Environmental assessment of Biorefinery processes for the valorization of lignocellulosic wastes into oligosaccharides

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Abstract

The European Commission is adopting strategies in order to "closing the loop" of product life cycles in industrial production systems through better recycling and re-use under the perspective of circular economy. One of the most relevant goals in the application of this approach is to convert low-value side streams into more valuable products. In this sense, the conversion of lignocellulosic biomass into biofuels and chemicals is a major challenge not only from the technological but also from the economic and environmental perspectives.

In this study, the production of pectin-derived oligosaccharides (POS) from sugar beet pulp (SBP) was environmentally assessed by means of the Life Cycle Assessment methodology under a cradle-to-gate approach. Two different scenarios at pilot scale were considered: Scenario 1 based on conventional autohydrolysis at high temperature and Scenario 2 based on enzymatic hydrolysis.

The outcomes of this environmental study are highly dependent on the production yield of the target compounds (POS) and the valorisation strategy considered. In fact, the POS yield of the autohydrolysis approach is around 20% higher than in the enzymatic one. According to the results, Scenario 1 reports the worst results when a functional unit based on the amount of valorised material (100 kg of oven-dried SBP) is considered. However, the profile entirely changes when a unit based on the economic revenue (1 €) is managed. Therefore, attention should be paid on the selection of the functional unit since decision making strategies should highly depend on it.

Without waiting for the opportunity to conduct LCA of already-developed processes of the biorefinery system, the development of new alternatives must be carried out with sustainability in mind. Accordingly, the proposal of valorisation strategies for secondary streams should include the analysis of the environmental impacts associated to each alternative, even at the pilot plant stage.

Keywords: environmental profile; life cycle assessment; pectin-derived oligosaccharides; prebiotics; sugar beet pulp

1. Introduction

Sugar beet pulp is an abundant co-product from the sugar industry (Al-Tamimi et al., 2006; Zheng et al., 2013). Around 5 Mtons are produced in European countries (Ziemiński et al., 2014), of which nearly 20% is produced in Spain mainly for animal feed (Martínez et al., 2009a; Concha Olmos and Zúñiga Hansen, 2012).

The sustainable development of bio-processes in the short and medium-term is receiving special attention due to the fast depletion of fossil fuels, their fluctuating price as well as the increasing concerns on greenhouse gases (GHG) emission (Huisingh et al., 2015; Montazeri and Eckelman, 2015; Philp, 2015). Therefore, the current industry must then face the challenge to transform industrial low-value side products into more value-added materials (Pin et al., 2014; González-García et al., 2016; Van Uytvanck et al., 2014). In this sense, the implementation of the biorefinery scheme in the framework of the sugar beet industry must promote the innovation technologies that increase not only the yield and profitability of the processes but also that improve the environmental profile (Huisingh et al., 2015; González-García et al., 2016; Russell and Shiang, 2013).

Thus, sugar beet pulp (from now SBP) - a lignocellulosic source, could be considered a promising by-product with potential valorisation in a biorefinery scheme due to its composition and abundance. In the sugar beet processing system, the main product is sucrose, which accounts for 10-12% of the total biomass processed. However, the analysis of the SBP composition also comprises 20-25% cellulose, 25-36% hemicelluloses (mainly arabinans), 20-25% pectin, 10-15% protein and 1-2% lignin (Concha Olmos and Zúñiga Hansen, 2012; Ziemiński et al., 2014).

Although feed formulation is the main use of SBP (Concha Olmos and Zúñiga Hansen, 2012), other applications are also possible (Ziemiński et al., 2014), such as in the production of composites (Liu et al., 2005), galacturonic acid and arabinose (Leijdekkers et al., 2013) or biogas (Ziemiński et al., 2014) as well as in the papermaking industry due its low lignin content (Bellido et al., 2015). In recent studies, SBP has been evaluated as a potential source for the production of functional carbohydrates, paying attention to neutral and acidic oligosaccharides by means of a direct enzymatic saccharification treatment (Concha Olmos and Zúñiga Hansen, 2012; Martínez et al., 2009a).

Oligosaccharides are attracting increasing interest as prebiotic functional food ingredients (Rastall, 2010; Patel and Goyal, 2011) as they may confer health benefits on the host associated with the modulation of microbiota (Martínez et al., 2009b), especially pectin-derived oligosaccharides (POS) (Rastall, 2010; Patel and Goyal, 2011). POS can be produced from waste biomass or low-cost byproducts by applying a selective fractionation based on physical, chemical and enzymatic methods (Sun and Hughes, 1998; Patel and Goyal, 2011).

To the best of our knowledge, only one environmental study has been published with special focus on the environmental footprints of different production schemes of soluble saccharides of polymeric and oligomeric nature from woody residual streams (González-García et al., 2016). In this work, the assessment of the environmental impacts associated to the valorisation of SBP from the sugar refining industry for the production of POS was performed. To do this, a Life Cycle Assessment (LCA) was undertaken to analyse two valorisation scenarios based on different extraction routes considering SBP as raw material. On the basis of experimental results carried out at semi-pilot scale, the environmental *hotspots* responsible of the largest environmental impacts were identified. This environmental methodology considers all the resources (mass and energy balances) required to make a product, the wastes generated as well as the environmental burdens associated with the product (Goedkoop et al., 2008). In addition, this methodology can provide useful information to stakeholders and policy makers on decision making of processes under development. The principles established by ISO standards (ISO 14040, 2006) were followed in this research study.

2. Materials and methods

2.1 Goal and scope definition

This study aims to assess the environmental performance of different extraction routes of SBP from the sugar industry to obtain a POS extract with high content in arabino-oligosaccharides and oligogalacturonides. Side-streams are also derived from the system which could be used for further applications such as a solid stream rich on cellulose for bioethanol production and a liquid stream rich on monosaccharides. The description of both valorisation scenarios is included below.

- Scenario 1 based on the autohydrolysis of SBP (hydrothermal processing under non-isothermal conditions) performed in a stirred and pressurised stainless steel reactor at 163ºC (Martínez et al., 2009b).

- Scenario 2 based on the enzymatic hydrolysis of SBP performed by a combined enzyme concentrate of Cellulast and Viscozyme at 37ºC (Martínez et al., 2009a).

A cradle-to-gate approach was considered in the scenarios under assessment that is, considering the extraction of raw materials to produce the required inputs and the production of POS but not the phases of use and/or final disposal of POS. This perspective was assumed since the production systems are at semi-pilot scale and the products are not available in the markets yet. Among the processes considered throughout the production life cycle of both valorising schemes, centrifugation, membrane concentration and freeze-drying are performed after the extraction phase.

Considering that SBP is a co-product of the sugar refining process, the background process of SBP production (activities directly linked to the sugar production) was excluded from the assessment. Thus, derived environmental impacts were entirely allocated to the sugar.

The LCA functional unit must be selected carefully to allow comparisons between the valorising systems under study. Thus, the functional unit is defined as the valorisation of 100 kg of dry SBP at the factory gate, provided by a local pulp factory (Martínez et al., 2009b).

2.2 Description of the SBP valorisation scenarios

Each valorisation scenario destined to the production of POS was divided in five different subsystems which are depicted in **Figure 1**: hydrolysis (autohydrolysis - SS1.1 or enzymatic hydrolysis - SS1.2), centrifugation (SS2), concentration (SS3), diafiltration (SS4), freeze-drying (SS5) and wastewater treatment (SS6). The subsystems were assessed from the production of raw materials (resources) up to the final product at the pilot plant gate. The analysis of a pilot scale process located in the Faculty of Sciences from the University of Vigo (Orense, NW Spain) was performed. As indicated above, further processing and transport activities were excluded from the system boundaries as well as the activities related with the production of the SBP used as raw material. In both scenarios, SBP (70-72% moisture) was provided by a local pulp factory, homogenised in a single lot to avoid compositional differences, and stored in polyethylene bags at -18°C until use.

<**Figure 1** around here>

Scenario 1 – Autohydrolysis treatment

SBP is subjected an aqueous processing (autohydrolysis treatment – SS1.1) with tap water in a ratio of 12 g water per g dry pulp. In this work, the reactor was heated up to achieve a maximum temperature of 163ºC, the optimum conditions reported for the production of pectic-oligomers from SBP (Martínez et al. 2009a). The autohydrolysis treatment permits the selective breakdown of pectic polymers to give valuable soluble hydrolysis products such as pectin-oligomers (POS) and a solid fraction rich in cellulose and lignin. At the end of treatment, the reactor was rapidly cooled to 60ºC for 12 min, and the liquors were separated from the spent solids by centrifugation (SS2). **Table 1** shows the composition of the autohydrolysis liquors.

<**Table 1** around here>

Scenario 2 – Enzymatic Hydrolysis treatment

Based on previous studies (Martínez, 2009b), POS mixtures were obtained by enzymatic processing of SBP (SS1.2) using commercial enzymes (Celluclast 1.5L cellulases from *Trichoderma reesei* and Viscozyme 1.5L endopolygalacturonases from *Aspergillus aculeatus*). The experimental conditions considered were the following: water/solid ratio of 12 g/ g dry pulp, endopolygalacturonase/solid ratio of 10 U[1]/g, cellulase/endopolygalacturonase ratio of 0.725 FPU[2]/U and reaction time of 12.8 h. Sodium acetate buffer was used to maintain the medium at pH~5. At the end of process, liquors were separated by centrifugation (SS2). The experiments were carried out at 37ºC in Erlenmeyer flasks with orbital agitation (150 rpm). **Table 2** shows the composition of the hydrolysates obtained by enzymatic treatment.

<**Table 2** around here>

The autohydrolysis and enzymatic liquors (from SS1.1 and SS1.2 respectively) were treated for purification and concentration using a membrane processing unit (SS3 and SS4) in order to get a stream rich on POS. The experiments were carried out using a polymeric spiral membrane with molecular weight cut-off of 1 kDa and pressure of 8 bar. The processing was carried out at room temperature.

The processing started with the concentration of both streams to achieve a volume/concentration (VCR) ratio of 5 (SS3). For additional refining, water was added to the retentate to reach initial volume, and the resulting solution was concentrated again (discontinuous diafiltration – SS4) to achieve the same VCR. At the end of processing, two streams were obtained, a retentate rich on POS and a permeate rich on monosaccharides and other non-saccharide compounds. Finally, the retentate stream was freeze-dried (SS5) and permeates from SS4 and SS5 in both scenarios were sent to a wastewater treatment plant (SS6) for further treatment.

2.3 Inventory data collection and allocation approach

A reliable environmental assessment requires the collection of Life Cycle Inventory (LCI) data. In this study, inventory data for the foreground system (direct inputs and outputs for each stage) such as electricity requirements (estimated with power and operational data from the different units: reactors, centrifuges, membranes, orbital shakers and freeze-dryers) as well as the use of chemicals, enzymes

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[1] U: unit of enzymatic activity. It is defined as the amount of enzyme catalyzing the formation of 1 µmol of D-galacturonic acid per minute at 37ºC and pH 5.

[2] FPU: Filter Paper Activity

and water were average data of the pilot plant (primary data). A summary of the primary data is displayed in **Table 3** for the different valorisation scenarios. According to this table, the POS production yield (the main desired product) is around 20% higher in the autohydrolysis based scenario than in the enzymatic one. This result could be expected due to the enzymatic treatment commonly produces low weight POS which should derive on largest losses ratios in the purification units (membranes).

<**Table 3** around here>

Concerning the background system, the inventory data corresponding to the production of the different inputs to the systems (electricity, sodium acetate and tap water) and the wastewater treatment process were taken from Ecoinvent database® v3.1. Regarding sodium acetate, the specific production process is not included in the database and therefore, a representative process corresponding to the production of inorganic chemicals was considered instead of excluding it from the system boundaries. Regarding the production of enzymes (Viscozyme and Celluclast),information concerning the environmental burdens has been directly supplied by Novozymes[3] under confidential issues. Detailed information with regard to the background processes is summarised in **Table 4**.

<**Table 4** around here>

All the scenarios under assessment are multi-outputs systems with more than one product. Allocation of the environmental impacts is required for multi-functional processes and the selection of an allocation approach can have a strong effect on the results. According to the functional unit chosen based on the amount of waste valorized per batch (100 kg of dry SBP), no allocation procedure was required. The economic value of all the bioproducts differs significantly, which should motivate the use of an economic based approach. Therefore, an alternative functional unit in terms of economic value was considered based on the expected economic revenues of the bioproducts obtained in each scenario. **Table 5** reports the market prices considered for the different co-products and the expected net revenue.

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[3] http://www.novozymes.com .

<**Table 5** around here>

2.4 Impact assessment methodology

LCA evaluates the environmental burdens by identifying resource and energy consumption as well as emissions to different environmental compartments associated to the life cycle of the process under assessment, including the identification of priority areas to apply improvement actions (ISO 14040, 2006). The characterisation factors reported by the Centre of Environmental Science of Leiden University - CML 2001 method (Guinée et al. 2001) v2.05 were considered in this study for the analysis. The following impact categories were evaluated: abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), photochemical oxidation potential (POFP), ozone layer depletion potential (ODP), human toxicity potential (HTP), terrestrial ecotoxicity potential (TEP), freshwater aquatic ecotoxicity potential (FEP) and marine aquatic ecotoxicity potential (MEP). Moreover, SimaPro 8.02 was the software used for the computational implementation of the LCI (PRé Consultants, 2016).

3. Results and discussion

The environmental assessment in terms of characterisation results obtained for both schemes is displayed in **Table 6**. As previously indicated, the production of SBP, the main raw material, was excluded from the study because it was managed as a waste stream from sugar factories. Thus, environmental burdens derived from sugar processing are totally allocated to the main product of the production systems, i.e. sugar.

<**Table 6** around here>

According to the environmental results presented in **Table 6**, remarkable differences can be identified between both valorising schemes of SBP for the production of POS, which should be directly related with differences on the production systems. Although they share a number of stages in common (centrifugation – SS2, concentration – SS3, diafiltration – SS4, freeze-drying – SS5 and wastewater treatment – SS6), the main difference between both routes is focused on the first stage or subsystem, that is the hydrolysis of the SBP (SS1.1 and SS1.2 for scenarios 1 and 2, respectively). In Scenario 1, it is a hydrothermal processing under non-isothermal conditions carried out at high temperature (163ºC). On the contrary, Scenario 2 considers an enzymatic step based on the use of a cocktail of enzymes at moderate temperature (37ºC). This fact entails differences on the electricity requirements, being 565 times larger in Scenario 1 than Scenario 2. However, Scenario 2 requires enzymes whose production also entails energy consumption. Accordingly, Scenario 1 reports the worst environmental results in most categories except ODP, HTP, MEP and TEP. A detailed analysis of these results will be discussed below.

Contributions per subsystems involved

Figure 2a and 2b displays the distribution of environmental burdens per subsystems involved in the production schemes for Scenarios 1 and 2, respectively.

<**Figure 2** around here>

According to **Figure 2a**, the majority of the environmental burdens associated with Scenario 1 are related to the freeze-drying step (SS5) and the autohydrolysis stage (SS1.1). Freeze-drying process requires electricity consumption in order to obtain the final product (rich on POS and with low content on monosaccharides) while autohydrolysis is also energy intensive since the reactor operates at 163ºC. Both subsystems are responsible (on average) for 69% and 20% of the total contributions, respectively (see **Figure 2a**) and the difference in energy requirement is very relevant: 3.5 times higher in SS5 than in SS1.1 (**Table 3**). The equipment used in the subsequent steps (centrifuge and membranes) requires the lowest amounts of electricity and therefore, their contributions to the environmental profile are negligible regardless the impact category.

Concerning **Figure 2b**, modifications on the environmental profile can be identified. Once again SS1.2 and SS5 are the steps responsible for the majority of contributions to environmental impacts although with differences on the relative values and categories. SS5 is the environmental *hotspot* in all the categories with contributions ranging from 53% to 80% except in terms of MEP where SS1.2 is the main contributing subsystem with a contributing ratio of 74%. Enzymes, acetate and electricity production are the processes behind this impact. Enzymes production is a high intensive process, which demands large amounts of energy. In addition, enzymes production requires the addition of chemicals for the formulation of the culture medium and, the background processes related to their production are the main responsible of contributions to MEP.

If the source of the environmental burdens derived from SS1.2 is assessed in more detail, two inputs are identified as major responsible of impacts: the production of the enzyme cocktail for the enzymatic hydrolysis and the production of acetate for pH control. **Figure 3** displays the distribution of impacts derived from SS1.2 between the involved processes and, in line with the results, the production of acetate should be an environmental key factor, being responsible of the majority of the impacts in all the categories with ratios ranging from 54% to 88% except for MEP and TEP, where the production of the enzymes required for the hydrolysis contribute with 98% and 79% of the total impacts.

<**Figure 3** around here>

Total electricity requirements per batch in Scenario 2 are only 13% of the electricity consumed in Scenario 1 and enzymatic hydrolysis step reports the lowest energy requirements followed by SS2, SS3, SS4 and SS5, However, in Scenario 1 the highest electricity requirement is also observed in SS5 followed by SS1.1, SS3, SS4 and SS2. **Table 3** displays the distribution of electricity requirements between the subsystems directly involved in the valorising systems, excluding SS6 since the wastewater treatment plant is beyond the premises of the manufacture plant.

Alternative functional unit and allocation strategies

According to the results reported so far, Scenario 1 presents much higher environmental burdens than Scenario 2 in six impact categories. These results are related to a functional unit based on the amount of SBP used: 100 kg of dry SBP. This functional unit can be considered useful when valorising systems are being analysed and where multiple by-products are obtained since it corresponds to the amount of valorised material per batch (Pérez-López et al., 2014; González-García et al., 2016). Nevertheless, the amount of valuable by-products, which also present different market prices, depends on the scenario. Therefore, the potential revenue obtained per scenario should be different depending on the valorising strategy. The selection of the functional unit to report the results has just been previously discussed in numerous studies where biosystems have been environmentally analysed (Kim and Dale, 2006; Pérez-López et al., 2014; González-García et al., 2016). According to these studies, special attention must be paid on the selection of the functional unit to estimate the environmental profiles since strategic decisions highly depend on it.

For that reason, an alternative unit based on the potential economic benefit expected from each valorisation scenario could be of interest. In addition, an allocation procedure was also proposed here considering an economic allocation approach. The alternative functional unit proposed is the generation of 1 € of economic revenue from the valorisation of SBP into high added value products. Market prices available in the literature (Mercopress, 2006; Marketing study, 2009; Sigma-Aldrich, 2016; Megazyme, 2016) were managed and presented in **Table 5**.

Figure 4 displays the comparative profile between both scenarios considering 1 € of economic revenue as functional unit and it considerably changes in comparison with the profile corresponding to a functional unit based on the amount of processed biomass per batch. According to the results reported, Scenario 1 should involve the lowest impacts in all the categories under study. The reductions on the impacts should be remarkable in terms of MEP and TEP, where the enzymatic treatment based scenario reports 3.8 and 1.6 times higher burdens than Scenario 1. Both impact categories are significantly affected by the contributions from the enzymatic hydrolysis subsystem (SS1.2) as depicted in **Figure 2b,** being the enzyme production the main responsible factor (see **Figure 2b**).

<**Figure 4** around here>

If an economic allocation is considered on the basis of the production of POS and other by-products with economic value, the share of the environmental burdens between the different products should be carried out taking into account the allocation factors reported in **Table 4**. Thus, 96.9% and 95.6% of the impacts reported in **Table 5** for Scenario 1 and 2 respectively should be allocated to POS. The majority of burdens should correspond to the production of POS and negligible burdens should be assigned to the remaining by-products (except the uronic acids), mostly due to the lower price of the by-products (lignin, cellulose and hemicellulose). Around 3.1% and 4.4% of the impacts should be attributed to uronic acids. Therefore, when referring to the amount of POS produced, the environmental behaviour should be similar to the results reported in **Figure 4**, presenting Scenario 2 the worst profile.

According to González-García et al. (2016), purification activities (commonly concentration and freeze-drying processes) as well as autohydrolysis can be identified as the major responsible of environmental burdens when valorising routes into prebiotics are analysed. In our study, hydrolysis and freeze-drying were also identified as environmental *hotspots* specifically due to the high electricity requirements and enzymes (and chemicals) production. Thus, special attention and improvements should be paid on both activities since, regardless the valorisation route and raw material processed, are identified as critical steps.

Limitations of study

LCA methodology can be considered as a valuable and useful tool to support decision making strategies, specifically for production schemes which are still under development. LCA helps to identify the potential environmental risks associated with the production sequence in advance to their complete implementation. Therefore, it can be considered a predictive support not only from environmental but also from economic perspective. However, there are inherent difficulties in performing a LCA of a new bioproduct or production system.

In this case study under development, the major obstacles include the uncertainty arising from the immature nature of the technology and markets since the goal product (pectin-derived oligosaccharides) is not still available at commercial scale. However, and according to the literature (Gómez et al., 2016; Moniz et al., 2016) natural products and food ingredients with functional and healthy properties are receiving growing interest by consumers. Therefore, research efforts are required in order to enhance their efficiency and improve/optimise their production systems. Nowadays, the commercial oligosaccharides are inulin, lactose and sucrose (Moniz et al., 2016). Thus, the production of oligosaccharides by means of alternative sources such as lignocellulosic biomass is being boosted for multiple reasons not only economic but also environmental. In fact, xylo-oligosaccharides from lignocellulosic biomass are the only oligosaccharides available at present in the market although their market is still limited (Moniz et al., 2016).. The unwilling approach to provide extensive information on the processes under development could also be a limitation specifically in terms of the collection of good quality inventory data. This approach should be carefully managed specifically if the production systems are going to be analysed at pilot scale. Moreover, the lack of risk-associated information and the modelling assumptions (e.g. the use of proxy processes, system boundaries) are items that must be meticulously handled specially in decision making strategies.. Moreover, it has been demonstrated that choice of the reference unit in terms of which the environmental results are reported and analysed can considerably change the valorisation strategy selected.

4. Conclusions

The valorisation of refinery side-stream products is receiving special attention and it is a challenge of today’s industry. This study has analysed two different valorising routes of sugar beet pulp, by-product of the sugar industry, with the aim of obtaining POS, a product with prebiotic properties. According to the results, special attention must be paid on two specific stages: hydrolysis and freeze-drying of the final product. Moreover, the choice of the functional unit considered for analysis is really important since the results considerably change. The enzymatic based hydrolysis involved the requirement of enzymes whose production also requires energy. In contrast to the conventional hydrolysis carried out at high temperature, the consumption of electricity is 565 times lower. The valorising sequences analysed in this study appear to be attractive options to produce high-added value products with multiple applications. According to the outcomes, further research should be focused in order to improve the current valorising techniques at pilot scale. Inherent difficulties in performing the LCA of these new biorefinery systems related to the uncertainty arising from the immature nature of the technology are avoided in large scale systems. However, the results from this study help to identify the stages which require special effort to develop and optimize.

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Figure

Figure 1. System boundaries and process chain under study corresponding to the Scenario 1 - Autohydrolysis treatment and Scenario 2 – Enzymatic hydrolysis treatment. Processes marked in black were excluded from the system boundaries. Processes and lines marked in grey correspond exclusively to Scenario 2.

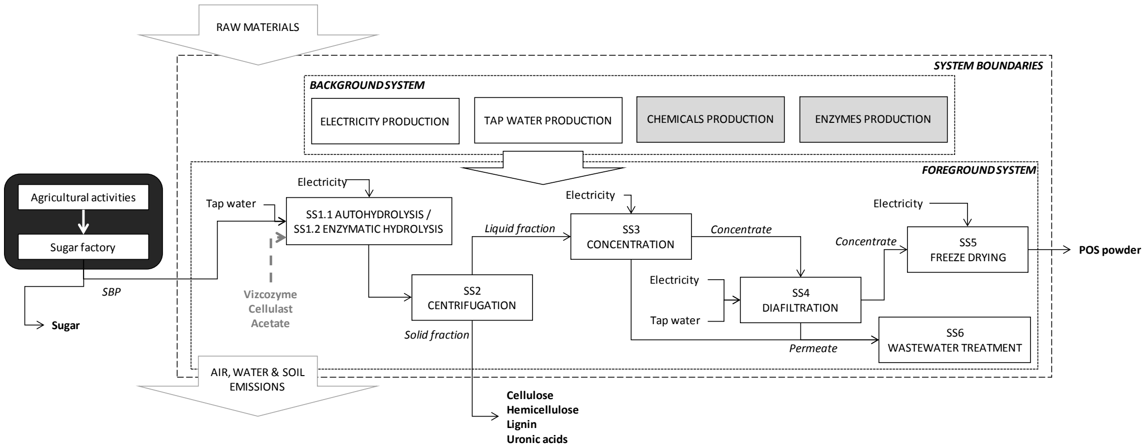

Figure 2. a) Distribution of environmental impacts per subsystems involved in Scenario 1; b) Distribution of environmental impacts per subsystems involved in Scenario 2. Acronyms: abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion potential (ODP), human toxicity potential (HTP), freshwater aquatic ecotoxicity potential (FEP), marine aquatic ecotoxicity potential (MEP), terrestrial ecotoxicity potential (TEP) and photochemical oxidation potential (POFP).

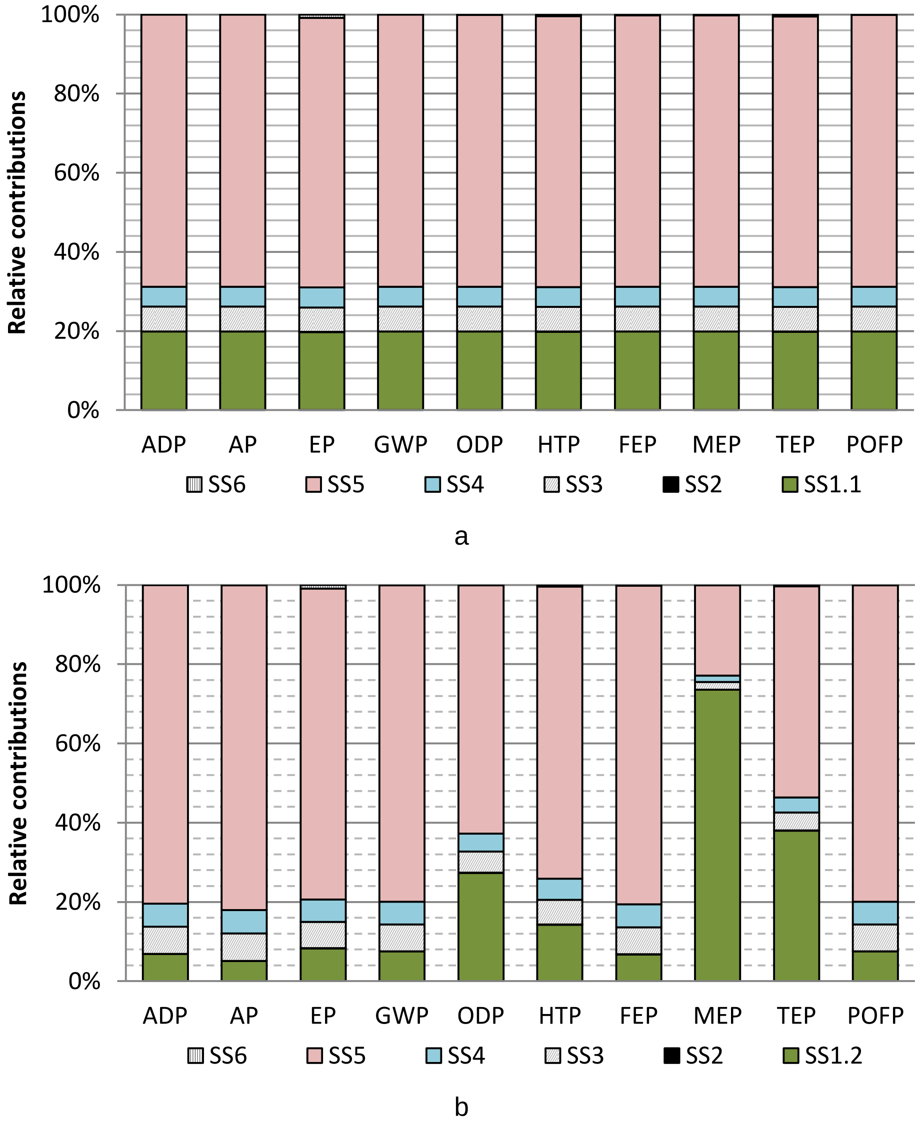

Figure 3. Distribution of impact burdens derived from SS1.2 between the different processes involved. Acronyms: abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion potential (ODP), human toxicity potential (HTP), freshwater aquatic ecotoxicity potential (FEP), marine aquatic ecotoxicity potential (MEP), terrestrial ecotoxicity potential (TEP) and photochemical oxidation potential (POFP).

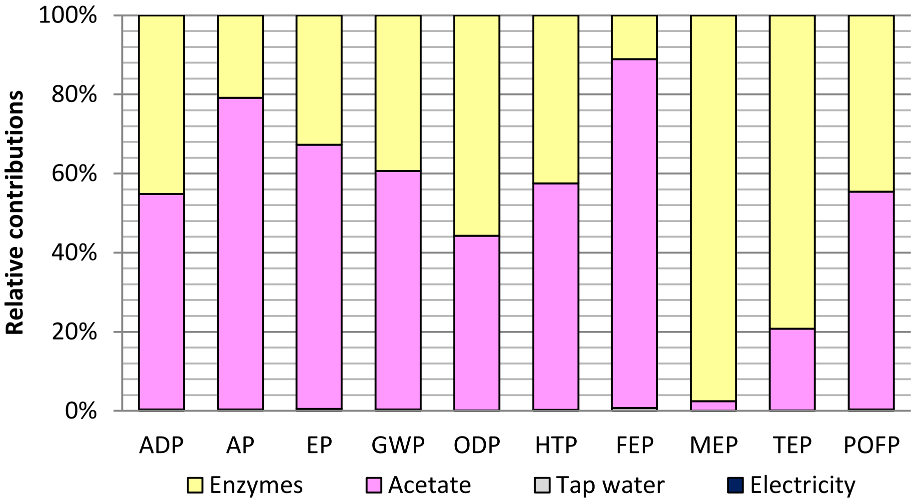

Figure 4. Comparative environmental profile considering 1 € of potential revenue as functional unit. Scenario 1 – Autohydrolysis treatment; Scenario 2 – Enzymatic hydrolysis treatment. Acronyms: abiotic depletion potential (ADP), global warming potential (GWP), ozone layer depletion potential (ODP), human toxicity potential (HTP), freshwater aquatic ecotoxicity potential (FEP), marine aquatic ecotoxicity potential (MEP), terrestrial ecotoxicity potential (TEP), photochemical oxidation potential (POFP), acidification potential (AP) and eutrophication potential (EP).

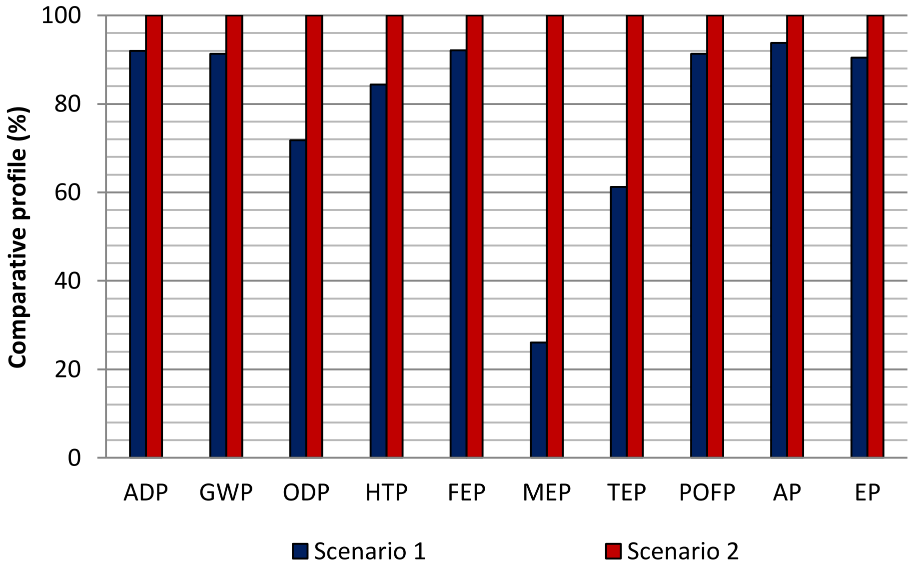

Table 1. Composition of liquid fraction (rich on pectic oligosaccharides) obtained by autohydrolysis treatment.

Component	**Composition**
Monosaccharides	
Glucose	2.36 g L^{-1}
Galactose	2.43 g L^{-1}
Arabinose	0.39 g L^{-1}
Pectin-derived oligosaccharides (POS)	
GlcOS	1.61 g L^{-1}
GalOS	2.96 g L^{-1}
AraOS	14.44 g L^{-1}
AcO	2.06 g L^{-1}
OGalA	11.86 g L^{-1}
Volatile compounds	
Acetic acid	0.38 g L^{-1}
Other non-volatile compounds	8.21 g L^{-1}

GlcOS = glucooligosaccharides; GalOS = galactooligosaccharides; AraOS = arabinooligosaccharides; AcO = acetyl substituents in oligomers; OGalA = oligogalacturonides

Table 2. Composition of hydrolysates (rich on pectic oligosaccharides) obtained by enzymatic processing.

Component	**Composition**
Monosaccharides	
Glucose	4.89 g L^{-1}
Galactose	2.90 g L^{-1}
Galacturonic acid	3.50 g L^{-1}
Arabinose	0.31 g L^{-1}
Pectin-derived oligosaccharides (POS)	
GlcOS	6.59 g L^{-1}
GalOS	3.02 g L^{-1}
AraOS	11.21 g L^{-1}
AcO	1.62 g L^{-1}
OGalA	10.29 g L^{-1}
Volatile compounds	
Acetic acid	0.55 g L^{-1}
Other non-volatile compounds	13.87 g L^{-1}

GlcOS = glucooligosaccharides; GalOS = galactooligosaccharides; AraOS = arabinooligosaccharides; AcO = acetyl substituents in oligomers; OGalA = oligogalacturonides

Table 3. Summary of main relevant inventory data per functional unit for POS powder production from SBP under two valorising scenarios: Scenario 1 - . Autohydrolysis treatment and Scenario 2 - Enzymatic hydrolysis treatment.

	Scenario 1	**Scenario 2**
Inputs		
Autohydrolisis (SS1.1)		
SBP (oven-dried)	100 kg	--
Tap water	945 kg	--
Electricity	1802.3 MJ	--
Enzymatic hydrolysis (SS1.2)		
SBP (oven-dried)	--	100 kg
Tap water	--	912.5 kg
Electricity	--	3.19 MJ
Viscozyme	--	0.18 kg
Celluclast	--	3.30 kg
Sodium acetate	--	30.0 kg
Centrifugation (SS2)		
Electricity	3.51 MJ	3.51 MJ
Concentration (SS3)		
Electricity	567 MJ	577.8 MJ
Diafiltration (SS4)		
Electricity	456.3 MJ	487.8 MJ
Tap water	726.2 kg	768.4 kg
Freeze-drying (SS5)		
Electricity	6234 MJ	6808 MJ
Outputs		
POS powder from SS5	25.75 kg	21.80 kg
Purified POS	25.40 kg	20.60 kg
Monosaccharides	0.35 kg	1.20 kg
Wastewater to treatment (from SS3+SS4)	1452.4 kg	1536.8 kg
Solid fraction from SS2	390.6 kg	338.9 kg
Cellulose (dry basis)	14.60 kg	6.70 kg
Hemicellulose (dry basis)	7.71 kg	10.33 kg
Lignin (dry basis)	7.50 kg	7.70 kg
Uronic acids (dry basis)	3.95 kg	4.90 kg

Table 4. List of the main ecoinvent database ® processes considered in this study

Input	**Ecoinvent database ® process**
Electricity	Electricity, medium voltage {ES}| market for | Alloc Rec, U
Tap water	Tap water {Europe without Switzerland}| market for | Alloc Rec, U
Sodium acetate	Chemical, inorganic {GLO}| market for chemicals, inorganic | Alloc Rec, U
Wastewater	Wastewater, average {CH}| treatment of, capacity 1E9l/year | Alloc Rec, U

Table 5. Market prices and net economic yield expected for each valorising scenario as well as allocation factors based on economic allocation approach.

		Allocation factors	
Co-products	**Market price**	**Scenario 1**	**Scenario 2**
POS powder	16.5 €·g$^{-1(1)}$	96.9%	95.6%
Lignin	302 €·t$^{-1(2)}$	0.0%	0.0%
Cellulose	686 €·t$^{-1(2)}$	0.0%	0.0%
Hemicellulose	102 €·t$^{-1(3)}$	0.0%	0.0%
Uronic acids	3.39 €·g$^{-1(4)}$	3.1%	4.4%
Economic yield			
Scenario 1	438,279 €·batch^{-1}		
Scenario 2	376,319 €·batch^{-1}		

[1]Megazyme (prices of arabinan); [2]Mercopress, 2006; [3]Marketing study, 2009; [4]Sigma-Aldrich, 2016

Table 6. Impact assessment characterisation values corresponding to the production of POS powder under two valorising schemes, per functional unit (100 kg of oven-dried SBP at the factory gate) and relative environmental difference between both scenario.

Impact categories	**Scenario 1**	**Scenario 2**	**Scenario 1 /Scenario 2**
ADP (kg Sb eq)	9.45	8.82	+7%
GWP (kg CO_2 eq)	1299	1221	+6%
AP (kg SO_2 eq)	12.37	11.33	+9%
EP (kg PO_4^{-3} eq)	2.35	2.23	+5%
ODP (kg CFC-11 eq)	$8.23\cdot10^{-5}$	$9.84\cdot10^{-5}$	-16%
POFP (kg C_2H_4 eq)	$4.51\cdot10^{-1}$	$4.24\cdot10^{-1}$	+6%
HTP (kg 1,4-DB eq)	235	239	-2%
TEP (kg 1,4-DB eq)	$2.74\cdot10^{-1}$	$3.84\cdot10^{-1}$	-29%
FEP (kg 1,4-DB eq)	365	340	+7%
MEP (kg 1,4-DB eq)	1385	4458	-69%