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Processing concepts for the use of green leaves as raw materials for the food industry

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Large-scale processing of leaves for food applications requires quick processing or stabilisation to avoid perishability, due to the high moisture content in this biomass. Leaf perishability is compounded by the seasonal availability of crops, like sugar beet plants, of which the leaves are regarded as a potential protein source. This study evaluates the resource efficiency of a hypothetical sugar beet leaf processing chain by comparing supply chain options. First, two options consider leaf processing with and without stabilising the leaves by freezing. Then, these two options are considered in a centralised and decentralised process configuration. The latter places leaf freezing and pressing at the farm and further processes occur at a central facility. Energy usage and exergy consumption were used to quantify the thermodynamic performance of the processing options. Freezing has negligible effect on the processability of the leaves in terms of protein content and protein yield. The overall resource efficiency of the process was dominated by the amount of leaf material effectively used, which stresses the importance of full use of all (side-)streams. This outcome also explains the limited additional energy requirements for freezing. Exergetic indicators were affected by variations on the dry matter content of the starting biomass, compared to a negligible effect of other parameters (equipment scale, efficiency or energy use). Transportation load and soil quality were also discussed for the centralised and decentralised configurations. On-farm processing of the leaves (decentralised chain) clearly reduces the transportation load due to the large difference in bulk densities of leaves (73 kg/m3) and leaf juice (1000 kg/m3). Additionally, decentralised scenarios enable direct returning of the leaf pulp to the soil and thereby improving soil quality (i.e. nutrient retention and fertility). Soil quality is required to fully assess the use of biomass that is currently regarded as waste, but that actually plays a role in soil fertility. Therefore, the preferred chain configuration would be a decentralised system where the leaves are directly pressed at the farm, the pulp is used to fertilise the soil, and the leaf juice is chilled transported to a centralised factory.

1. Introduction

Green leaves are a potential source of functional food ingredients, such as bioactive compounds (Azmir et al., 2013); amino acids (Lammens et al., 2012); and valuable proteins for food (Pirie, 1966) and food supplements (Rathore, 2010). Despite our knowledge about leaf as a protein source and the existing extraction methods, the challenges for leaf processing are in the scale-up of the process and in the overall chain feasibility (Bals et al., 2012). Large-scale processing of leaves is limited by their high moisture content, which translates into large volumes and heavy weight in relation to the quantity of usable contents (Papendiek et al., 2012). This has implications for transportation, but also for spoilage of the leaves, which are prone to fast enzymatic and microbial decay (Kammes et al., 2011). Moreover, a full assessment requires evaluation of the implications for soil quality as well. This is in particular true for leaves that are crop byproducts and that currently remain on the soil and that have an effect on soil quality. Therefore, the feasibility of leaf processing for food should consider not only the extraction processes to obtain high added value products (e.g. proteins, bioactive compounds), but also the initial handling (e.g. harvest, storage) and stabilisation of the leaves, and the actual value of the biomass.

An important leaf source in Europe are sugar beet plants, being

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one of the most produced crops in several countries. Sugar beet leaves (SBL) are already explored for food applications, from process development (Jwanny et al., 1993) and improvement (Tamayo Tenorio et al., 2016), to protein characterisation (Sheen, 1991) and functionality (Merodio and Sabater, 1988), or as a sustainable food source (Lammens et al., 2012). The current practice, though, is to leave the SBL on the land after harvesting the primary product (i.e. sugar beet). When SBL are considered as a food source, the challenge of dealing with a biomass of high moisture content is compounded by their seasonal availability. The high water content of SBL can be reduced by pre-processing at the farm with a decentralised process configuration, while the seasonal availability translates into large peak capacities and process bottlenecks. The latter arise from the large amount of leaves per harvesting campaign. In the Netherlands, harvesting all SBL would result in ~27 kt/day of SBL over 4 months of harvest (Factfish.com, 2014). Therefore, seasonal availability of SBL also translates in the need for stabilisation to extend the leaf's shelf-life to ease processing bottlenecks. Those two issues are also due to the fact that SBL are not the primary product of the crop. In case leaves are the primary product, like alfalfa or spinach leaves, a different harvesting strategy is allowed.

Routes to stabilise fresh leaves include cooling, freezing and drying (van der Goot et al., 2016). Drying is the most energy intensive option (Berghout et al., 2015), given the large volumes of water that need to be removed in case of leaves. The average water content of leaves ranges between 85 and 90%, whereas that of protein crops (e.g. soybean, lupine beans) ranges between 8 and 15% (Kandlakunta et al., 2008). Assuming an energy requirement of 6 MJ per kg water (Berghout et al., 2015), drying the leaves would result in 6818 kJ/kg SBL or 380 MJ/kg protein, which exceeds the energy used for plant based proteins (37 MJ/kg protein) (Pimentel and Pimentel, 2003). Besides, drying the leaves damages their nutritive value (Bals et al., 2012), hinders the extractability of proteins (Hojilla-Evangelista et al., 2016), and requires harsh conditions to achieve high protein recovery (Zhang et al., 2014). This renders cooling and freezing as most suitable stabilisation methods. For seasonal crops like SBL, the harvesting peaks demand long time storage before all the leaves can be centrally processed. In that case, only freezing is suitable to extent the shelf life of leaves (5–7 days) over months, provided that the extraction and properties of final products are not compromised.

The suitability of freezing as a stabilising method, will be assessed on its sustainability (concerning the use of resources), together with the impact on the quality of extracted final products (i.e. protein extract). Exergy use is employed as an indicator for the use of resources, which are important in ensuring sustainability. Exergy is a state variable that is based on the first and second law of thermodynamics and indicates the maximum (i.e. available) work that can be extracted from a stream in relation to an environment of reference (Apaiah et al., 2006). Exergy-based indicators (e.g. exergy efficiency and exergy losses) reflect the environmental impact of a process/product in terms of irreversible destruction of natural resource use (Zisopoulos et al., 2017). Moreover, exergy can capture different forms of energy (i.e. thermal, pressure, electrical etc.) in one single unit (the Joule), for any system independently of its size, and therefore it considers also life cycle aspects (i.e. from farm to factory) (Genc et al., 2017). Therefore, exergy analysis can be used to objectively identify best processing conditions and practices before the actual implementation of a novel process and to find critical points in the process.

Furthermore, process decentralisation has been suggested as a processing practice to overcome negative environmental impact (i.e. soil nutrient losses) from SBL processing (van Dijk et al., 2013), and as a supply chain configuration for biomass with short shelf life and low transport density (e.g. lignocellulosic feedstock) (Hong et al., 2016). Instead of processing in a central facility, decentralisation implies the localisation of the first process steps on the farm, allowing easy return of unused side streams to the land to maintain soil quality (Bruins and Sanders, 2012). This processing approach brings along other benefits like increase of biomass bulk density and subsequent reduction of transportation volumes (Kudakasseril Kurian et al., 2013), and decrease of perishability effects by immediate processing (Kolfschoten et al., 2014). Hence, two network configuration scenarios (i.e. centralised versus decentralised) will be analysed together with freezing as stabilisation method.

The aim of this paper is to compare the resource efficiency of different processing concepts for the industrial use of SBL, using experimental data at lab scale and literature-based data at larger scales. Here, freezing was considered as a stabilisation treatment to ease peak production during further extraction of valuable leaf components, such as proteins. The resource efficiency of this stabilising method was assessed in terms of energy requirement and exergy indicators that quantify thermodynamic performance. Furthermore, we evaluated how decentralisation of the process would affect the stabilisation treatments and the overall resource efficiency of leaf valorisation. Finally, the assessment was extended with reported information on soil quality associated to SBL as an attempt to include aspects that are normally neglected when assessing the use of available biomass. The latter is evidenced by the use of the term 'waste' for byproduct streams.

2. Material and methods

2.1. General description of initial leaf processing

2.1.1. Leaf processing and stabilisation

Leaf processing implies collection, stabilisation, pressing and further processing into the desired products. For this, we consider two scenarios:

(A) fresh leaves are directly processed without stabilisation; and
(B) leaves are stabilised by freezing after harvesting to extend their shelf life, and consequently extend the time for mechanical pressing.

The sizes and composition of products streams that we propose here for sugar beet leaves (SBL) are based on a lab-scale method described by Tamayo Tenorio et al. (2016) (Fig. 1). The equipment capacity and typical energy consumption are based on pilot scale equipment. Initially, the leaves are pressed with a twin-screw press having a capacity of 315 kg SBL/h that uses 42.2 kJ of electricity/kg SBL (HUBER). The pressing step produces a leaf juice, while the leaf fibres are collected at the farthest end of the screws.

After pressing, the fibrous pulp (~27 w/v% of the initial biomass) is discarded. The extracted juice is heated to 50 °C for 30 min with hot water at 60 °C and cooled to room temperature with cold water at 10 °C. For the heating and cooling water we assume that they are readily available on-site. A burner using natural gas is used for heating the water. The juice is centrifuged in a continuous process and the resulting supernatant and sediment are collected. Stabilisation of fresh leaves and leaf juice is done by freezing with a plate-freezer using ammonia as cooling agent, which requires 337 kJ/kg SBL (ASHRAE, 2006). The frozen material is stored at −20 °C to be processed year round, requiring an average energy input of 0.5 kJ/m^3 (Koelcelvink, 2014). The frozen leaves are thawed before the mechanical pressing, using water at ambient temperature available on-site.