste on the beaches of Rostock, in which many seem to be promising approaches. However, it needs to be assessed whether these approaches are feasible in terms of national and regional waste recycling regulations that are already in place. As a first step, the waste reduction hierarchy will be analysed to find the most sustainable path to replacing plastic dishes, cutlery and packaging with bio-based alternatives on the beaches of Rostock. In the EU, Waste Framework Directive (Directive 2008/98 /EC) Article 4 sets out the five steps of the waste hierarchy. Prevention or reduction of waste is, of course, the main priority. However, when waste is created, the hierarchy gives precedence to the most environmentally friendly solution where and whenever possible. This cascading approach will be utilised until the most environmentally suitable approach is determined per waste product.

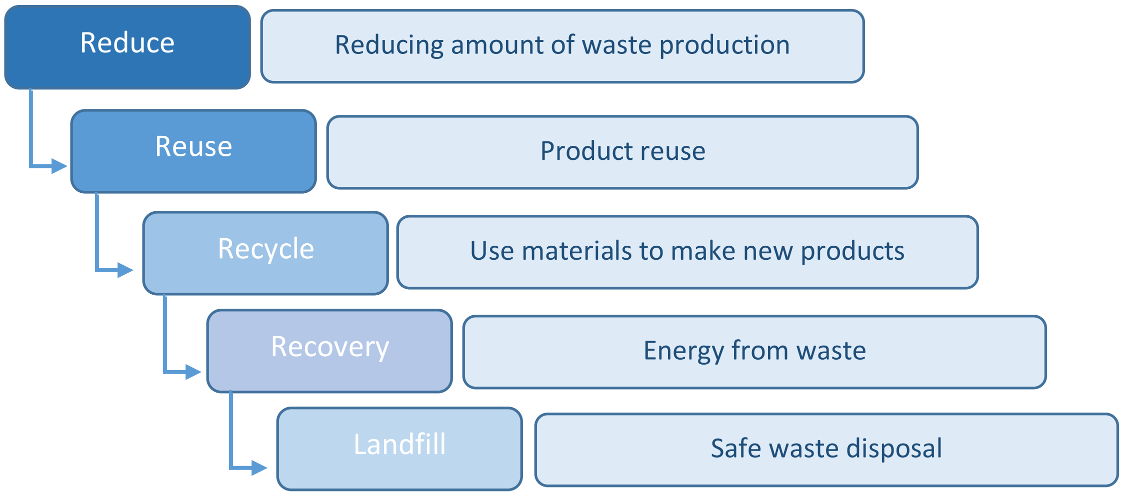

Figure 1: *Waste reduction hierarchy. From most favoured to the least favoured option. After EU Waste Framework Directive*

2.1 Reduce packaging

Besides going to a restaurant, beach visitors often prefer takeaway food. A big problem arises here because takeaway food mainly is packaged in disposable containers, which include polystyrene, aluminium, plastic and paper packaging. Due to its flexibility, high durability and easy handling, plastic has become a widely used material. To restrict the use of these items, laws and regulations play a crucial role. Products, which cannot be reused, are eventually set aside as unusable or unwanted and end up in the garbage. Therefore, attention shall be paid in terms of reduction, especially when it comes to single-use products made of plastic.

The tourism industry in Mecklenburg-Western Pomerania has been active in terms of sustainability. In 2014, the German Youth Hostel Association (DJH) developed a sustainability strategy that is continuously being improved. The DJH uses the help of social media (e.g. Instagram) to inform the widest possible audience. All 14 German Youth Hostels in Mecklenburg-Western Pomerania focus on education and measures to reduce waste. Priority is the avoidance of small packaging and convenience products as well as the use of beverage filling stations. Educational courses and workshops are offered to school classes and families on the topic of waste in the sea and the influence of humans on the ecosystem of the Baltic Sea[2].

2.2 Reusable products

Reusable products aid in the goal to reduce the amount of waste that comes from packaging, while simultaneously reducing the use of fossil raw materials. Glass containers and refill stations offer a great alternative. This would require a uniform depository system, which should be implemented beforehand in order to ensure that customers have the option to dispose of (or give back) these products in many locations, and not just necessarily from the location in which they purchased it. However, glass also represents a risky alternative for the beach area, because glass shards are poorly recognisable in the sand and pose a high risk of injury.

The City of Rostock has already determined that the use of depository systems with reusable articles as well as the use of dishwashers is not feasible. Due to flood protection, water and sewage connections are limited, and therefore, the possibilities of waste avoidance are limited for restaurants located at the beach[3].

2.3 Improved disposal/ recycling

The last three steps of the waste hierarchy are recycling, energy recovery and disposal, which all start with the same first step - waste collection. This step in particular can make a major contribution to reducing waste by improving the waste disposal system. In Germany, the system of waste disposal follows the same overall system. Waste separation is carried out through the utilisation of a colour code system; whereas the colours blue, yellow and grey/black each determine a specific type of waste that is adhered to nationwide.

Figure 2: *Colour coding of German waste bins.*[4]

Due to incorrect sorting, a bin rarely contains the exact materials (waste) predetermined by this system. This means that unwanted materials are sorted out in several selection processes. For example, domestic waste undergoes a mechanically biological waste treatment, whereby biological waste is separated and disposed of on composting plants. The remaining waste, which was treated

[2] Deutsche Jugendherberge. URL: https://www.jugendherbergen-mv.de/nachhaltigkeit/. [29.07.2020]
[3] Hanse- und Universitätsstadt Rostock (2018). Umweltmanagement am Strand. URL: https://www.rostock.de/aktiv/strand-meer/umweltmanagement-am-strand.html#biologisch-abbaubares-geschirr
[4] We future cycle (2015). Waste Management in Germany, 87% recycling rate. URL: https://wefuturecycle.com/2015/07/15/waste-management-in-germany-87-recycling-rate/. [20.07.2020]

mechanically, can be split into calorific value-rich, calorific value-low fraction and scrap metals. The calorific value-rich fraction has a higher calorific value than the initial raw waste. Often, it is obtained in a lower degree of processing and used with or without post-treatment for steam and power generation. The remaining percentage is then subsequently incinerated. In Germany and other European countries, it is now forbidden to simply dump household waste into landfills. What can be reused is recycled, whereas in 2016, Germany recycled 89 % of its paper waste and 50 % of its plastic waste. The remaining waste is burned (Große, 2018).

The collected bio-waste from households, industries etc. is used for the production of biogas, bio-methane and composting. Just as with all the other waste processes, the waste is thoroughly sorted after being collected. The collected organic waste often contains garbage bags made of plastic, as well as food that is still packed. Which is sorted out and fed into the residual waste. After the waste has been treated appropriately and biogas has been obtained, the fermentation residues are mixed with fresh bio-waste and are industrially composted. Thus, bio-waste offers an opportunity in our plan to rid the beaches of single-use packaging, because packaging made of biodegradable material can later be added to the biomass content. This approach will be discussed further in the following chapter.

In order to achieve a higher overall recycling rate, waste containers in German cities are often marked in colour according to the material they shall collect, as previously described. The colour-marked waste bins are not always found at beaches, but care is currently being taken to find waste bins at regular intervals[5]. Now beaches often have separate waste containers for cigarette butts.

2.4 Biodegradable packaging

Food packaging has to meet many requirements in terms of food safety. Its longevity and flexibility give plastic packaging an immense advantage, which make its use often irresistible. The requirements for food packaging are high and mainly originate from the food industry. Among other things, the packaging must behave inertly. In other words, plastics must not react or only react very little with their content, and provide the guarantee that a transfer of substances is impossible, so that the food's safety is not adversely affected. Furthermore, food packaging must be odourless, ensure the longevity of its content and must protect food from environmental influences such as moisture, light, contamination and damage (Lebensmittelverband Deutschland 2020). Some of these properties are less relevant for catering and take-away packaging.

For years, there has been an urgent search for plastic substitutes and the alternatives to plastic packaging are diverse. Some examples include packaging made of paper or tree fibres, or bio-based plastic made of poly lactic acid or cornstarch. There are many products currently in the market, which aim to replace common single-use packaging like styrofoam, aluminium or plastic. Almost half of the produced packaging in Germany is made of paper or cardboard. These materials can potentially substitute up to 21 %of all used plastic packaging (Kreuzer, 2020). It should be noted that paper packaging often does not only consist of only pure paper. To- go Coffee-cups, for example, must be stable and dense. To protect the paper from softening, it is coated with a very thin layer mainly made of plastic foil. During waste separation, the sorting machine is unable to recognise the paper cup container is more than just pure paper. Hence, it is sorted into the residual waste, where it is then incinerated. Even if a biodegradable coating was created for this purpose, it could still not be utilised as an effective alternative to the plastic foil coating. This is because sorting machines cannot

[5] Telephone interview with a representative of the Tourismuszentrale Rostock + Warnemünde. 18.09.2020,

distinguish between biodegradable and fossil-based coatings. There would therefore need to be a better labelling system in place primarily (on cups and depository bins) whereas individuals can distinguish the difference whereas the machine cannot. This is a large task however; it is still in the interest of the biodegradable approach, as it could lower the environmental impact of the littered material. Therefore, all properties need to be biodegradable in nature and not just under industrial composting conditions.

To classify a product as sustainable, the whole product including all materials used must be considered. The life cycle assessment does also include the end-of-life phase including the recycling possibilities and related environmental impacts. As a result, biodegradable or bio-based plastics are not always as sustainable as first thought. First, clarification is needed because biodegradable products can be fossil-based and not all bio-based products are biodegradable (InnProBio 2016). The latter in particular is a problem because the waste in most composting plants has around four weeks to rot. Nevertheless, many biodegradable plastics need at least around 12 weeks at 60°C to biodegrade by 90 % (Bornett, Karin 2020). Microorganisms decompose the material into carbon dioxide, water and mineral additives. However, when decomposing biodegradable plastics humus will not be created. The heat released during the decomposition process is often lost, and unused. Hence, under the current recycling regime it is much more efficient to incinerate biodegradable plastic with the other not recyclable waste, because during the incineration progress at least the energy is recovered. In the end, the product is only disposed of because it does not meet the recycling requirements.

However, this does not mean that bio-based plastics made from biogenic raw materials such as corn, potato starch, wood or sugar cane, are not an option. It is essential to identify the most effective use of bio-based plastic products that excludes an interference with their respective disposal or recycling processes. Compostable materials belong in composting plants, and plastic packaging and paper should not end up in residual waste. For example, often the food waste cannot be separated from the packaging material, which would mean that the food waste would be lost for biogas production and/or composting but if the packaging is also biodegradable, the food can be disposed of into the bio waste bin together with its packaging.

Small plastic forks and mixing sticks are one of those plastic products, which are especially easy lost at beaches, whereas wind can carry the light packaging away fast and often unnoticed. Nevertheless, there is an alternative, which has been determined as wood. This is nothing new, as wooden replacements have already existed for a few years. However, those wooden forks and mix sticks are still just as easily lost at the beach and found in the sand. Despite the advantage of being biodegradable, it is important to realise that biodegradable products, even if they are able to biodegrade in nature (soil, sea and fresh water[6]), will still for a considerable time, become waste if not disposed properly. Therefore, any communication should avoid suggesting that these products can be disposed of within nature. The only difference to wood in consideration of its plastic counter parts, is that wood products will fully biodegrade after a limited time (several months), whereas non-biodegradable plastics would not.

Many non-traditional materials can also serve as a replacement to plastic. In many Asian and African countries, the food is still served on banana or palm leaves, which after use can easily be thrown away.

[6] Please note that the most often used biodegradable plastic material PLA does not biodegrade in nature. Most promising materials is PHA. However, this innovative material is not used at commercial level yet for products relevant for this PSF. See: https://bioplasticsnews.com/2019/01/21/pha-bioplastics-2019/.

Both leaves are often used for the production of bio-based products in the catering sector. These natural and environmentally friendly alternatives have a great advantage by disposing them to the bio waste bin, as they can also serve as biomass material. On the other hand, social acceptance might still stand in the way as a barrier to the use of such leaves as described.

Table *1: Summary of the individual approaches of the five-step waste hierarchy to reduce plastic packaging, dishes and cutlery on the beaches of Rostock with regard to their feasibility and necessary.*

Approaches	Feasibility	Actions/Description
Reduce packaging	Feasible	- Personal responsibility of the beach visitors - Rules and laws that prohibit/restrict the use of plastic materials
Reusable products	Not feasible	- Use of a deposit system for reusable articles - High risk of injuries from glass and ceramic shears
Improved disposal/ recycling	Feasible	- More frequent distribution of waste bins - Provide better recycling options near the beach
Biodegradable packaging	Feasible	- Substitution of plastic packaging, tableware, dishes & cutlery with biobased alternatives made of cornstarch, bamboo, wood fibres etc. in restaurants and kiosk stalls.

3. Policy and statistical data related to project technology concept

Directives and current laws in Germany (and especially in Mecklenburg-Western Pomerania) are currently being examined, concerning waste prevention and recycling. The study also focuses on biomass, as the use of biodegradable packaging has the potential to be composted together with bio waste.

The Circular Economy Act (KrWG), which entered into force in 2012, describes the core element of the German circular economy. The core principles include among others the polluter-pays principle, the five-step waste hierarchy (Figure 3) and introduces the principle of the shared public and private responsibility for waste management (Waste Management in Germany 2018). With the polluter pays principle the producer of waste has to pay for waste treatment and its disposal (Nelles et al. 2016). The Circular Economy Act states that since 2015 the sorting of waste is mandatory. Since 2020, a recycling rate of 65 % by weight of all municipal waste is compulsory. This directive was been implemented from the EU Directive 2018/851/EC into national law (KrWG 2012).

In addition to the federal law (Circular Economy Act), the respective federal states have waste management laws, which contain supplementary provisions and other statutory ordinances and administrative regulations. In Mecklenburg-Western Pomerania (MV), this is the Waste Management Act for MV, short AbfWG-MV. It is important to mention the fact that small businesses are not part of a separate waste collection directive. Meaning that the waste from catering firms count as residual household waste (Pfrogner, Bever, & Lindtner, November 2018).

Manufacturers and distributors of sales packaging that are sold to private-end-users, for example households, are obliged to join a dual disposal system. This ensures a comprehensive and regular collection of used sales packaging (e.g. yellow bin) or their delivery to collection containers and recycling centres (Daten zur Abfallwirtschaft 2017).

In 2018, each German citizen generated around 68 kg of sales packaging waste per capita (Figure 3), of which, 30 kg per capita were light packaging including aluminium, tinplate and composite, which made up the largest share of the packaging waste collected by private households. Mecklenburg-Western Pomerania contained a total of 83 kg per capita, and was determined as the state with the most packaging waste in 2018. Reasons why Mecklenburg-Western Pomerania was on top of the list were not given (Statistisches Bundesamt (Destatis), 2020), and no information was found on the proportion of bio-based packaging in Germany. However, the share bioplastics produced in Europe is at 25 % compared to the 2.11 million tonnes worldwide.[7] With the replacement of the Packaging Regulation by the Packaging Act on 1 January 2019, the packaging problem is further exacerbated, as it aims to prevent packaging waste and to prepare it for recycling.

With the ban on disposable single-use plastic products such as plastic cutlery, plates, straws, stirrers, to-go cups made of Styrofoam, cotton swabs and balloon sticks, the Federal Government recently implemented the Directive (EU) 2019/904 of the European Parliament and of the Council. These products are no longer permitted on the market. The law does not apply to products that are still in stock, and a useless annihilation is to be excluded.[8] This law is a long-awaited step in the fight against global plastic pollution, as the EU ban is supposed to be implemented in all EU countries by 2021.

As shown in Figure 4, more than a third of the collected waste for recycling in Mecklenburg-Western Pomerania consist of organic, garden and park waste. Out of this, waste from the bio waste bins alone contribute to the biomass amount of around 4.5 million tonnes. Twenty-eight composting plants, eight waste fermentation plants and 41 recycling plants are located in Mecklenburg- Western Pomerania (Daten zur Abfallwirtschaft 2017). Biogas, as well as high-quality compost, is obtained and used as fertiliser and soil additive (Nelles et al. (2016); Dr Jaron, A. & Kossmann, C. (2018)). If the sorting machine recognised the biodegradable tableware as such, it could be used for biological waste recycling. However, recycling facilities are currently not able to recognise these materials.

Any removal of contaminants from waste streams is expensive, time-consuming and results in increased staff costs. This problem is especially hindering when sorting organic waste, whereas no positive change in the situation has been observed in recent years. This effort reflects on the costs for the fee payer. If bio-based packaging does not biodegrade in the necessary time under industrial composting conditions, the material is sorted out and fed into the incineration pathway. Additionally, biodegradable materials cannot be distinguished from other plastics in the waste stream and are sorted out. Furthermore, in order to exceed the individual limit values required by the Fertiliser Regulation, biomass often has to go through elaborate processing steps, which filter out the individual pollutants (Schulte, Martin 2020). Any remains of plastics (even if biodegradable) could hamper the quality of the composts as it is analysed according to this regulation.

[7] European Bioplastics (2020). Report-Bioplastics market data 2019, p. 4

[8] Agrar-Europe (29 June 2020). Bundesregierung beschließt Verbot von Einwegkunststoffprodukten. Edition 27/20, p.8

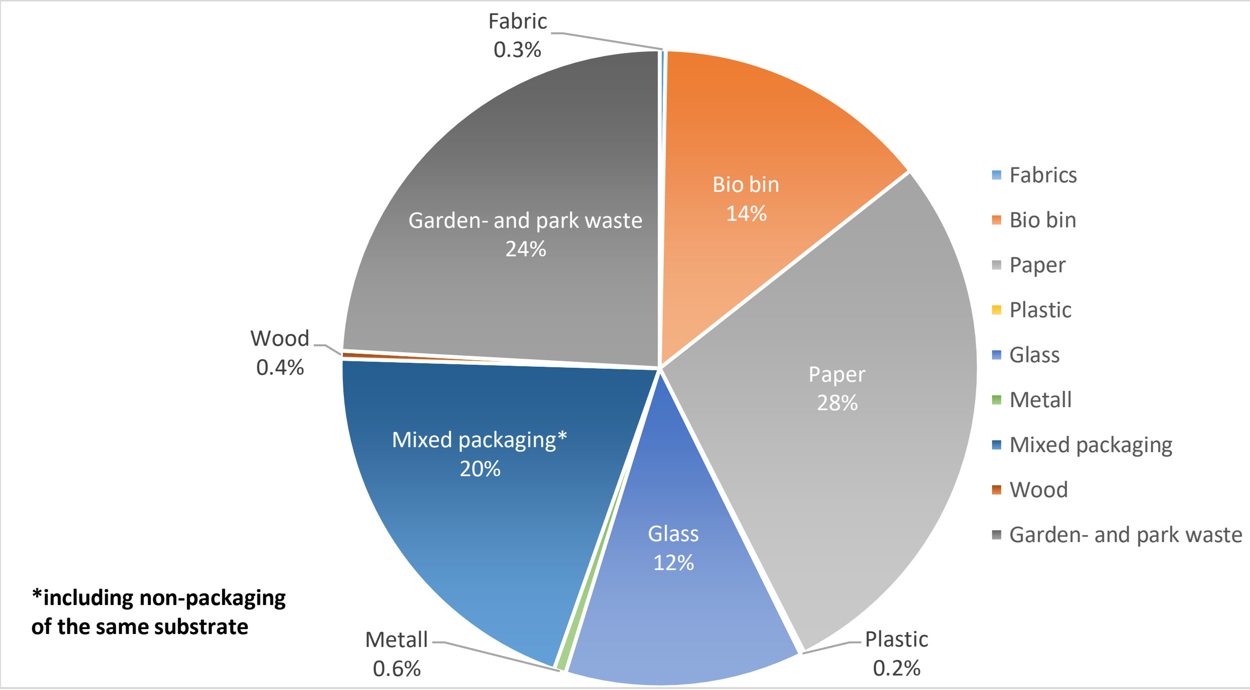

Figure 3: *Separately collected waste for recycling in Mecklenburg-Western Pomerania in 2017*[9]

Compost is widely used in Germany, for example in 2014, 60.6 % were recycled in agriculture, and 16.6 % in soil manufactory and 7.6 % were used equally for landscaping/re C cultivation and individual gardening. The remaining 7.6 % was used elsewhere as described by Nelles et al. (2016).

The increase of collected bio waste in Mecklenburg-Western Pomerania (Figure 5) is mainly due to an improved and expanded collection of bio waste, which was in 2017 at 29 kg per inhabitant, alone. The city of Rostock is in third place among the administrative districts of Mecklenburg-Western Pomerania with 44 kg per capita of organic waste collected through the bio waste bin (Daten zur Abfallwirtschaft 2017).

[9] LUNG (2017). Daten zur Abfallwirtschaft. *Landesamt für Umwelt, Naturschutz und Geologie*, p. 14

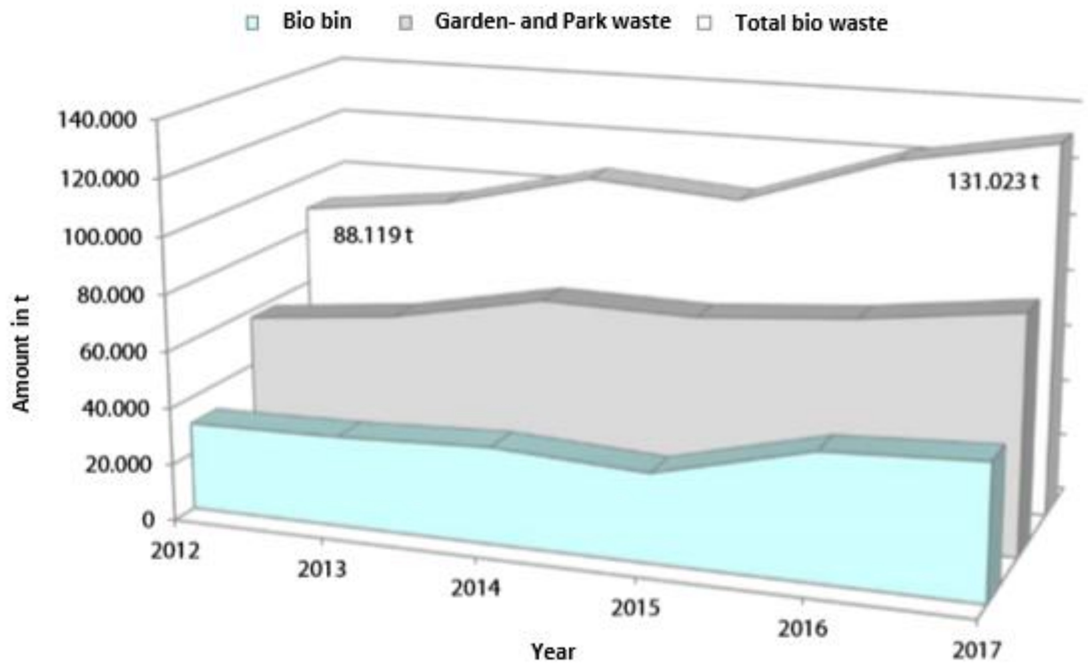

Figure 4: *Development of the collected amount of bio-waste in Mecklenburg-Western Pomerania from 2012 to 2017 (Source: Daten zur Abfallwirtschaft 2017)*

The Biowaste Ordinance regulates the recycling of treated and untreated organic waste and its use as fertiliser on agricultural, forestry and garden areas. Among other things, the treatment requirements, toxin restricts the maximum application quantity, investigators, as well as reporting and verification obligations, are described. This does not apply to households, utility and small gardens, the self-recuperation of plant bio waste and waste that has to be discarded under different enactments (e.g. sewage sludge).

The waste management industry has become a powerful sector in Germany's economy with "more than 270,000 people working in some 11,000 companies with an annual turnover of around 70 billion euros" in 2018, according to Dr Jaron, A. & Kossmann, C. (2018), p. 5. The average waste management costs per inhabitant of Mecklenburg-Western Pomerania amounted to 78 € in 2017. This is an increase of 3 €/capita over the previous year. However, the amount varies within the states and even cities (Daten zur Abfallwirtschaft 2017).

In 2017, 54.1 % of the primary energy consumption in Germany came from biomass and the total electricity generated from biomass came to 51.4 TWh out of which 63.2 % were produced by biogas (FNR 2019). Above all, the increased collection of bio waste has potential, i.e. in terms of reaching the expansion targets according to the Renewable Energy Sources Act. This means for MV an energy supply of 150 MW must be provided by the end of 2020 using biomass alone.

Since the amendment of the Renewable Energy Sources Act (EEG) 2012, the Biomass Ordinance has become less important for new commissioning of EEG-biomass plants, as a differentiated remuneration according to the type and origin of the biomass is omitted. On the other hand, the Market Incentive Program 2020 (support programme for heating with renewable energies from 2020) has improved the promotion of biomass plants for heat generation significantly.

In June 2020, Germany recorded a cumulative gross increase of 141.3 MW in the biomass sector out of 3.9 MW was recorded in Mecklenburg-Western Pomerania. Mainly biomass power plants for the production of biogas were put into operation and had a total commissioning volume of 23.3 MW. Plants for the production of biomethane accounted for 2.9 MW and plants for solid biomass for 2.0 MW (Federal Network Agency 2020[10]). Biodegradable plastic is a potential feedstock for biogas plants. However, so far only 7 % decomposed within 90 days. The most promising material is polylactic acid (PLA) and experiments are still ongoing investigating the decomposition of bio-based plastic as many studies show (Hobbs et al. 2019).

Sustainable and green thinking is also part of the food catering industry, which is an important step, as this industry, in particular, is heavily dependent on disposable packaging (Gawenda (2019); Hoffmann (2020)). Organic disposable cutlery consists, as previously described, of wood, bamboo, banana and palm leaf variations. The customer's demand for environmentally friendly alternatives is increasing likewise. However, those alternatives call for further urgently needed actions. In order to guarantee an efficient life cycle of the product, proper disposal must be ensured. Consequently, the provision of waste bins for packaging, paper, residual waste as well as for organic waste is desirable. This applies not only to beach sections but also to all tourist areas where alternative crockery and packaging is used. Furthermore, better labelling for bio-based packaging is important because consumers often have difficulties to distinguish between bio-based and fossil based. This problem mainly addresses bio-based plastics, because it is very hard to differentiate them from conventional plastic products. Furthermore, it often is not clear whether the thin coating of drinking cups made of cardboard, which prevents the cup from softening, is made of bio-based material. The bio-based materials often look similar to the fossil-based ones, which complicates an easy differentiation. [11]

The study aims to assess the feasibility of using bio-based and compostable packaging products as a solution to reduce the plastic litter problem caused by littered packaging for food and other catering products on Rostock's beaches. Ideally, the final chosen solution should not produce any waste. In reality, this is not feasible at all. Hence, the best way to do this is to find an environmentally friendly substitute for plastic single-use products, which is either reused or recycled in a cascading process.
In this section, the state of development of each of the measures described in chapter 2 is evaluated according to the Technology Readiness Level (TRL).

There are quite a lot of regulations and laws, which support and facilitate the transition from fossil-based packaging to bio-based packaging. However, since avoiding packaging on the beaches of Rostock does not require any technology, no TRL can be assigned to it.
As already mentioned in chapter 2.2 *Reusable products*, the introduction of reusable dishes & cutlery and crockery is not suitable for the beach area. Due to the risk of flooding, sewage connections in restaurants near the beach are limited. The measure of improving the recycling and disposal system on the other hand can be rated TRL 7. Waste bins are distributed on the beaches of Rostock; however, waste separation cannot be carried out on the beaches of Rostock, as the existing waste bins do not provide the opportunity to separate between papers, packaging and residual waste.

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[10] Marktstammdatenregister der Bundesnetzagentur (2020, 22. July). Evaluation period: Jan. 2020 – June 2020.
[11] Labels for bioplastics. European bioplastics URL: https://www.european-bioplastics.org/bioplastics/standards/labels/. [17.09.2020]

The City of Rostock and the Rostock & Warnemünde Tourist Office decided to introduce biodegradable tableware on the beaches of Rostock with the goal that these beaches will eventually switch to biodegradable tableware.
This project combines several stages of the waste hierarchy such as reduction, recycling and recovery. While using bio-based packaging, the amount of plastic used and distributed at the beaches can be significantly reduced. Furthermore, the recycling process is improved by distributing more waste bins along the beach area, which can be found at regular and shorter distances.
The project, which started in 2018 with the aim to replace plastic packaging used by the kiosks and beach bars /restaurants near the beaches of Rostock, by bio-based dishes & cutlery. In the first two years, 14 project participants signed a declaration of self-commitment, which was replaced in 2020 by a contract whereas the participants agreed to replace disposable plastic tableware by alternatives made of corn starch, palm leaves, sugar cane, wood and cardboard. The restaurant and kiosk stall owners, who decided to take care of the procurement of the materials themselves, have to guarantee that their dishes & cutlery are bio-based, with the exception to beer cups made of bio-based plastic. Those did not biodegrade during the rotting test.[12] For this purpose, extra waste containers were also distributed on the beaches to facilitate a later separation of biodegradable packaging. The extra waste bin was tested as a pilot project in a small part of the city Rostock (Warnemünde). For the project, it is very crucial to see how visitors of the beach accept the idea of an extra waste bin. This part of the project is seen as challenging due to its dependence on public opinion. The introduction of a further waste bin, in addition to the already existing ones (paper, plastic and residual waste bin) could lead to confusion.

The specially introduced waste containers are emptied daily by the tourist office and handed over to the building ward. The separately collected waste is then transported to the waste treatment plant of Veolia Umweltservice Nord for mechanical and biological treatment.
The sorted biological part of the waste is added to the collected biomass from households for the production of electricity and biogas, which is then fed into the energy network of Rostock. According to Joachim Westphal, authorised representative of EVG mbH, waste management and collecting corporation of Rostock, the decomposition process has been tested beforehand and the biodegradable waste decomposes with dry fermentation.

It should be noted that the bacterial decomposition of biodegradable products could take several years if the product is not properly disposed into the bio waste bin, and instead simply thrown into nature. Of course, the product would biodegrade by itself eventually; however, until that point it could remain in the sea or on the beach and cannot be considered as anything other than waste.[13]

The project was implemented in terms of the beaches in Rostock, more precisely, the beaches of Warnemünde and Markgrafenheide - since June 2018. Within the first year of the experiment, the Tourist Board Rostock + Warnemünde observed that a waste separation system did not work. Hence, the waste cans, which were specially set up for the project to collect the biodegradable tableware now serve as general waste bins. The plastic, which can now be found in the garbage cans on the 16 km long beach, mainly originates from the disposable packaging, which the beach visitors brought themselves. In the course of the project, bio-based and biodegradable plastics (polylactic acid) were

[12] Telephone interview with a representative of the Tourist Board Rostock + Warnemünde on Friday, 18.09.2020
[13] Hanse- und Universitätsstadt Rostock. Biologisch abbaubares Geschirr. URL: https://www.rostock.de/aktiv/strand-meer/umweltmanagement-am-strand.html[29.07.2020]

also tested in a rotting experiment, but the material did not decompose. The Tourist Board Rostock + Warnemünde incurred only low marketing costs for the implementation of this project (for the promotion of the campaign). The exact costs could not be determined because the kiosk and stall owners themselves take account of their purchases, and did not want to reveal any details about the costs.[14]

In conclusion, and due to these determinations, the project can be rated with a TRL 8-9. The project was organised the material decomposition as well as the specific waste system have been tested beforehand, and the project is still ongoing. However, the plans had to be adjusted, as the planned waste separation was not carried out as expected. Thus, the materials are only fed into the bio-waste during the separation of the residual waste if they are recognised as such during the sorting process. Nonetheless, the sustainability of the approach can still be improved because the bio-based products are not fed directly into the organic waste, but have to be sorted out beforehand. Even through the technology of the sorting machines is already well developed; the machines often have a hard time distinguishing between bio-based materials and fossil ones. When separating the residual waste, the products are not recognised and are thus not sorted into the organic waste but burned together with the residual waste. In addition, vice versa, when sorting the organic waste the bio-based materials are often added to the “residual waste” stack. This is currently done in Germany, as it is the most economical solution so far.

In order to improve the sustainability of the project by feeding the products directly into the bio waste, changes need to be made. On the one hand, it is necessary to examine whether the adaptation of certain laws and directives can improve waste recycling, since laws often overlap and limit individual scope for action. In addition, a better labelling of bio-based and biodegradable products is necessary to ensure a better waste separation. Turning around the composting process would lead to a similar result. That means that the bio waste is first composted and then sorted. However, it needs to be checked whether this bottom-up approach would be economically beneficial, especially regarding time and costs. It is also necessary to check whether this affects the quality of the compost. The advantage of the approach is a lower incineration rate of bio waste. Nevertheless, this idea still requires further research. Another solution would be to permit only plastic materials for food packaging, which is biodegradable. However, although concepts for this approach exist, such packaging solutions are not available in a scale, which would allow implementing such restrictions by law. The issue with the long composting time could be dealt with by sieving materials, which have not biodegraded yet and put them back into new composting piles until they are fully biodegraded.

The use of bio-based packaging can give biomass power plants a new meaning if biodegradable packaging is increasingly used in the future. Only if bio-based packaging meets the industrial composting requirements and if it can be ruled out that, it will be incinerated at the end of the waste recycling process.

4. Regional market situation

The assessment of the regional market plays an essential part in assessing the most suitable possibility in replacing plastic packaging, dishes and cutlery with sustainable bio-based products on the beaches of Rostock.

[14] Telephone interview with a representative of the Tourist Board Rostock + Warnemünde on Friday, 18.09.2020

Due to the prohibition of disposable plastic, companies are therefore forced to switch to alternatives. The supermarket groups REWE and Penny have already taken care of this and can save up to 8,900 tons of plastic packaging by using paper or cardboard as well as natural materials such as straw or bamboo (Kreuzer, Stephanie 2020).

Thirteen beaches around Rostock and three marinas are part of the "Blue Flag", which provides information and implements environmental measures. Such measures (among others) are the availability of waste disposal bins/containers at the beach in adequate numbers, which must be regularly maintained; an adequate number of toilets and restrooms; availability of facilities for the separation of recyclable waste at the beach and a strict control of animal access to the beach[15]. Every owner or operator of beaches, marinas and boats who is awarded by the "Blue Flag" needs to fulfil a number of strict environmental, educational, safety and accessibility criteria.

The ban on disposable single-use plastics products by the Directive (EU) 2019/904 of the European Parliament and of the Council the urge to act is prominent. As already mentioned, the market situation in the catering sector (chapter 3) and in the tourism sector (chapter 2.1) has also adapted to this change. The introduction of biodegradable packaging, dishes & cutlery is feasible due to the market situation, since biodegradable products are now available in almost all supermarkets or can easily be ordered online. [16, 17]

5. Conclusion

In order to assess the possibility of replacing plastic packaging such as, dishes and cutlery with sustainable bio-based products on the beaches of Rostock, this study examined various solutions. Among others, the existing project launched in 2018 at the beaches in Warnemünde and Marktgrafenheide, which focuses on replacing plastic-based crockery and tableware with a biodegradable alternative in the catering sector. The project fulfils its essential objective. Plastic at Rostock's beaches is reduced and people are stimulated towards a more sustainable lifestyle as well as to rethink their behaviour.

In summary, the idea of reusing cutlery and crockery made of ceramic, glass or other reusable materials in the catering industry is excluded from the list of possibilities, due to a limited availability of water connections for catering facilities near the beach.

Other solutions, such as the reduction of packaging, the improvement of disposal/recycling and the usage of biodegradable packaging, all correspond to the five-stage system of the waste hierarchy, and are found in the studied project. The use of biodegradable materials such as cardboard, wood, palm leaves and bamboo reduces plastic waste. However, this leads to an increased amount of paper and

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[15] Blue Flag. Sustainable development goals. URL: https://static1.squarespace.com/static/55371ebde4b0e49a1e2ee9f6/t/5f43a1bd09e9764cd302f7d7/1598267874672/Blue+Flag+criteria+and+the+SDGs+-+Beach.pdf. [14.09.2020]

[16] Biofutura. Einweggeschirr & Besteck. URL: https://www.biofutura.com/de/bio-einweggeschirr-besteck?msclkid=be66cc15387a15351f379387809910b1&utm_source=bing&utm_medium=cpc&utm_campaign=DE%20-%20Search%20-%20Non-brand&utm_term=%2Bgeschirr%20%2Bbiologisch%20%2Babbaubar&utm_content=Geschirr%20-%20biologisch%20-%20abbaubar. [23.10.2020]

[17] REWE. Einweggeschirr. URL: https://shop.rewe.de/c/kueche-haushalt-geschirr-besteck-geschirr-einweggeschirr/. [23.10.2020]

bio waste. In the course of the project, the waste system was able to be improved by installing more waste bins along the beaches and extra waste bins for biodegradable packaging.

Conclusion for further Baltic Sea Countries and beach communities.

The substitution of single-use plastic with biodegradable alternatives and it is subsequent cascading into biogas/biomethane still needs further development. The project is served as a basis for this aim and identifies challenges for bio-based production caused by the German waste system. It was determined from the project that people are willing to change their behaviour, but still require education and training in the field of sustainability and waste separation.

The project has potential to be implemented into other systems, e.g. into systems with a longer composting cycle.

References:

Internet literature

Bornett, Karin (2020). Kunststoff adé? Die ganze Wahrheit über Verpackungen aus Plastikalternativen. CulumNatura für Haut und Haar, Blog – Blog-detail. URL: https://www.culumnatura.com/de/blog-detail/plastikverpackungen.html. Last accessed June 23, 2020.

City Bonn. Information on the German system of waste disposal. URL: https://www.mpifr-bonn.mpg.de/2878166/Waste-disposal.pdf. Last accessed July 20, 2020.

Deutsche Jugendherberge (2020). Nachhaltigkeit. Gemeinsam für unsere Zukunft. URL: https://www.jugendherbergen-mv.de/nachhaltigkeit/. Last accessed July 29, 2020

Die Bundesregierung (24 June 2020). Einweg-Plastik wird verboten. Teller, Besteck, To-go-Becher. URL: https://www.bundesregierung.de/bregde/themen/nachhaltigkeitspolitik/einwegplastik-wird-verboten-1763390. Last accessed July 28, 2020.

Gawenda, Martina (16 October 2019). Praxispeispiele für nachhaltiges Catering. *Event Partner – Fachmagazin für Event-Marketing*. Edition 4/2020. URL: https://www.event-partner.de/catering/praxisbeispiele-fuer-ein-nachhaltiges-catering/. Last accessed September 17, 2020.

Gibbens, Sarah (5 June 2019). You eat thousands of bits of plastic every year. Though abundant in water, air, and common foods, it's unclear how it might affect our health. *National Geographic.* URL: https://www.nationalgeographic.com/environment/2019/06/you-eat-thousands-of-bits-of-plastic-every-year/. Last accessed July 3, 2020.

Große, Patrick (26 November 2018). Was passiert mit dem deutschen Müll. DW. Made for minds. URL: https://www.dw.com/de/das-passiert-mit-dem-deutschen-m%C3%BCll/a-46458099. Last accessed August 10, 2020.

Hanse- und Universitätsstadt Rostock (2018). Biologisch abbaubares Geschirr. In Hanse- und Universitätsstadt Rostock, URL: https://www.rostock.de/aktiv/strand-meer/umweltmanagement-am-strand.html#biologisch-abbaubares-geschirr.last accessed June 13, 2020.

Hoffmann, Kai (14 February 2020). Gastro Vision 2020: Mehr Nachhaltige Produkte und Konzepte in der Branche. Published in Restaurant Reporter. URL: https://www.restaurant-reporter.de/gastro-vision-2020-mehr-nachhaltige-produkte-und-konzepte-in-der-branche/?cn-reloaded=1. Last accessed September 21, 2020.

InnProBio (2016). Biodegradability: Exposing some of the myths and facts. Factsheet No. 3. InnProBio. URL: https://innprobio.innovation-procurement.org/fileadmin/user_upload/Factsheet/Facts-heet_n_3.pdf. Last accessed July 28, 2020.

Lebensmittelverband Deutschland (2020). Lebensmittelbedarfsgegenstände. Lebensmittelverband Deutschland – Lebensmittel - Verpackungen.

URL: https://www.lebensmittelverband.de/de/lebensmittel/verpackung, last accessed June 13, 2020.

McNaughton, S., Nowakoski, K. (June 2019). How China's plastic waste ban forced a global recycling reckoning. The country once imported nearly half of the plante's plastic recyclables. ow the world is scrambling to adjust. URL: https://www.nationalgeographic.com/magazine/2019/06/china-plastic-waste-ban-mpacting-countries-worldwide/. Last accessed September 02, 2020.

Statistisches Bundesamt (Destatis) (2020). Pressemitteilung Nr. 103 vom 19 März 2020. URL: https://www.destatis.de/DE/Presse/Pressemitteilungen/2020/03/PD20_103_321.html;jsessionid=9BF08E5D8E2922A0220D960031B15A7D.internet8711. Last accessed July 23, 2020.

Schulte, Martin (24 July 2020). Müll im Müll treibt die Gebühren hoch und schadet der Umwelt. Abfallwirtschaft – Tonnenweise Fremdstoffe wie Plastik im Bioabfall erfordern großen Aufwand beim ZAKB. *Mannheimer Morgen.* URL: https://www.morgenweb.de/bergstraesser-anzeiger_artikel,-bergstrasse-muell-im-muell-treibt-die-gebuehren-hoch-und-schadet-der-umwelt-_arid,1665489.html. Last accessed July 24, 2020.

We future cycle (2015). Waste Management in Germany, 87% recycling rate. URL: https://wefuturecycle.com/2015/07/15/waste-management-in-germany-87-recycling-rate/. Last accessed July 20, 2020.

Literature

Agrar-Europe. Bundesregierung beschließt Verbot von Einwegkunststoffprodukten. 29 June 2020. Edition 27/20, p.8

Bauske, B., Münchhausen, M. von, Plitharas, A., Tsoukalas, K., Obersteiner, G., Cociancing, M., Fichtl, O., Annegg, F. (2019). Stop the flood of plastic. Effective measures to avoid single-use plastics and packaging in hotels. Berlin, Germany: *WWF Germany*.

Bräsel, M. (2019, November). Mikroplastik drastisch reduzieren. *Biogas Journal 6_2019*, pp. 80 - 83

World Economic Forum, Ellen MacArthur Foundation and McKinsey & Company (2016). The New Plastics Economy – Rethinking the future of plastics. *Ellen MacArthur Foundation,* Charity Registation No. 1130306, EU transparency register N°389996116741-55.

FNR (2019). Bioenergy in Germany Facts and Figures 2019. Solid fuels, Biofuels, Biogas. *Fachagentur Nachwachsende Rohstoffe e. V. (FNR)*. Order no. 484. Gülzow-Prüzen, Germany.

EUROPEAN PARLIAMENT; COUNCIL OF THE EUROPEAN UNION. (2008, 11 22). Directive 2008/98/EC of the European Parliament and of the council of 19 November 2008 on waste and repealing Directives. *Official Journal of the Europena Union*, p. L 312/3.

European Bioplastics (February 2020). Bioplastics market data 2019. Global production capacities of Bioplastics 2019-2014. *Report European Bioplastics*. Berlin, Germany.

Hobbs, S. R., Parameswaran, P., Astmann, B., Devkota, J. P., Landis, A. E. (2019): Anaerobic codigestion of food waste and polylactic acid: effect of pretreatment on methane yield and solid reduction. Published in: Hindawi. Advances in materials science and engineering, Volume 2019, Article ID

715904. https://doi.org/10.1155/2019/4715904.

Jambeck, J. R., Geyer, R., Wilcoy, C., Siegler, T. R., Perryman, M., Andrady , A., . . . Law, K. L. (2015). Plastic waste inputs from land into the ocean. *Science, 347(6223)*, 768 - 771.

Jaron, A. & Kossmann, C. (2018). Waste Management in Germany 2018. Facts, data, diagrams. *Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).* Druck- und Verlagshaus Zarbock GmbH & Co.KGLebensmittelverband Deutschland (2020).

Kreuzer, Stephanie (2020). Gesucht: grüne Alternative. Packaging 360°. Inspiration Nachwachsende Rohstoffe, p. 38-4?

LUNG MV (2018). Daten zur Abfallwirtschaft 2017. Schriftenreihe des LUNG MV 2018, Heft 2. Güstrow, Deutschland: *LUNG MV.*

Majer, S., & Oehmichen , K. (2017). *BIOSURF Deliverable D5.5: "Comprehensive methodology on calculating entitlement to CO2 certificates by biomethane producers".*

Marktstammdatenregister der Bundesnetzagentur (2020, 22 July). Meldung ausgewählter Energieträger. Auswertungszeitraum: Januar 2020 - Juni 2020.

NABU (2017). Vorverpackungen bei Obst und Gemüse. Zahlen und Fakten 2010 bis 2016. (2. Aufl.). Belrin, Germany: *NABU*.

Nelles, M., Grünes, J., & Morscheck, G. (2016). Waste Management in Germany – Development to a Sustainable Circular Economy? *Procedia Environmental Sciences*, 35 6-14.

Pfrogner, S., Bever, L., & Lindtner, M. (November 2018). Daten zur Abfallwirtschaft 2017 Mecklenburg Vorpommern. *Schriftenreihe des Landesamtes für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommern 2018, Heft 2* (p. 70). Güstrow: Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommern.

Stolte , A., Forster, S., Gerdts, G., & Schubert, H. (2015). Microplastic concentrations in beach sediments along the German Baltic coast. *Marine Pollution Bulletin, 99 (1-2)*, 2016 - 229.

Strazza, C., Olivieri, N., De Rose, A., Stevens, T., Peeters, L., Tawil-Jamault, D., & Buna, M. (2017, 12 21). Guidance principles for renewable energy technologies. Brussels: *European Commission - Directorate-General for Research and Innovation.*

Telephone interview with a representative and consultant in the project "Kein Plastik für die Fische". 18.09.2020, 07:57 - 08:19 am.

UN Environment Programme Report. (05 June 2018). Single- use plastics. A Roadmap for Sustainability. Fact-sheet for Policymakers. (rev. 1). *United Nations Environment Programme (UNEP)* and *International Environmental Technology Centre (IETC) Economy Devision of UNEP.*