

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

30 **Keywords:** environmental profile; life cycle assessment; pectin-derived oligosaccharides; prebiotics;
31 sugar industry

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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 implementation and 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 those 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). Nevertheless, other biorefinery promising alternatives focused on the production of biofuels are still under

58 development (Leijdekkers et al., 2013). In recent studies, SBP has been evaluated as a potential
1 59 source for the production of functional carbohydrates, paying attention to neutral and acidic
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3 60 oligosaccharides by means of a direct enzymatic saccharification treatment (Concha Olmos and
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5 61 Zúñiga Hansen, 2012; Martínez et al., 2009a).
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10 62 Oligosaccharides are attracting increasing interest as prebiotic functional food ingredients (Rastall,
11 63 2010; Patel and Goyal, 2011) as they may bestow health benefits on the host associated with the
12 64 modulation of microbiota (Martínez et al., 2009b), especially pectin-derived oligosaccharides (POS)
13 65 (Rastall, 2010; Patel and Goyal, 2011). POS can be produced from waste biomass or low-cost
14 66 byproducts by applying a selective fractionation based on physical, chemical and enzymatic methods
15 67 (Sun and Hughes, 1998; Patel and Goyal, 2011).
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24 68 To the best of our knowledge, only one LCA study has been published with special focus on the
25 69 environmental footprints of different production schemes of soluble saccharides of polymeric and
26 70 oligomeric nature from woody residual streams (González-García et al., 2016). In this work, the
27 71 assessment of the environmental impacts associated to the valorisation of SBP from the sugar refining
28 72 industry for the production of POS was performed. To do this, a Life Cycle Assessment (LCA) was
29 73 undertaken to i) analyse two valorisation scenarios based on different extraction routes considering
30 74 SBP as raw material and based on experiments and protocols carried out at semi-pilot scale, ii)
31 75 identify the environmental *hotspots* responsible of the largest impacts, and iii) define the best
32 76 valorisation route in terms of minimal environmental impacts. This environmental methodology
33 77 considers all the resources (mass and energy balances) required to make a product, the wastes
34 78 generated as well as the environmental burdens associated with the product (Goedkoop et al., 2008).
35 79 In addition, this tool can provide useful information to industry and policy makers on decision making
36 80 towards the consideration of sustainability in processes under development.
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57 82 **2. Materials and methods**

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83 Life Cycle Assessment (LCA) methodology in compliance with the principles established by ISO
1 84 standards (ISO 14040, 2006) was performed from an attributional perspective in order to analyse the
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4 85 production of pectin-derived oligosaccharides (POS) from sugar beet pulp (SBP).
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8 86 **2.1 Goal and scope definition**

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12 87 This study aims to assess the environmental performance of different extraction routes of SBP from
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14 88 the sugar industry to obtain a POS extract with high content in arabino-oligosaccharides and
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16 89 oligogalacturonides. Side-streams are also derived from the system which could be used for further
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18 90 applications such as a solid stream rich on cellulose for bioethanol production and a liquid stream rich
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20 91 on monosaccharides. The description of both valorisation scenarios is included below.
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24 92 ▪ Scenario 1 based on the autohydrolysis of SBP (hydrothermal processing under non-
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26 93 isothermal conditions) performed in a stirred and pressurised stainless steel reactor at 163°C
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28 94 (Martínez et al., 2009b)
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32 95 ▪ Scenario 2 based on the enzymatic hydrolysis of SBP performed by a combined enzyme
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34 96 concentrate of Cellulast and Viscozyme at 37°C (Martínez et al., 2009a).
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39 97 A cradle-to-gate approach was considered in the scenarios under assessment that is, considering the
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41 98 extraction of raw materials to produce the required inputs and the production of POS but not the use
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43 99 and/or final disposal phase of POS after use. Among the processes considered throughout the
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45 100 production life cycles of both valorising schemes, centrifugation, membrane concentration and freeze-
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47 101 drying are performed after the extraction phase. Considering that SBP is a co-product of the sugar
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49 102 refining process, the background process of SBP production was excluded from the assessment.
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51 103 Thus, derived environmental impacts were entirely allocated to the sugar.
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55 104 The LCA functional unit must be selected carefully to allow comparisons between the valorising
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57 105 systems under study. Thus, the functional unit is defined as 100 kg of oven-dried SBP at the factory
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59 106 gate, provided by a local pulp factory (Martínez et al., 2009b).
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107 2.2 Description of the SBP valorisation scenarios

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4 108 Each valorisation scenario destined to the production of POS was divided in five different subsystems
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6 109 which are depicted in **Figure 1** and **Figure 2** for Scenario 1 and Scenario 2 respectively:
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8 110 autohydrolysis (SS1.1), enzymatic hydrolysis (SS1.2), centrifugation (SS2), concentration (SS3),
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10 111 diafiltration (SS4), freeze-drying (SS5) and wastewater treatment (SS6). The subsystems were
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12 112 assessed from the production of raw materials (resources) up to the final product at the pilot plant
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14 113 gate. As indicated above, further processing and transport activities were excluded from the system
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16 114 boundaries as well as the activities related with the production of the SBP used as raw material.

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20 115 In both scenarios, SBP (70-72% moisture) was provided by a local pulp factory, homogenised in a
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22 116 single lot to avoid compositional differences, and stored in polyethylene bags at -18°C until use.

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31 32 33 34 119 *Scenario 1 – Autohydrolysis treatment*

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39 120 SBP is subjected an aqueous processing (autohydrolysis treatment) with tap water in a ratio of 12 g
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41 121 water per g dry pulp. In this work, the reactor was heated up to achieve a maximum temperature of
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43 122 163°C, the optimum conditions reported for pectic-oligomers production from SBP (Martínez et al.
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45 123 2009a). The autohydrolysis treatment permits the selective breakdown of pectic polymers to give
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47 124 valuable soluble hydrolysis products such as pectic-oligomers (POS) and a solid fraction rich in
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49 125 cellulose and lignin. At the end of treatment, the reactor was rapidly cooled to 60°C for 12 min, and the
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51 126 liquors were separated from the spent solids by centrifugation. **Table 1** shows the composition of the
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53 127 autohydrolysis liquors.

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129 Scenario 2 – Enzymatic Hydrolysis treatment

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4 130 Based on previous studies (Martínez, 2009b), POS mixtures were obtained by enzymatic processing
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6 131 of SBP using commercial enzymes (Celluclast 1.5L cellulases from *Trichoderma reesei* and
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8 132 Viscozyme 1.5L endopolygalacturonases from *Aspergillus aculeatus*). The experimental conditions
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10 133 considered were the following: water/solid ratio of 12 g/ g dry pulp, endopolygalacturonase/solid ratio
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12 134 of 10 U/g, cellulase/endopolygalacturonase ratio of 0.725 FPU/U and reaction time of 12.8 h. At the
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14 135 end of process, liquors were separated by centrifugation. The experiments were carried out at 37°C in
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16 136 Erlenmeyer flasks with orbital agitation (150 rpm). **Table 2** shows the composition of the hydrolysates
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18 137 obtained by enzymatic treatment.

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26 139 The autohydrolysis and enzymatic liquors were treated for purification and concentration using a
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28 140 membrane processing unit in order to get a stream rich on POS. The experiments were carried out
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30 141 using a polymeric spiral membrane with molecular weight cut-off of 1 kDa and pressure operation of 8
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32 142 bar. The processing was carried out at room temperature.

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36 143 The processing started with the concentration of both streams to achieve a volume/concentration
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38 144 (VCR) ratio of 5. For additional refining, water was added to the retentate to reach initial volume, and
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40 145 the resulting solution was concentrated again (discontinuous diafiltration) to achieve the same VCR. At
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42 146 the end of processing, two streams were obtained, a retentate rich on POS and a permeate rich on
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44 147 monosaccharides and other non-saccharide compounds. Finally, the retentate stream was freeze-
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55 150 **2.3 Inventory data acquisition and allocation approach**

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151 A reliable environmental assessment requires the collection of high value Life Cycle Inventory (LCI)
152 data. In this study, inventory data for the foreground system (direct inputs and outputs for each stage)
153 such electricity requirements (estimated with power and operational data from the different units:
154 reactors, centrifuges, membranes, orbital shakers and freeze-dryers) as well as use of chemicals,
155 enzymes and water were average data of the pilot plant (primary data). A summary of the primary data
156 is displayed in **Table 3** for the different valorisation scenarios.

157 <**Table 3** around here>

158 Concerning the background system, the inventory data corresponding to the production of the different
159 inputs to the systems (electricity, chemicals and tap water) and the wastewater treatment process
160 were taken from Ecoinvent database® and data for enzyme production were found in Nielsen et al.
161 (2007).

162 All the scenarios under assessment are multi-outputs systems with more than one product. Allocation
163 of the environmental impacts is required for multi-functional processes and the selection of an
164 allocation approach can have a strong effect on the results. According to the functional unit chosen
165 (100 kg of oven-dried SBP), no allocation procedure was required since it is referred to the raw
166 material processed per batch instead of to the amount of products obtained. The economic value of all
167 the bioproducts differs significantly, which should motivate the use of an economic based approach.
168 Therefore, an alternative functional unit in terms of economic value was considered based on the
169 expected economic revenues of the bioproducts obtained in each scenario. **Table 4** reports the market
170 prices considered for the different co-products and the expected net revenue.

171 <**Table 4** around here>

173 **2.4 Impact assessment methodology**

174 LCA evaluates the environmental burdens by identifying resource and energy consumption as well as
175 emissions to different environmental compartments associated to the life cycle of the process under
176 assessment, including the identification of priority areas to implement improvement actions (ISO
177 14040, 2006). The characterisation factors reported by the Centre of Environmental Science of Leiden
178 University - CML 2001 method (Guinée et al. 2001) v2.05 were considered in this study for the
179 analysis. The following impact categories were evaluated: abiotic depletion potential (ADP),
180 acidification potential (AP), eutrophication potential (EP), global warming potential (GWP),
181 photochemical oxidation potential (POFP), ozone layer depletion potential (ODP), human toxicity
182 potential (HTP), terrestrial ecotoxicity potential (TEP), freshwater aquatic ecotoxicity potential (FEP)
183 and marine aquatic ecotoxicity potential (MEP). Moreover, SimaPro 8.02 was the software used for
184 the computational implementation of the LCI (PRé Consultants, 2016).

185 3. Results and discussion

186 The purpose of this work is to evaluate the environmental performance of two different valorising
187 routes for the production of POS from sugar beet pulp as raw material under a biorefinery perspective.
188 Both valorising schemes involve the production of POS together with a residual stream (solid fraction)
189 from the hydrolysis reactors, the latter presents a composition rich in valuable products - such as
190 cellulose, hemicellulose, lignin and uronic acids .

191 The environmental assessment in terms of characterisation results obtained for both schemes is
192 displayed in **Table 5**. As previously indicated, the production of SBP, the main raw material, was
193 excluded from the study because it was managed as a waste stream from sugar factories. Thus,
194 environmental burdens derived from sugar processing are totally allocated to the main product of the
195 production systems, i.e. sugar.

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197 According to the environmental results reported, remarkable differences can be identified between
198 both valorising schemes of SBP for the production of POS, which should be directly related with

199 differences on the production systems. Although they share a number of stages in common
200 (centrifugation – SS2, concentration – SS3, diafiltration – SS4, freeze-drying – SS5 and wastewater
201 treatment – SS6), the main difference between both routes is focused on the first stage or subsystem,
202 that is the hydrolysis of the SBP (SS1.1 and SS1.2 for scenarios 1 and 2, respectively). In Scenario 1,
203 it is a hydrothermal processing under non-isothermal conditions carried out at high temperature
204 (163°C). On the contrary, Scenario 2 considers an enzymatic step based on the use of a cocktail of
205 enzymes at moderate temperature (37°C). This fact involves differences on the electricity
206 requirements, being 5600 times larger in Scenario 1 than Scenario 2. However, Scenario 2 requires
207 enzymes whose production also entails energy consumption (Nielsen et al., 2007). Accordingly,
208 Scenario 1 reports the worst environmental results in most categories except ODP, HTP, MEP and
209 TEP. A detailed analysis of these results will be discussed below.

210 *Contributions per subsystems involved*

211 **Figure 3** and **Figure 4** displays the distribution of environmental burdens per subsystems involved in
212 the production chains for Scenarios 1 and 2, respectively.

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214 <**Figure 4** around here>

215 According to **Figure 3**, the majority of the environmental burdens associated with Scenario 1 are
216 related to the freeze-drying step (SS5) and the autohydrolysis stage (SS1.1). Freeze-drying process
217 requires electricity consumption in order to obtain the final product (rich on POS and with low content
218 on monosaccharides) while autohydrolysis is also energy intensive since the reactor operates at
219 163°C. Both subsystems are responsible (on average) for 69% and 20% of the total contributions,
220 respectively (see **Figure 3**) and the difference in energy requirement is very relevant: 3.5 times higher
221 in SS5 than in SS1.1 (**Table 3**). The equipment used in the subsequent steps (centrifuge and
222 membranes) reports the lowest amounts of electricity and therefore, their contributions to the
223 environmental profile is negligible regardless the impact category.

224 Concerning **Figure 4**, modifications on the environmental profile can be identified. Once again SS1.2
1 225 and SS5 are the steps responsible for the majority of contributions to environmental impacts although
2 226 with differences on the relative values and categories. SS5 is the environmental *hotspot* in all the
3 227 categories with contributions ranging from 53% to 80% except in terms of MEP where SS1.2 is the
4 228 main contributing subsystem with a contributing ratio of 74%. Enzymes, acetate and electricity
5 229 production are the processes behind this impact.
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14 230 If the source of the environmental burdens derived from SS1.2 is assessed in more detail, two inputs
15 231 are identified as major responsible of impacts: the production of the enzyme cocktail for the enzymatic
16 232 hydrolysis and the production of acetate for pH control. **Figure 5** displays the distribution of impacts
17 233 derived from SS1.2 between the involved processes and, in line with the results, the production of
18 234 acetate should be an environmental key factor, being responsible of the majority of the impacts in all
19 235 the categories with ratios ranging from 54% to 88% except for MEP and TEP, where the production of
20 236 the enzymes required for the hydrolysis contribute with 98% and 79% of the total impacts.
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38 239 Total electricity requirements per batch in Scenario 2 are only 13% of the electricity consumed in
39 240 Scenario 1 and enzymatic hydrolysis step reports the lowest energy requirements followed by SS2,
40 241 SS3, SS4 and SS5, However, in Scenario 1 the highest electricity requirement is also observed in SS5
41 242 followed by SS1.1, SS3, 224 and SS2. **Figure 6** displays the distribution of electricity requirements
42 243 between the subsystems directly involved in the valorising systems, excluding SS6 since the
43 244 wastewater treatment plant is beyond the premises of the manufacture plant.
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248 *Alternative functional unit and allocation strategies*

249 According to the results reported so far, Scenario 1 presents much higher environmental burdens than
250 Scenario 2 in six impact categories, excluding ODP, HTP, MEP and TEP, which considerably depend
251 on the burdens associated to the enzyme production. These results are related to a functional unit
252 based on the amount of SBP used: 100 kg of SBP. This functional unit can be considered useful when
253 valorising systems are being analysed and where multiple by-products are obtained since it
254 corresponds to the amount of valorised material per batch (Pérez-López et al., 2014; González-García
255 et al., 2016). Nevertheless, the amount of valuable by-products, which also present different market
256 prices, depends on the scenario. Therefore, the potential revenue obtained per scenario should be
257 different depending on the valorising strategy. The selection of the functional unit to report the results
258 has just been previously discussed in numerous studies where biosystems have been environmentally
259 analysed (Kim and Dale, 2006; Pérez-López et al., 2014; González-García et al., 2016). According to
260 these studies, special attention must be paid on the selection of the functional unit in order to report
261 the environmental profiles since the decision strategies highly depend on it.

262 For that reason, an alternative functional unit based on the potential economic benefit expected from
263 each valorisation scenario could be of interest. In addition, an allocation procedure was also proposed
264 here considering an economic allocation approach. The alternative functional unit proposed is 1 € of
265 economic revenue. Market prices available in the literature (Mercopress, 2006; Marketing study, 2009;
266 Sigma-Aldrich, 2016) were managed and presented in **Table 4**.

267 **Figure 7** displays the comparative profile between both scenarios considering 1 € of economic
268 revenue as functional unit and it considerably changes in comparison with the profile corresponding to
269 a functional unit based on the amount of processed biomass per batch. According to the results
270 reported, Scenario 1 should involve the lowest impacts in all the categories under study. The
271 reductions on the impacts should be remarkable in terms of MEP and TEP, where the enzymatic
272 treatment based scenario reports 3.8 and 1.6 times higher burdens than Scenario 1. Both impact

273 categories are significantly affected by the contributions from the enzymatic hydrolysis subsystem
1 274 (SS1.2) as depicted in **Figure 4**, being the enzyme production the main responsible factor (see **Figure**
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10 11 12 277 <**Figure 7** around here> 13 14 15

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20 279 If an economic allocation is considered on the basis of the production of POS and other by-products
21 280 with economic value, the partition of the environmental burdens between the different products should
22 281 be carried out taking into account the allocation factors reported in **Table 4**. Thus, 96.9% and 95.6% of
23 282 the impacts reported in **Table 5** for Scenario 1 and 2 respectively should be allocated to POS. The
24 283 majority of burdens should correspond to the production of POS and negligible burdens should be
25 284 allocated to the remaining by-products (except the uronic acids), mostly due to the lower price of the
26 285 by-products (lignin, cellulose and hemicellulose). Around 3.1% and 4.4% of the impacts should be
27 286 allocated to the uronic acids. Therefore, when referring to the amount of POS produced, the
28 287 environmental behaviour should be similar to the results reported in **Figure 7**, presenting Scenario 2
29 30 31 32 33 34 35 36 37 38 39 288 the worst profile.

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47 290 *Comparison with related studies* 48 49 50

51 291 According to the literature revised, no LCA studies are available for prebiotic products obtained from
52 292 SBP. González-García et al. (2016) analysed the production of soluble saccharides of polymeric and
53 293 oligomeric nature (POHs) from residual woody chips. In that study, different valorising routes were
54 294 environmentally evaluated which derived on the production of multiple by-products (lignin, cellulose,
55 295 monosaccharides, antioxidant extract, levulinic acid and formic acid) together with POHs. The results
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296 determined the best valorising route from an environmental perspective and identified the critical
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2 297 subsystems or production stages. Thus, purification activities which involve concentration and freeze-
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4 298 drying as well as autohydrolysis were identified as the major responsible of environmental burdens. In
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6 299 our study, hydrolysis and freeze-drying were also identified as environmental *hotspots* specifically due
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8 300 to the high electricity requirements and enzymes (and chemicals) production. Thus, special attention
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10 301 and improvements should be paid on both activities since, regardless the valorisation route and raw
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12 302 material processed, are identified as critical steps.

16 303 4. Conclusions

20 304 The valorisation of refinery side-stream products is receiving special attention and it is a challenge of
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22 305 today's industry. This study has analysed two different valorising routes of sugar beet pulp, by-product
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24 306 of the sugar industry, with the aim of obtaining POS, a potential product with prebiotic properties.
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26 307 According to the results, special attention must be paid on two specific stages: the hydrolysis and the
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28 308 freeze-drying of the final product. However, the one based on an enzymatic treatment should report
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30 309 the best environmental results regardless the functional unit considered for analysis. The enzymatic
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32 310 based hydrolysis involved the requirement of enzymes whose production also requires energy. In
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34 311 contrast to the conventional hydrolysis carried out at high temperature, the consumption of electricity
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36 312 is 5600 times lower. The valorising sequences analysed in this study appear to be attractive options to
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38 313 produce high-added value products with multiple applications. According to the outcomes, further
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40 314 research should be focused in order to improve the current valorising techniques at pilot scale.

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Santiago de Compostela, 12th July 2016

Dear Dr. **Huisingh**:

We are pleased to enclose the revision of our original manuscript entitled **“ENVIRONMENTAL ASSESSMENT OF BIOREFINERY PROCESSES FOR OLIGOSACCHARIDE PRODUCTION INTEGRATED TO THE SUGAR BEET INDUSTRY”** by S. González-García, B. Gullón and MT. Moreira, which can hopefully be published in *Journal of Cleaner Production*. This paper has not been previously published, in whole or in part, and is not under consideration by any other journal.

A challenge of today's industry is to convert low-value side streams into more valuable products. In this sense, the conversion of lignocellulosic biomass into fuels and chemicals represents not only scientific but also economic and technical challenges, covering different fields of chemical and environmental engineering.

In this study, the production of pectin-derived oligosaccharides (POS) - promising candidates for prebiotic properties, from sugar beet pulp (SBP) - a by-product of the sugar industry very abundant in Europe, has been assessed from an environmental perspective using the Life Cycle Assessment methodology (cradle-to-gate approach). Two different scenarios have been designed at pilot scale: 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 route followed. In fact, POS yield is around 20% higher in the autohydrolysis approach than in the enzymatic one. Finally, to keep the biorefinery options sound from an environmental perspective, it is mandatory to take into account the impacts associated to the valorisation of secondary streams, even at the pilot plant stage.

We hope that this work is appropriate for publication in *Journal of Cleaner Production*.

Yours sincerely,

Sara González García

Figure 1. System boundaries and process chain under study corresponding to the Scenario 1 - Autohydrolysis treatments. Processes marked in black were excluded from the system boundaries.

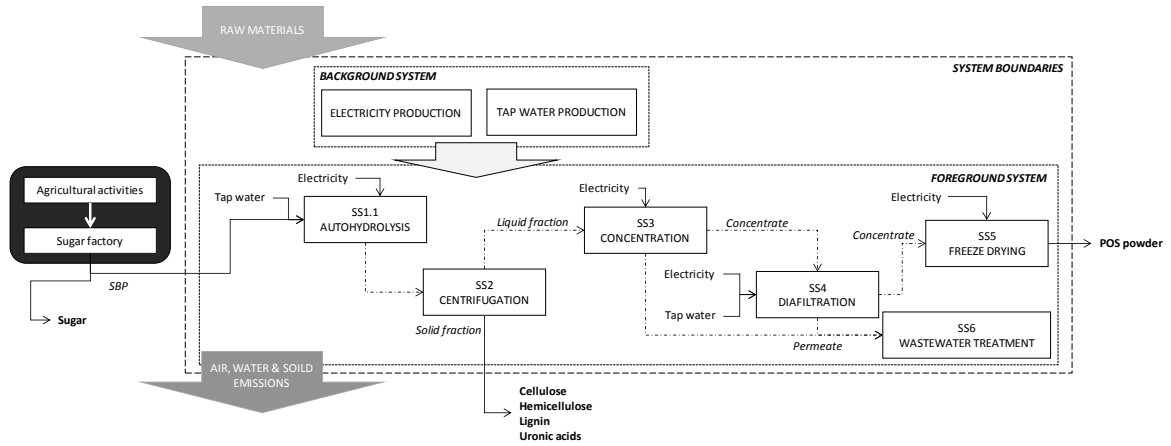


Figure 2. System boundaries and process chain under study corresponding to the Scenario 2 - Enzymatic Hydrolysis treatment. Processes marked in black were excluded from the system boundaries.

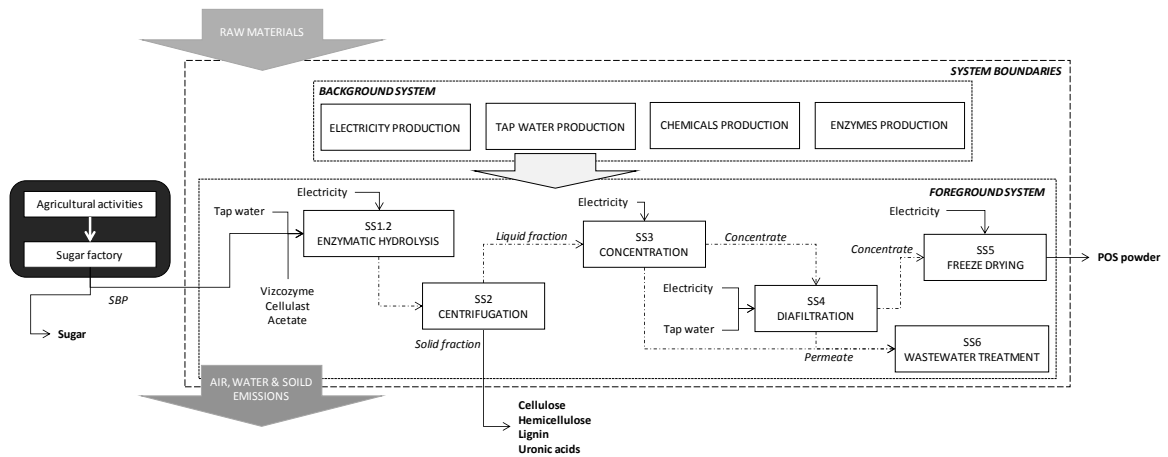


Figure 3. Distribution of environmental impacts per subsystems involved in Scenario 1. Acronyms: abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion potential (ODP), human toxicity potential (HTP), freshwater aquatic ecotoxicity potential (FEP), marine aquatic ecotoxicity potential (MEP), terrestrial ecotoxicity potential (TEP) and photochemical oxidation potential (POFP),

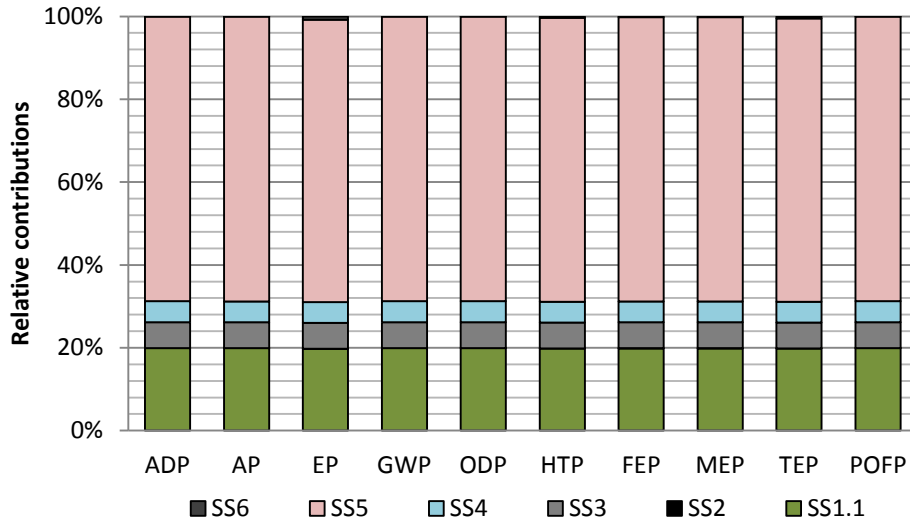


Figure 4. Distribution of environmental impacts per subsystems involved in Scenario 2. Acronyms: abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion potential (ODP), human toxicity potential (HTP), freshwater aquatic ecotoxicity potential (FEP), marine aquatic ecotoxicity potential (MEP), terrestrial ecotoxicity potential (TEP) and photochemical oxidation potential (POFP),

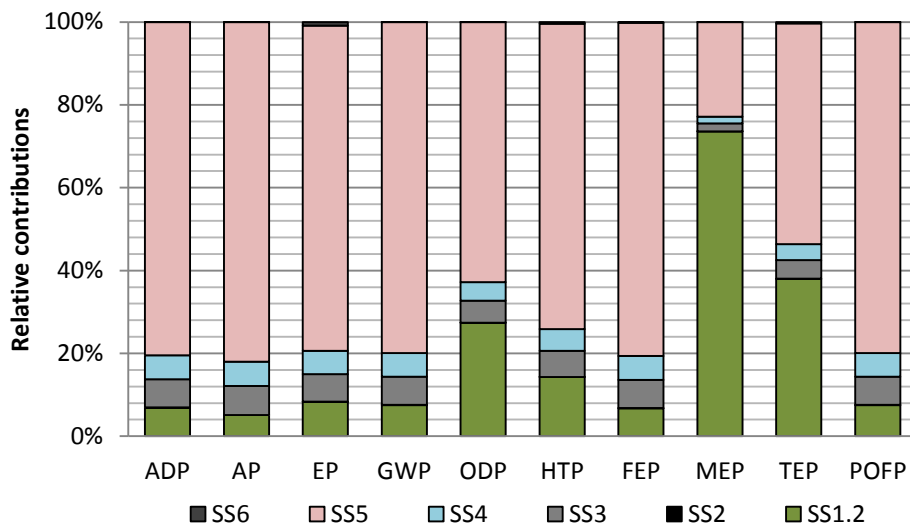


Figure 5. Distribution of impact burdens derived from SS1.2 between the different processes involved. Acronyms: abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion potential (ODP), human toxicity potential (HTP), freshwater aquatic ecotoxicity potential (FEP), marine aquatic ecotoxicity potential (MEP), terrestrial ecotoxicity potential (TEP) and photochemical oxidation potential (POFP),

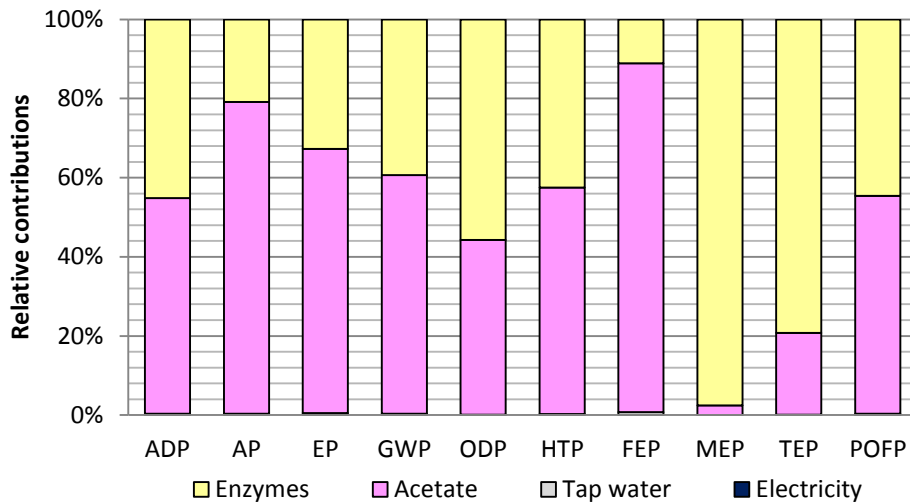


Figure 6. Distribution of electricity consumption per subsystems involved in each scenario. Scenario 1 – Autohydrolysis treatment; Scenario 2 – Enzymatic hydrolysis treatment. Acronyms: hydrolysis (SS1), centrifugation (SS2), concentration (SS3), diafiltration (SS4) and freeze-drying (SS5).

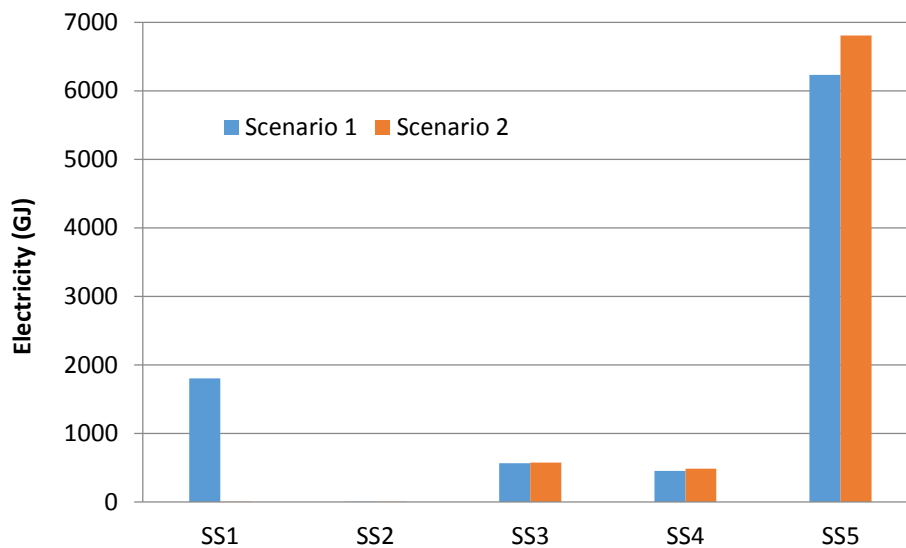
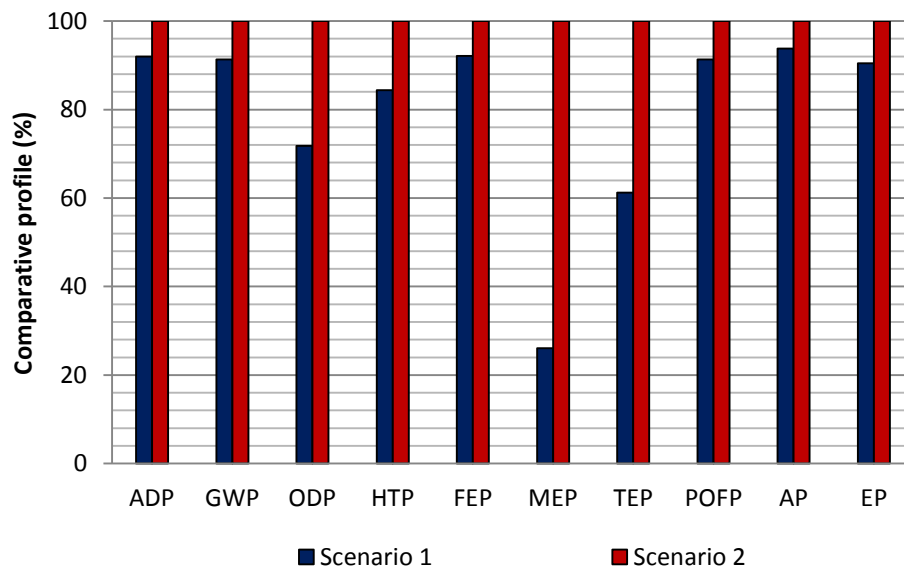


Figure 7. Comparative environmental profile considering 1 € of potential revenue as functional unit. Scenario 1 – Autohydrolysis treatment; Scenario 2 – Enzymatic hydrolysis treatment. Acronyms: abiotic depletion potential (ADP), global warming potential (GWP), ozone layer depletion potential (ODP), 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),



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

Component	Composition
<i>Monosaccharides</i>	
Glucose	2.36 g L ⁻¹
Galactose	2.43 g L ⁻¹
Arabinose	0.39 g L ⁻¹
<i>Pectin-derived oligosaccharides (POS)</i>	
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
<i>Volatile compounds</i>	
Acetic acid	0.38 g L ⁻¹
<i>Other non-volatile compounds</i>	
	8.21 g L ⁻¹

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

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

Component	Composition
<i>Monosaccharides</i>	
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
<i>Pectin-derived oligosaccharides (POS)</i>	
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
<i>Volatile compounds</i>	
Acetic acid	0.55 g L ⁻¹
<i>Other non-volatile compounds</i>	
	13.87 g L ⁻¹

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

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12 **Table 3.** Summary of main relevant inventory data for POS powder production from SBP under two valorising
 13 scenarios: Scenario 1 - . Autohydrolysis treatment and Scenario 2 - Enzymatic hydrolysis treatment.
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	Scenario 1	Scenario 2
Inputs		
<i>Autohydrolysis</i>		
SBP (oven-dried)	100 kg	--
Tap water	945 kg	--
Electricity	1802304 kJ	--
<i>Enzymatic hydrolysis</i>		
SBP (oven-dried)	--	100 kg
Tap water	--	912.5 kg
Electricity	--	3192.3 kJ
Vizcozyme	--	0.18 kg
Cellulast	--	3.30 kg
Acetate	--	30.0 kg
<i>Centrifugation</i>		
Electricity	3510 kJ	3510 kJ
<i>Concentration</i>		
Electricity	567000 kJ	577800 kJ
<i>Diafiltration</i>		
Electricity	456300 kJ	487820 kJ
Tap water	726.2 kg	768.4 kg
<i>Freeze-drying</i>		
Electricity	6234000 kJ	6808000 kJ
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

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20 **Table 4.** Market prices and net economic yield expected for each valorising scenario as well as allocation
 21 factors based on economic allocation approach.

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

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26 **Table 5.** Impact assessment characterisation values corresponding to the production of POS powder under two
 27 valorising schemes, per functional unit (100 kg of oven-dried SBP at the factory gate).

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Impact categories		Scenario 1	Scenario 2
Abiotic depletion potential	ADP	9.45 kg Sb eq	8.82 kg Sb eq
Global warming potential	GWP	1299 kg CO ₂ eq	1221 kg CO ₂ eq
Acidification potential	AP	12.37 kg SO ₂ eq	11.33 kg SO ₂ eq
Eutrophication potential	EP	2.35 kg PO ₄ ⁻³ eq	2.23 kg PO ₄ ⁻³ eq
Ozone layer depletion potential	ODP	8.23·10 ⁻⁵ kg CFC-11 eq	9.84·10 ⁻⁵ kg CFC-11 eq
Photochemical oxidation potential	POP	4.51·10 ⁻¹ kg C ₂ H ₄ eq	4.24·10 ⁻¹ kg C ₂ H ₄ eq
Human toxicity potential	HTP	235 kg 1,4-DB eq	239 kg 1,4-DB eq
Terrestrial ecotoxicity potential	TEP	2.74·10 ⁻¹ kg 1,4-DB eq	3.84·10 ⁻¹ kg 1,4-DB eq
Freshwater aquatic ecotoxicity potential	FEP	365 kg 1,4-DB eq	340 kg 1,4-DB eq
Marine aquatic ecotoxicity potential	MEP	1385 kg 1,4-DB eq	4458 kg 1,4-DB eq

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