STAR-ProBio

Sustainability Transition Assessment and Research of Bio-based Products

Grant Agreement Number 727740

Deliverable D2.3

Life cycle inventory of feedstock production and upstream processing

Version 1.0, [25/08/2019]

This project is funded by the European Union's Horizon 2020 Research and innovation action under grant agreement No 727740 with the Research Executive Agency (REA) - European Commission. Duration: 36 months (May 2017 – April 2020).
Work Programme BB-01-2016: Sustainability schemes for the bio-based economy
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REPORT

Deliverable identifier	D2.3
Document status	Final
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Lead Beneficiary	USC
Deliverable Type	Report
Dissemination Level	Public
Month due (calendar month)	Month 28 (August 2019)

DOCUMENT HISTORY

Version	Description
0.1	First draft
0.2	Second draft
1.0	Final

Abstract

This report has a three-fold perspective: 1) to assess the life cycle inventory (LCI) of upstream processes; 2) to show preliminary results of life cycle impact (LCIA) assessment and 3) to apply the hybridized indicators, assessed in the Deliverable 3.1 (WP3), for upstream processes. The uppermost purpose of this sudy is to summarize the LCI of feedstock production and upstream processing for sugar beet pulp, maize grain and maize stover and model sugar production. Sugars, such as glucose and xylose, are fermentable feedstocks capable of producing a variety of bio-products, such as polylactic acid (PLA) and polybutylene succinate (PBS). Maize grain is a starch-rich crop, easily broken down into glucose by enzymatic hydrolysis. Also, sugar beet pulp and maize stover are rich in ligno-hemicellulose, which can also be converted into a mixture of sugars (glucose, xylose, arabinose, galactose…) by enzymatic hydrolysis. However, it is necessary to carry out a pretreatment process to break the ligno-hemicellulosic polymers.

The materials and energy flows for maize and sugar beet agricultural activities and maize processing were gathered from literature and databases. Data for the pretreatment and enzymatic hydrolysis processes of the lignocellulose-rich maize stover and sugar beet pulp were designed and modelled by our AUA partners. 20 different fermentable sugar scenarios were considered, including 10 for maize grain, 4 for maize stover and 6 for sugar beet pulp. Although this study represents the life cycle inventory phase, it was decided to include and anticipate some preliminary LCIA results only for two agricultural systems, considering some of the environmental impact categories proposed in Deliverable 2.2. Among the hybrid indicators, four were applied for upstream processes: hazardous chemical use, feedstock efficiency, waste factor and energy efficiency.

Suggested citation

STAR-ProBio (2019), STAR-ProBio Deliverable D2.3, Life Cycle Inventory for feedstock production and upstream processing. Available from Internet: www.star-probio.eu.

Disclaimer

STAR-ProBio has received funding from the European Union's Horizon 2020 Program research and innovation programme under grant agreement No. 727740.

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Executive summary

In the current context of the bioeconomy, the use of renewable materials as a substitute for fossil fuels to produce bio-products has aroused growing interest. Fermentable sugars (glucose, xylose, galactose…) are materials derived from carbohydrate-rich feedstocks, such as starch crops (e.g. maize and wheat grain), sugar crops (e.g. sugar beet and sugarcane) and lignocellulosic materials (e.g. wheat straw, maize stover, woodchips). The processing of first-generation crops to produce bioproducts potentially affecting food production is a controversial issue. The population continues to grow, which directly influences the increased demand for food. This puts great pressure on the ecosystem and that diminishes the benefits generated to the mankind, the so-called ecosystem services. Thus, the use of non-edible biomass or that which does not compete with food/feed markets, i.e. second-generation raw materials, are considered more sustainable alternatives as feedstock in the production of bio-products. However, the technology for processing second-generation biomass is still in its early stages of development, compared to first-generation raw materials.

The main objective of this deliverable is to detail the life cycle inventory (LCI) phase of feedstock production and upstream processing with respect to the production of fermentable sugars from maize grain, maize stover and sugar beet pulp. This delivery is part of Task 2.4 and has been carried out in accordance with previous Tasks 2.1, 2.2 and 2.3 and Deliverables 2.1 and 2.2, where the criteria for the selection of environmental indicators, LCA impact methods and system boundaries were evaluated in collaboration with WP2 partners (Figure 1).

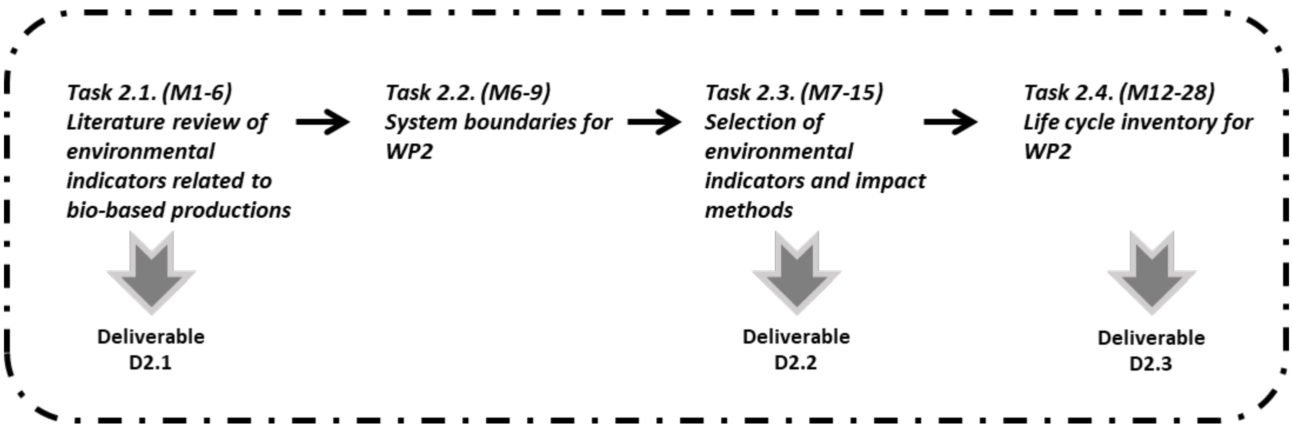

Figure 1: Work carried out in WP2

Deliverable D2.3, as part of Task 2.4, identifies the materials, energy, activities and processes needed to evaluate the environmental impacts of upstream processes of bio-based products. The quality and reliability of the data gathered in this report are key elements for carrying out Task 2.5 and Deliverable 2.4, concerning the life cycle impact assessment and interpretation.

In addition to the LCI study conducted in this report, some preliminary results are presented for two agricultural systems: sugar beet in the UK, as well as maize grain and stover in the US. Moreover, the hybridised indicators, applied in the Deliverable 3.1 (WP3) for downstream processes, are carried out for upstream activities using four indicators: hazardous chemical use, feedstock efficiency, waste factor and energy efficiency.

Overview of main considerations

Table 1: Overview of main considerations

:	Main considerations
Main objective of this report	Life cycle inventory phase of fermentable sugars production from sugar beet pulp, maize stover and maize grain.
Background	❖ Most of the LCA studies related to upstream activities (agriculture + pre-processing) focus on feed/food production. ❖ There are few LCA studies that use fermentable sugars as a functional unit. Most of them center their attention on the end-product, such as biofuels and bio-products. ❖ Modeling upstream activities of bio-products is relevant since they are bottlenecks for biorefineries.
System boundaries	❖ Cradle to gate LCA, from agricultural activities, transportation and pre-processing phase. ❖ 20 scenarios are considered for the life cycle assessment study. 10 for maize grain, 4 for maize stover and 6 for sugar beet pulp. ❖ The background processes considered in this study are the production and transport of machineries and infrastructure, fertilisers, pesticides, fossil fuels and electricity. ❖ It was considered the transportation of the feedstock from the farm to the pre-processing industry, and the transport of the processed feedstock to the biorefinery (To WP3).
Functional unit - Case studies	The functional unit in WP2 is related to the amount of fermentable sugars needed to produce the three case studies of WP3, as described: ❖ 7.5 g of fermentable sugars to produce 1 PLA packaging film of 350 mm x 250 mm ❖ 220 kg of fermentable sugars to produce 1 ha of PLA agricultural mulch ❖ 2.77 kg of fermentable sugars to produce 1 kg of PBS
Pre-processing activities	❖ Maize grain - The aim is to separate the starch from the gluten (wet milling process) and to convert the starch into glucose (by enzymatic hydrolysis). ❖ Maize stover – as stover is a lignocellulosic-rich biomass, a pretreatment step is required to convert xylan into xylose. Furthermore, enzymatic hydrolysis converts cellulose into glucose. ❖ Sugar beet pulp - as pulp is a lignocellulosic-rich biomass, a pretreatment step to convert most of the hemicellulose carbohydrates into soluble sugars (xylose, arabinose, galactose…) is required. Moreover, an enzymatic hydrolysis is carried out to transform cellulose into glucose.

Field emissions	To have a fair comparison of the outcomes, field emissions were assessed with the same methods for all the agricultural scenarios. The chosen field emissions are: 1) Field emissions to air: N_2O, NO_2 and NH_3 and 2) Field emissions to water: N and P leaching and P run-off. Following revision of this document by UNIBO partner, it was recommended to include other types of field emissions. Therefore, pesticide and heavy metal emissions as well as CO_2 emissions from carbon stocks changes will be calculated in the next 2.4 deliverable.
Allocation	Pre-processing activities deliver valuable by-products, as in the case of the wet milling process. Two of the most common allocation methods were considered: mass and economic. If enough data is available, substitution approach will also be used to calculate the environmental impacts.
Life cycle impact assessment	11 impact categories were chosen, using a combination of different impact methods (from Deliverable 2.2): Acidification (AC); Particulate Matter (PM), Climate Change (CC), Affected Biodiversity (BIO),Terrestrial Eutrophication (TE), Freshwater Eutrophication (FE), Human Toxicity (HT), Land Use, soil quality index (LU), Soil Erosion (SE), Fossil Resource Depletion (FE) and Water Depletion (WD).
Preliminary results (LCIA)	The outcomes of life cycle impact assessment will be reported in Deliverable 2.4, due month 35. However, preliminary results can be assessed for agricultural activities. Results show that fertilisation and field emissions play a major role for both assessed scenarios sugar beet cultivation in UK as well as maize grain and stover in the US.
Hybridised indicators	Four hybridised indicators were applied for upstream processes: Hazardous chemical use, raw material efficiency, waste factor and energy intensity. Glucose production from maize grain showed a better performance in the three indicators (raw material efficiency, waste factor and energy intensity). As for harzardous chemical use, three substances were found that need to be replaced: glyphosate in agricultural activities, cyclohexane in maize processing and formaldehyde in sugar beet processing.

1. Background and introduction

The production of bio-based products is a great opportunity to boost the concept of bioeconomy and avoid the use of fossil fuels. However, the production of feedstocks must be carried out in a responsible and sustainable manner, given that changes can be inferred in the use of first-generation feedstocks for non-edible purposes and those affecting land use.

The goal of STAR-ProBio is to improve the current framework for evaluating the sustainability of bio-based products and to increase consumer recognition of their environmental, economic and social benefits. To this end, it is essential to identify the key aspects of sustainability at all stages of the product life cycle. STAR-ProBio aims to promote a policy framework for bio-products through the implementation of sustainability schemes such as bio-product labelling.

The purpose of Work Package (WP2) is to conduct LCA on feedstock production and upstream processing to support strategic and policy decision making on bio-based products. Deliverable 2.3 aims to summarize the work done in Task 2.4, regarding the inventory of feedstocks and upstream processing. With this objective, three biomass-based case studies (sugar beet pulp, maize grain and maize stover) were selected to assess their environmental analysis. The life cycle inventory step was performed using secondary data from bibliography and databases as well as data from AUA partner, which designed and modelled the pretreatment and hydrolyses of the lignocellulosic raw materials (maize stover and sugar beet pulp). Since agriculture depends on site-specific conditions, such as soil type, climate and geography, as well as the type of management practice, different scenarios in various regions are considered as an attempt to address the impact of different variables on agricultural systems.

A multitude of raw materials can be used to produce fermentable sugars for the manufacture of bio-products. They may comprise first generation feedstocks, which compete with food/feed markets (e.g. maize grain, wheat grain, sugar beet, sugarcane); residues from agricultural and forestry operations, i.e. second generation feedstock (e.g. wheat straw, maize stover); third generation feedstocks (macro and microalgae) and residues from industrial processes, namely fourth generation feedstocks (e.g. sugar beet pulp, municipal solid waste). The technological pathway to process first generation crops into fermentable sugars is well developed. However, it is necessary to make technological efforts with respect to the processing of lignocellulosic materials, since there is a great difficulty in breaking the polymeric structure of lignin (De Matos et al., 2015). Upstream processes are considered bottlenecks in biorefineries due to economic and technological constraints, especially the pretreatment of lignocellulosic raw materials.

Many LCA studies concerning agricultural and forestry operations and feedstock processing are focused on feed/food production(Fantin et al., 2017; Noya et al., 2015). As regards the use of fermentable sugars, most LCA publications are based on the final product as functional unit, mainly biofuels (Cherubini and Strømman, 2011; Muñoz et al., 2014), and to a lesser extent focused on bio-products (Eerhart et al., 2012). Despite few studies are found on this topic, LCA studies on sugar production for industrial fermentation processes have grown in recent years, as shown in Table 2, which summarizes the LCA studies on fermentable sugars as functional unit (FU).

Within this context, this report will cover the environmental life cycle inventory of the agricultural and pre-processing phases to produce fermentable sugars obtained from sugar beet, maize grain and maize stover. These raw materials were taken into account in terms of their content and availability of carbohydrates in the world, mainly in Europe. The deadline for this report is Month 28 (August 2019) and is part of Deliverable D.2.3 and Task T2.4 of WP2, being USC the lead beneficiary.

Table 2: LCA studies on fermentable sugars

	Biomass	FU	Reference
1	❖ Sugarcane ❖ Sugar beet ❖ Maize	1 tonne of saccharide	(Renouf et al., 2008)
2	❖ Hardwood mill residues ❖ Low value hardwood	1 kg fermentable sugar	(Thomas et al., 2012)
3	❖ Poplar	1 kg of sugars	(Tao et al., 2014)
4	❖ Maize stover ❖ Switchgrass ❖ Poplar ❖ Miscanthus	1 kg Fermentable Sugar	(Adom et al., 2014)
5	❖ Wheat, maize and potato	1 tonne of starch and glucose	(Vercalsteren and Boonen, 2015)
6	❖ Maize stover	1 kg of fermentable sugars	(Prasad et al., 2016)
7	❖ Softwood harvest residues	1 kg of sugar	(Nwaneshiudu et al., 2016)
8	❖ Sugar beet	1 kg of hexose equivalent	(Vargas-Ramirez et al., 2017)
9	❖ Spruce ❖ Maize	1 kg of C6 sugars	(Moncada et al., 2018)
10	❖ Maize starch	1 kg of glucose	Ecoinvent database®, version 3.5 (2018)
11	❖ Wheat	1 kg of glucose	(Salim et al., 2019)

2. Fundamentals of environmental life cycle assessment

According to ISO 14040, LCA is a *"compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle".* The LCA methodology is divided into four important stages, according to the ISO framework (ISO 14040, 2006; ISO14044, 2006) (Figure 2): 1) Goal and scope definition; 2) Life cycle inventory assessment; 3) Life cycle impact assessment; 4) Interpretation.

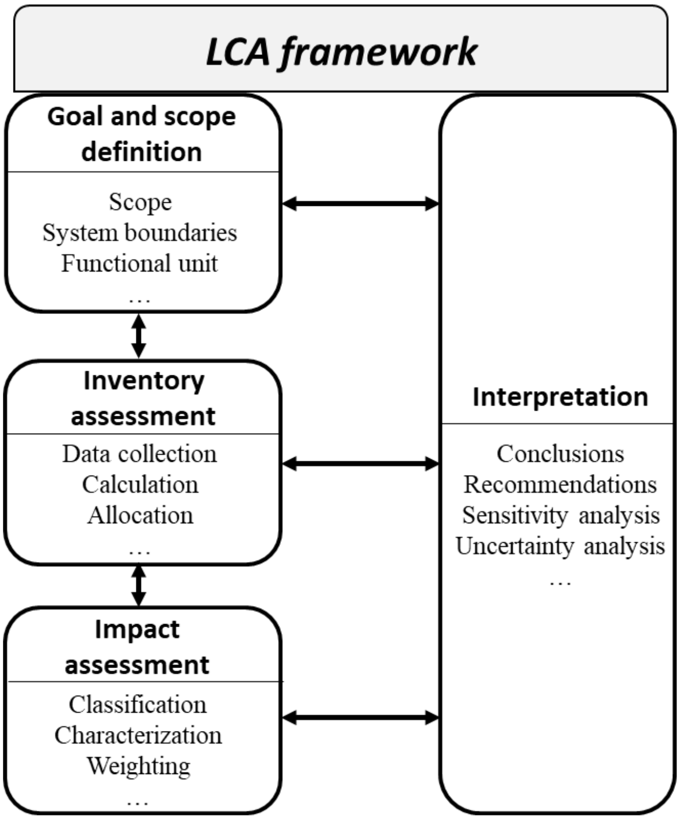

Figure 2: Life cycle methodology adapted from ISO 14040:2006

Goal and scope definition

The goal and scope should be very clear and concise as this stage will guide all the further steps of LCA. This first stage should define the scope of the study, functions, functional unit, system boundaries, limitations, allocation procedures, and so on. The definition of a functional unit (FU) is a very important work as all the environmental impacts will be expressed per FU. The value chain of a product life cycle typically comprises feedstock production and processing, transportation, use phase and end-of-life (Figure 3). The system under study may be a cradle-to-cradle, cradle-to-gate, cradle-to-grave, or gate-to-gate analysis depending on the purpose of the study.

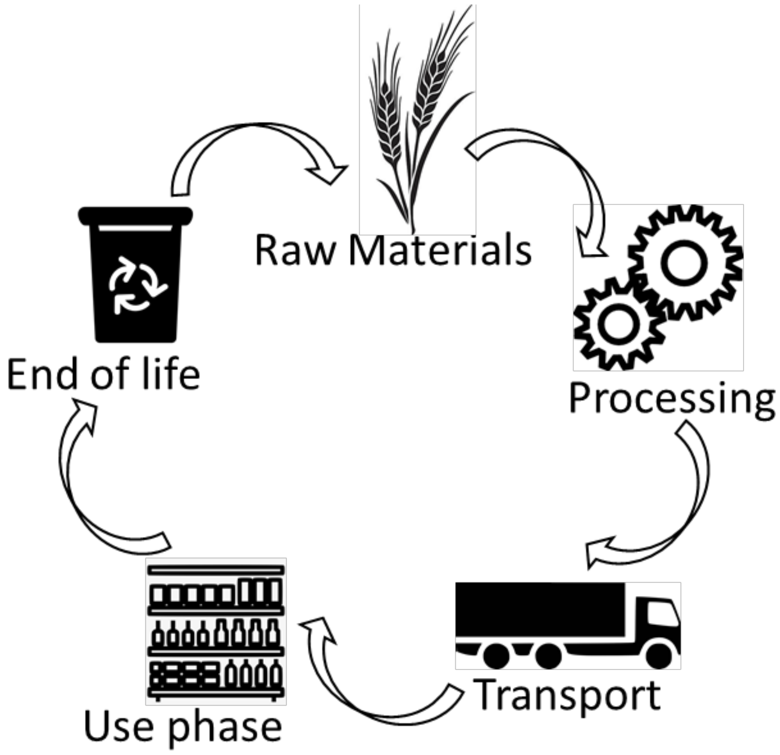

Figure 3: Generic value chain of a product life cycle

Life Cycle Inventory (LCI)

LCI includes data gathering and material and energy balances. It is, generally, the most time-consuming phase. All the input and output flows should be related to the system boundaries and functional unit. Depending on time and availability, data can be collected in the field (linked to actual systems or operations), literature or databases. The type of data used in the analysis should be clearly indicated.

The use of allocation is also defined in the LCI phase. Making decisions about which allocation to use is one of the most difficult steps in LCA. It is advisable to avoid allocation, however, whenever this is not possible, a good justification should be made to elucidate the reasons for the allocation options. There are many types of allocation (substitution, mass, economic…) and the best allocation method to use will depend on many variables, such as the quality of the data, the amount and type of by-products, whether attributional or consequential LCA is used, etc.

Life Cycle Impact assessment (LCIA)

The life cycle inventory process generates a long list of elementary flows that are difficult to interpret. This stage will help to translate the data through the use of environmental indicators, such as climate change. LCIA is divided into different categories, being classification and characterization mandatories steps (see Figure 4):

i) Classification: the allocation of inventory data to impact categories; that is the input and output flows of the inventory table are assigned to environmental indicators. To this aim, an impact assessment method and the impact categories will be chosen. There are many methods used for LCIA (ReCiPe, USEtox®, CML, Eco-Indicator 99…) as well as a variety of indicators (climate change, eutrophication, fossil depletion, acidification, ozone depletion…).

ii) Characterization: after classification, characterization factors will be assigned to determine the impact contribution of each parameter. In other words, it calculates the relative contribution of the inventory data to environmental indicators. For instance, CO_2 and N_2O contribute to climate change (classification), however, to different degrees (characterization).

iii) Normalization: this stage can also be considered similar to characterization. However, it has a geo-temporal reference. For instance, the greenhouse gas emissions divided by the European population in a given period.

iv) Weighting: This process should be taken with care as it leads to high uncertainty. Typically, it distributes a relative importance, a given weight, to the impact categories.

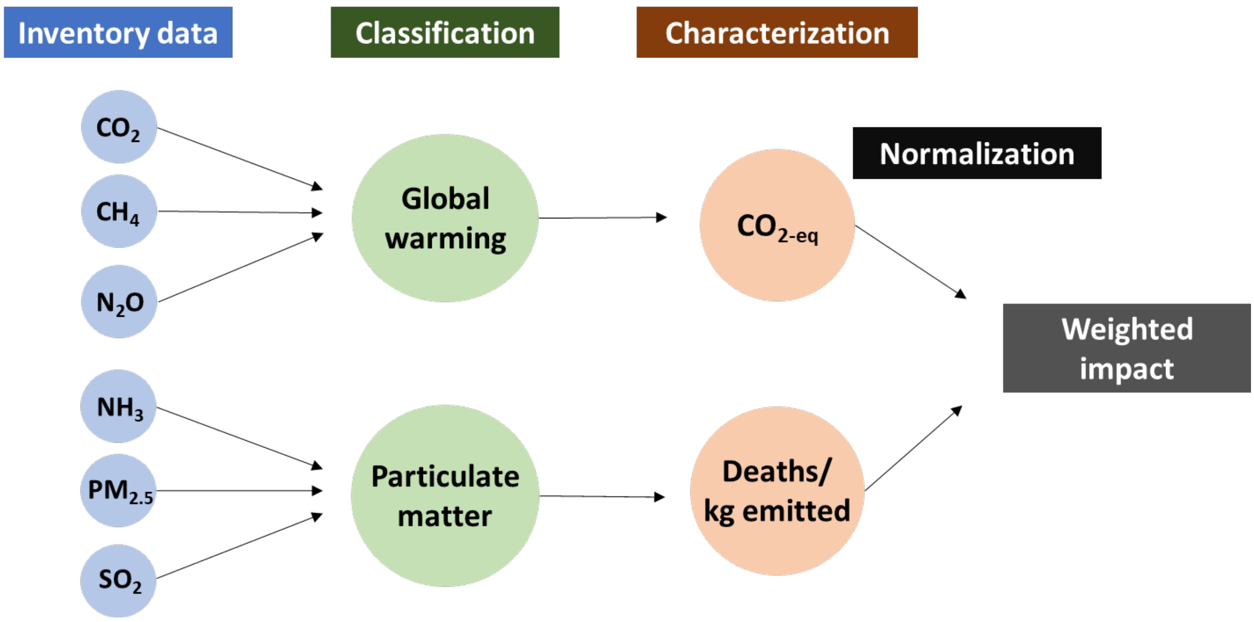

Figure 4: Stages of life cycle impact assessment (LCIA)

Interpretation

Interpretation, as shown in Figure 2, is a dynamic process, which should not be considered as the last step, but applied continuously throughout all stages of LCA. The results of the LCIA should be interpreted carefully and recommendations made for future improvements. Additional tools can be used to add more meaning and reliability to the interpretation, such as sensitivity and uncertainty analysis.

In the following sections an LCA of the selected case studies with respect to raw material production and upstream processing will be performed, i.e. LCA of fermentable sugars from maize grains, maize stover and sugar beet pulp.

3. Case studies

1. Goal and scope definition

The objective of this study is to model the production of fermentable sugars to be used downstream for bio-based products. This includes the system description and the flows generating an environmental impact. Maize grain, maize stover and sugar beet pulp are the raw materials that are converted into fermentable sugars. These feedstocks were selected for their considerable carbohydrate content and their worldwide availability. Fermentable sugars from maize grain are composed of glucose syrup, with 95 dextrose equivalent (DE), which is a substrate commonly used in fermentation processes (Wood and Rourke, 1995). On the other hand, maize stover and sugar beet pulp, representing lignocellulose rich raw materials, provide a combination of fermentable sugars after the hydrolysis process. As for maize stover, it represents glucose (59%), xylose (33%) and other sugars (8%); and sugar beet pulp, arabinose (41%), glucose (37%), galactose (10%), xylose (9%) and mannose (3%). This study is a cradle-to-gate LCA, from agricultural activities, biomass transport, processing of raw materials into sugars and transportation of fermentable sugars to the factory.

2. System boundaries

Figure 5 shows a generic system description for the production of fermentable sugars from maize grain, maize stover and sugar beet pulp. Three case studies of bio-products were taken as reference: 1 packaging film of 350 mm x 250 mm (Biaxially Poly Lactic Acid – Bo-PLA) with 5.58 g of PLA, 1 kg of polymer Polybutylene succinate (PBS) and 1 ha of agricultural land, made of PLA and bio-based co-polymer. The amount of fermentable sugars needed to produce the three case studies is:

- 1 PLA packaging film of 350 mm x 250 mm - 7.5 g of fermentable sugars
- 1 ha of PLA agricultural mulch - 220 kg of fermentable sugars
- 1 kg of PBS - 2.77 kg of fermentable sugars

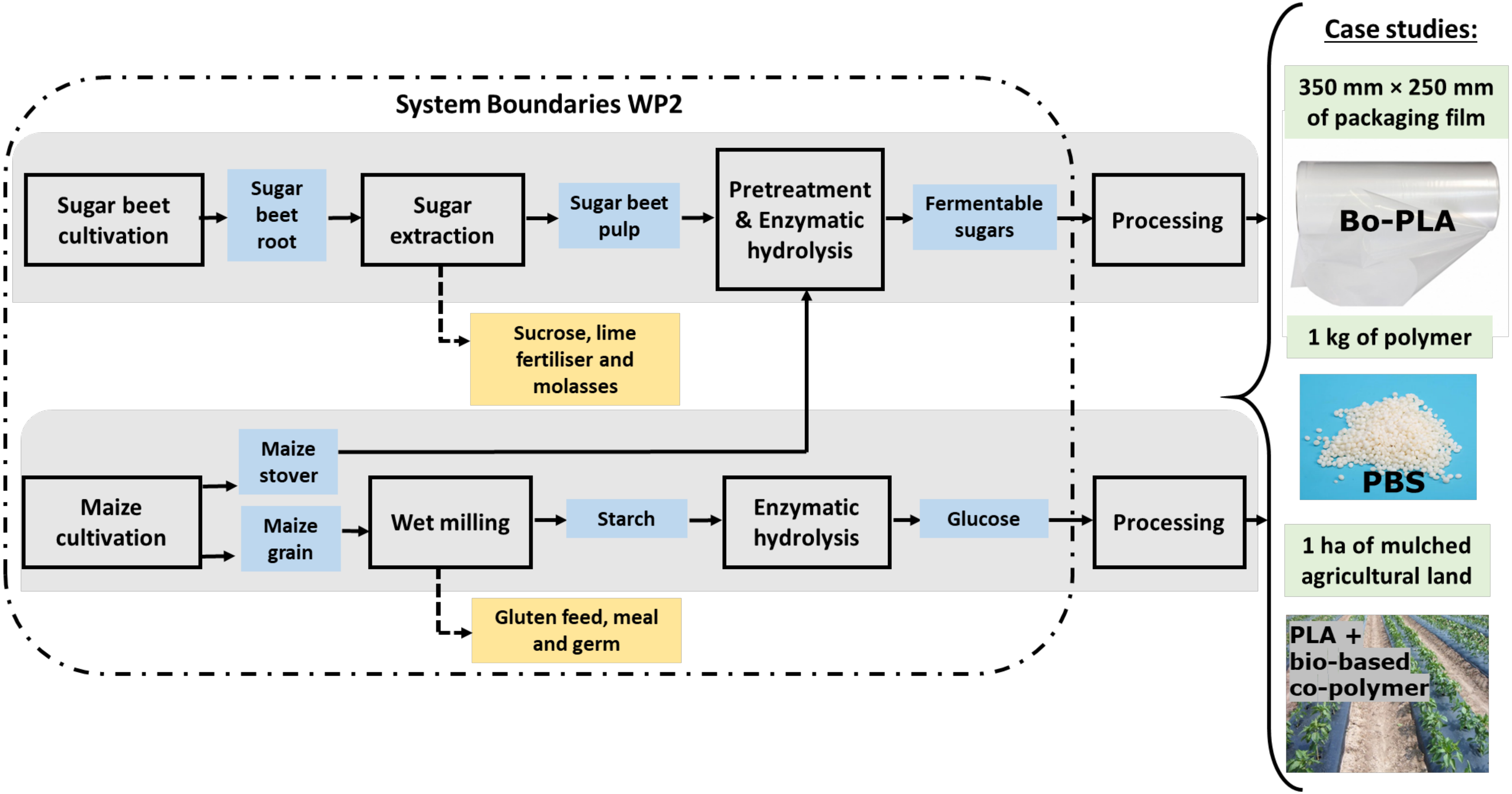

Figure 5: Generic overview of the system boundaries for WP2

The functional unit chosen in this study is the amount of fermentable sugars (from maize grain, maize stover or sugar beet pulp) necessary to produce these three bio-products. Table 3 depicts the three case studies and the functional units considered for the upstream processing, which in turn are input flows for downstream processes, which are under the responsibility of WP3. For more information concerning downstream activities, see Deliverable D3.1 of WP3.

The first case study, as indicated in Table 3, corresponds to Poly Butylene Succinate (PBS). It is a crystalline polyester composed of succinic acid and 1,4-butanediol, together with another monomer, such as dicarboxylic acid. Fermentable sugars, such as glucose, are the main source of carbon. In this report, succinic acid and 1,4 butanediol are considered 100% bio-based chemicals. Its fossil counterpart is Polystyrene, which is composed of fossil succinic acid and fossil 1,4 butanediol. PBS has multiple applications, such as packaging, agriculture, fibres, construction sector, etc. With respect to the second case study (BoPLA), its main application is in the food sector and is composed by lactic acid produced from fermentable sugars. BoPLA is an interesting material that can be replaced by the fossil-based biaxially oriented polypropylene (BoPP). Finally, the third case study (Ecovio® agricultural mulch film), which in this study is designed to be applied in the agricultural sector, is assumed to be 80% bio-based, and is composed of lactic acid, 1,4 butanediol as well as the fossil-based adipic acid and terephthalic acid. This bio-product has the ability to replace the fossil-based linear low-density polyethylene (LLDPE) mulch film.

Table 3: Description of case studies, applications and functional units (FU)

Case studies	**Bio-based platform chemical**	**Final bio-based product**	**Application**	**Fossil benchmark system**	**FU (WP2)**	**FU (WP3)**
Polybutylene succinate (PBS)	**PBS polymer:** Succinic acid (SA) 1,4-Butanediol (BDO)	PBS resin	Agriculture, packaging, fibres, construction and automotive sectors	Polystyrene (PS) Fossil SA Fossil BDO	2.77 kg of fermentable sugars	1 kg of PBS
Biaxially oriented Polylactic acid (BoPLA)	**PLA packaging:** Lactic Acid (LA)	PLA-based food packaging film	Food sector	Biaxially oriented polypropylene (BoPP) film	7.5 g of fermentable sugars	1 packaging film of 350 mm x 250 mm
Ecovio® mulch film	**PLA agricultural mulch:** Lactic acid (LA) 1,4-Butanediol (BDO)	Bio-based biodegradable mulch film	Agricultural sector	Linear low-density polyethylene (LLDPE) film converter	220 kg of fermentable sugars	1 ha of PLA agricultural mulch

As mentioned, the three case studies analysed are mainly composed of three bio-based chemicals, succinic acid (SA), butanediol (BDO) and lactic acid (LA). The conversion values to produce these chemical platforms is summarized in Figure 6 underneath.

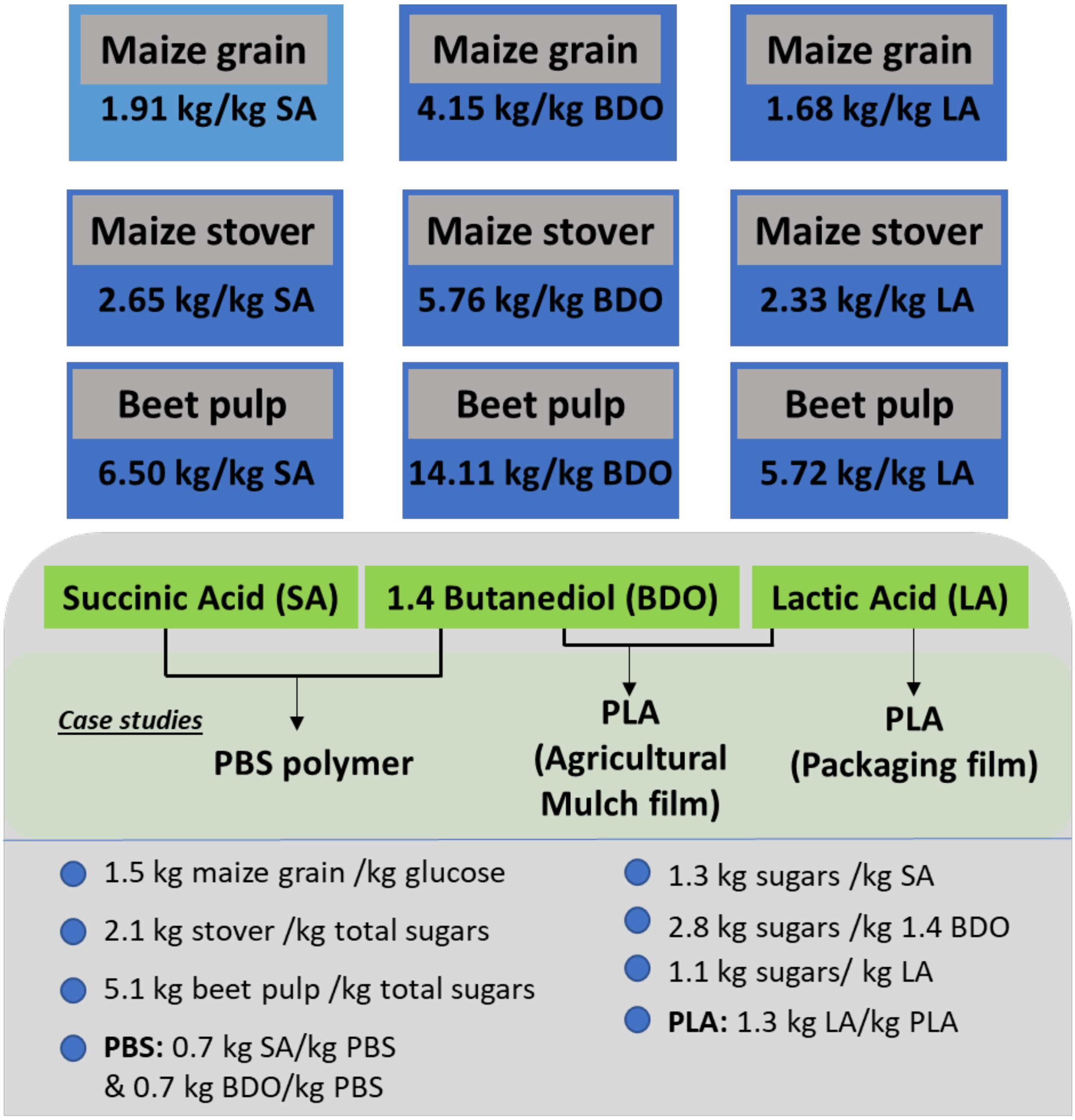

Figure 6: Amounts of feedstocks (Maize grain, stover and sugar beet pulp) needed to produce one kilogram of succinic acid (SA), 1-4 Butanediol (BDO) and Lactic Acid (LA)

3.1.1 Maize

The production route of fermentable sugars from maize grain and stover is depicted in Figure 7. The system boundaries include agricultural activities, pre-processing stages and transportation. The main products are glucose, from maize grain, and fermentable sugars (xylose, glucose) from maize stover.

Maize grain and stover – Agricultural activities

Maize is regarded as a starch crop because of its high carbohydrate content (up to 70%) (IfBB, 2018) and is considered one of the most important staple foods in the world. At present, the average global yield of maize amounts to 5.5 tonnes ha^{-1} and 200 million hectares of arable land in the world. Together, China and the United States produce more than 50% of the world's maize crop. In Europe, Romania and France are the greatest maize producers (FAOSTAT, 2017). This crop can be used for feed/food, biofuels and bio-products. In colder regions, it is more common to grow maize silage, while in warmer regions maize grain is grown. In southern areas, maize is usually grown for subsistence, while in northern geographical areas highly mechanized agriculture is used. The cultivation of maize generates residues such as maize stover (leaves, stalks and cobs), which is rich in lignocellulose, and, in turn, can also be converted into fermentable sugars.

Firstly, the maize grain is cultivated, which takes about 6 months from sowing to harvest. Activities related to the cultivation of maize are divided into field preparation (S1), where the tillage process begins, generally with the use of machinery, such as ploughs and harrows, to prepare the soil for further sowing. In the next stage, in crop growth (S2), weed control and fertilisation take place. Nitrogen nutrients are vital in maize cultivation. Normally, this crop does not require irrigation and depends solely on rainwater, although some regions, such as the Mediterranean, use a considerable amount of irrigation water (Kathage et al., 2016; Rüdelsheim and Smets, 2011). The final stage is the harvest of biomass and transport to the processing facility (S3). The harvesting process uses machinery, such as a combine harvester, which is capable of separating the maize kernel from the remains (maize stover).

The maize stover production varies across agricultural systems. However, in average, for each kg of maize grain, about 1 kg of stover is produced (Prasad et al., 2016). It is important to consider that stover is a soil amendment and that, depending on the type of soil and climate, the complete removal of stover from the soil may jeopardize soil quality. For very fertile farms, a large amount of stover removal can be considered. However, in non-fertile soils, little or no stover should be removed. Therefore, an average removal rate for all agricultural systems cannot be determined as it depends on each agricultural system. In addition, agricultural residues also protect the soil from soil erosion and other climate adversities. Hence, regions with high levels of wind, precipitation and slope should avoid stover removal.

In this system all the maize grain produced (scenario 3) is used to be processed into glucose (scenario S4). As far as stover production is concerned, it was approached in three different ways: 1) Maize agricultural system without stover removal, ie 100% is left in the field as a soil admendment; 2) Maize agricultural system with 50% stover removal, ie 50% is left in the field as soil admendment and 50% is processed into fermentable sugars (scenario S5) and 3) Maize agricultural system with 100% stover removal, ie all stover is used to be processed into fermentable sugars (scenario S5).

Maize grain and stover - pre-processing activities

Grain processing activities (S4) include wet milling and enzymatic hydrolysis. While dry milling technology aims to deliver flour as the main product, the core drive of the wet milling process is to separate starch from gluten. The wet milling process begins with a cleaning process to remove impurities from the grain, such as soil and small stones. The grain will go through a selection stage to separate the best grains by weight, size and shape. The clean grain will undergo a grinding stage to separate the germ (endosperm) from the grain. This lipid-rich germ usually goes through another stage to produce maize oil. The refined grain is soaked in water for up to 2 days in order to soften the grain, allowing the separation of starch and gluten. Not much is wasted in the manufacture of glucose from maize grain, as wet milling technologies generate valuable by-products, such as maize oil, gluten feed and gluten flour (Papageorgiou and Skendi, 2018). Gluten feed and meal are rich in protein and are usually used in animal feed.

The latter stage is enzymatic hydrolysis, in which liquefaction and saccharification activities are carried out. The aim of the liquefaction process is to dissolve starch molecules in water by adding enzymes (alpha-amylase) and inorganic chemicals, such as sodium hydroxide, transforming starch into soluble dextrin. This liquefied solution undergoes a saccharification process, using enzymes (glucoamylase) and acids, such as sulphuric acid, to finally transform dextrin into glucose.

For maize stover (leaves, stems and cobs), it is considered a rich soil conditioner that can also be used as a supplement to animal feed. Additionally, due to its high carbohydrate content, it is a potential feedstock for the production of biofuels and bio-products, through a fermentable sugar platform. This biomass is rich in lignocellulose, composed of cellulose (~38%), hemicellulose (~26%) and lignin (~19%)(Prasad et al., 2016). However, the conversion of lignocellulose into fermentable sugars has so far been limited to technological and economic barriers.

As regards stover processing (S5), after harvesting, the stover will be transported to the factory and a pre-treatment step will be carried out. Firstly, the stover is ground and a chemical hydrolysis occurs, using heat and sulfuric acid, to convert xylan (group of hemicelluloses) into xylose, reaching almost 100% conversion. As this pre-treatment step is not able to efficiently convert cellulose into glucose, enzymatic hydrolysis occurs, which is characterized by the addition of enzymes (cellulase). This process will convert the remaining carbohydrates (cellulose) into glucose at a conversion rate of more than 90%.

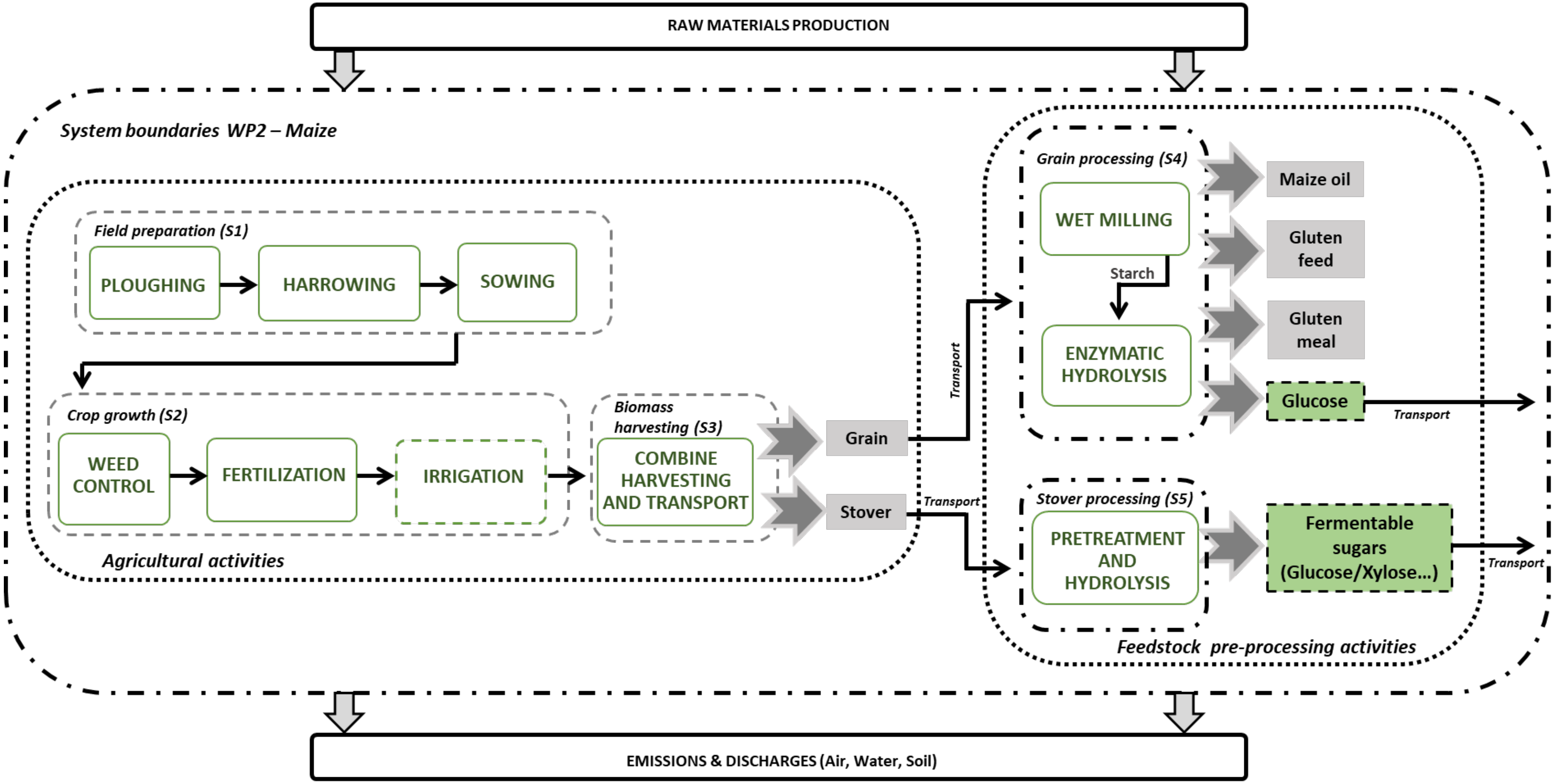

Figure 7: System description of fermentable sugars production from maize grain and stover

3.1.2 Sugar beet

The production route of fermentable sugars from sugar beet pulp is displayed in Figure 8. The system boundaries include agricultural activities, pre-processing stages and transportation. The main products are fermentable sugars (arabinose, glucose, galactose…).

Sugar beet – Agricultural activities

Sugar beet (*Beta vulgaris* L.) is a sugar crop due to its sucrose content. About ¼ of the world sugar is supplied by sugar beet and ¾ by sugarcane (ABSugar, 2018). Compared to other crops, such as maize and sugar cane, interest in growing sugar beet on a large scale began recently, when sugar cane exports to Europe were interrupted in Napoleonic times. Today, sugar beet is grown mainly in temperate zones, such as Europe, and the technology has allowed this crop to reach very high yields (up to 110 t ha^{-1}). Sugar beet production in Europe accounts for about 40% of world production, with France and Germany being the largest producers in this region. In 2017, Europe used about 1.5 million ha of land to grow sugar beet, with an average yield of 70 t ha^{-1} (FAOSTAT, 2017).

Sugar beet is a biannual crop that, in temperate climates, is sown in spring and harvested in autumn or early winter (Draycott, 2006). In sugar beet cultivation, the first stage is soil preparation (S1), where ploughing and harrowing are carried out in order to prepare the soil for sowing. Pesticides and fertilizers are used for cultivation (S2), as well as irrigation or rain water, depending on the geoclimatic conditions. The final step is harvesting and transport (S3) to the pre-processing facility. Sugar beet harvesting machines are capable of removing part of the soil, cutting leaves and roots simultaneously. The weight of the leaves is about 50% of the sugar beet. Although the leaves are rich in lignocellulose and can be used as raw material for industrial fermentation, in this study it is considered that the leaves are left in the field as soil conditioner. The leaves are composed of approximately 15% cellulose, 14% hemicellulose, 16% pectin and 5% lignin (Modelska et al., 2017).

Through photosynthesis, beets store sugars in their roots. The amount of sugar depends on geography, climate and harvest time. However, on average, it contains approximately ~14% sucrose, ~6% pulp and ~4% molasses on a wet basis (FAO, 2009). After harvest, the sugar content in the root will gradually decrease over time. Therefore, the pre-processing facility must be located at a tolerable distance.

Sugar beet - pre-processing activities

The main objective of this study, in relation to the sugar beet value chain, is the environmental assessment of fermentable sugars obtained from sugar beet pulp. The beet-based sugar industry is a well-developed technology. In the sugar beet processing factory (S4), the transported root is first washed to remove the remaining impurities and then cut into *cosettes* (small strips). Sugar extraction is done by diffusion using hot water and sulphuric acid. The diffusion process will generate raw sugar and sugar beet pulp as a by-product. Lime and carbon dioxide are used to purify this raw juice, removing the rest of the unsweetened compounds from the juice. The additional process is crystallization, which finally crystallizes the sugars by centrifugation, producing sucrose as the main product and molasses as a by-product (the part without crystals). Molasses is an interesting raw material for fermentation and has currently been used in the production of biofuels (Duraisam et al., 2017).

Although feasible, sucrose is not commonly used as fermentation feedstock, as it has an established market in the food industry and also due to higher prices compared to glucose from starch crops. However, the habit of sugar consumers is changing. There is a strong inclination to use other sweeteners, such as high fructose corn syrup (HFCS). In addition, new market policies are facilitating imports of cane sugar into Europe, reducing prices for beet sugar (Tomaszewska et al., 2018).

Sugar beet processing provides valuable by-products, such as sugar beet pulp (SSP), molasses and lime fertilizers. So far, SBP has been produced mainly for animal feed. However, it is an interesting raw material to be used in industrial fermentation processes, due to its high sugar content. However, it requires a pre-treatment and hydrolysis step to break the recalcitrant property of lignocellulose (Díaz et al., 2017). SBP is rich in polysaccharide cellulose (~23%), hemicellulose (~30%), pectin (~20%) and lignin (~6%) (Tomaszewska et al., 2018). The pre-treatment step, followed by hydrolysis, generates a mixture of sugars, such as glucose, xylose, arabinose, galactose and mannose. SBP are normally pressed into small granules to facilitate their transportation as they have a low bulk density (Habeeb et al., 2017).

With respect to sugar beet pulp processing (S5) a preliminary step is carried out, through chemical hydrolysis, to further process via enzymatic hydrolysis the pre-treated sugars into fermentable sugars. The pre-treatment step occurs through chemical hydrolysis, using heat and sulphuric acid, to convert most of the hemicellulose carbohydrates into soluble sugars (xylose, arabinose, galactose…). Moreover, an enzymatic hydrolysis occurs with the use of enzymes to transform cellulose into glucose.

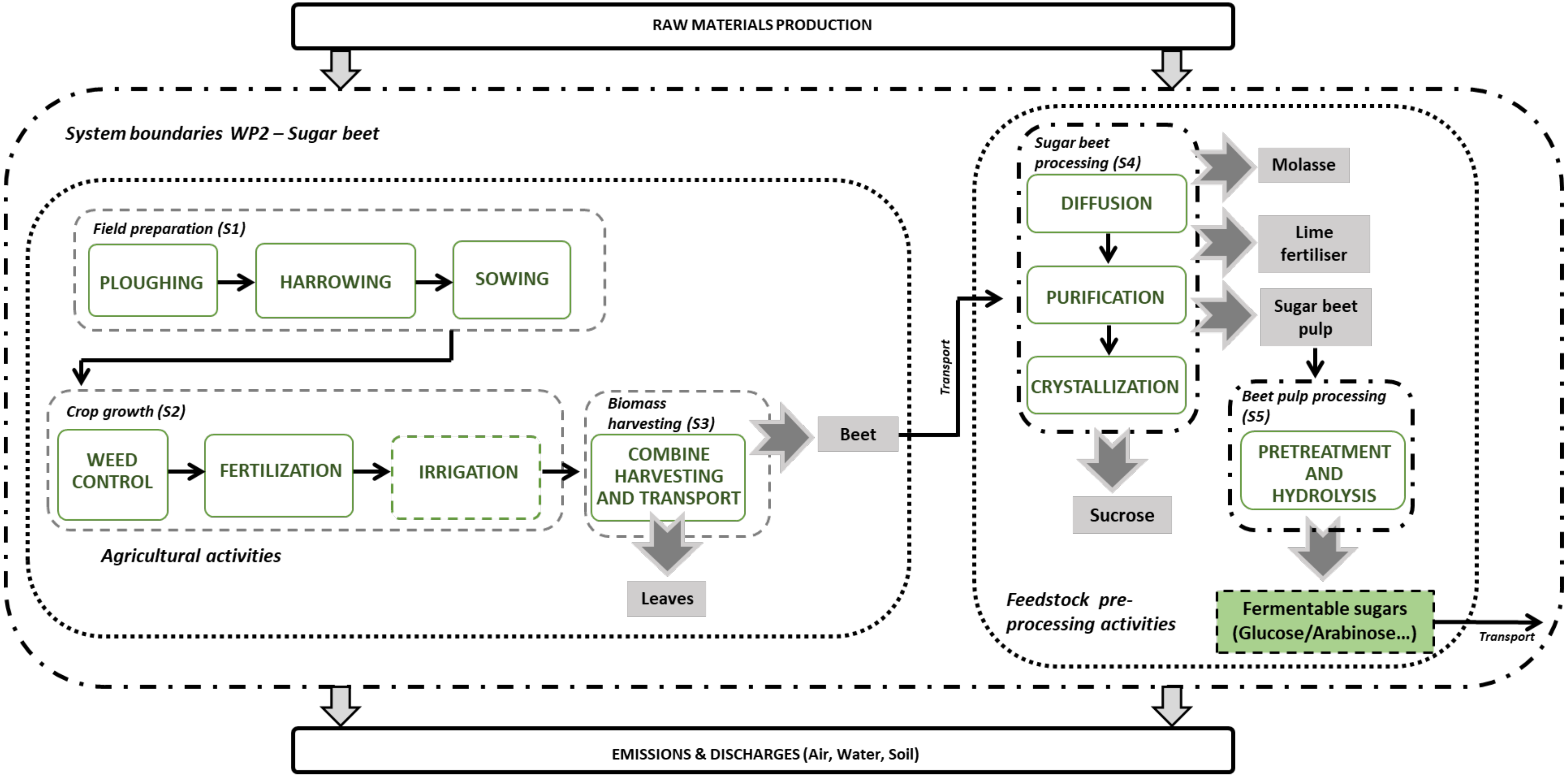

Figure 8: System description of fermentable sugars production from sugar beet and sugar beet pulp

3. Life cycle inventory (LCI) phase

This step is, generally, the most time-consuming and involves the collection of data related to the system boundary and the functional unit. Data may include primary data, collected through interviews, questionnaires, or on-site measurements. On the other hand, secondary data can be used when information is lacking or when there are insufficient resources and time to evaluate primary data. Secondary data may include databases, bibliography and simulations, for example. It is also important to decide which data are the most important to collect, as it is impossible to evaluate every detail of the entire value chain. For example, data for fertilizer and pesticides production are considered background data, which are evaluated through databases, as there is no time and resources to have specific and actual data for fertilizer production on each agricultural site.

Assessing the origin and fate of environmental impacts of agriculture is a difficult task, as agriculture is a complex system that comprises many variables that can be divided into anthropogenic parameters, such as machines used for soil cultivation, fertilizers, irrigation, pesticides, etc., and geo-climatic parameters, such as soil type, rainwater, wind, etc.

Most of the information gathered in the life cycle inventory phase to produce fermentable sugars came from the bibliography and databases as no primary data were available. Therefore, in order to have a broad spectrum of agricultural and processing activities, 20 different scenarios were considered for 6 countries: United Kingdom (UK), France (FR), Germany (DE), United States (US), Italy (IT) and Belgium (BE).

3.3.1 LCI – Agricultural and pre-processing activities

Agricultural and processing data (as described in Table 4) are coupled and the following 20 scenarios are considered for the life cycle assessment study (Table 5). The maize grain produced in scenarios A4, A5, A6, A7 and A8 will go to the maize processing phase (scenarios P3 and P4), generating 10 scenarios for maize glucose production. The stover that was removed (SR) in scenarios A4, A6, A7 and A8 is then subjected to a maize stover processing (scenario P5), accounting 4 scenarios for sugar production from maize stover. The sugar beets (scenarios A1, A2 and A3) go through a sucrose production facility (scenarios P1 and P2), delivering sugar beet pulp as by-product. This beet pulp will be processed into total sugars (scenario P6), delivering 6 scenarios for sugars from sugar beet pulp. The background processes in this study are the production and transportation of machineries and infrastructure, fertilisers, pesticides, fossil fuels and electricity. The transportation of the raw material from the farm to the pre-processing facility, as well the transport of the biomass processed to the downstream processes are considered.

Table 4: Scenarios considered for agricultural activities (A) and pre-treatment (P) processes

Agriculture	Scenario	Source
Sugar beet, UK	A1	(Renouf et al., 2008)
Sugar beet, FR	A2	(Muñoz et al., 2014)
Sugar beet, DE	A3	(Ecoinvent database®, 2015)
Maize grain and 50% stover removal (SR), US	A4	(Renouf et al., 2008)
Maize grain with non-stover removal (Non-SR), US	A5	(Renouf et al., 2008)
Maize grain and 100% SR, low yield (LY), IT	A6	(Noya et al., 2015)
Maize grain and 100 % SR, high yield (HY), IT	A7	(Noya et al., 2015)
Maize grain and 50% SR, BE	A8	(Boone et al., 2016)
Processing	**Scenario**	**Source**
Beet sugar. By-products: lime fertiliser and beet pulp	P1	(Renouf et al., 2008)
Beet sugar. By-products: molasse and beet pulp	P2	(Maravíc et al., 2015)
Maize glucose. By-products: maize gluten feed, meal and oil	P3	(Renouf et al., 2008)
Maize glucose. By-products: maize gluten feed, meal and germ	P4	(Moncada et al., 2018)
Fermentable sugars from maize stover	P5	Designed and modelled by AUA partner
Fermentable sugars from sugar beet pulp	P6	Designed and modelled by AUA partner

Table 5: Different types of scenarios for maize, maize stover and sugar beet pulp

Feedstocks	Fermentable sugars production Scenarios (Sc)	Agriculture (A) and pretreatment (P) code
Maize1	Sc1	A4P3
Maize2	Sc2	A4P4
Maize3	Sc3	A5P3
Maize4	Sc4	A5P4
Maize5	Sc5	A6P3
Maize6	Sc6	A6P4
Maize7	Sc7	A7P3
Maize8	Sc8	A7P4
Maize9	Sc9	A8P3
Maize10	Sc10	A8P4
Stover1	Sc11	A4P5
Stover2	Sc12	A6P5
Stover3	Sc13	A7P5
Stover4	Sc14	A8P5
Beet pulp1	Sc15	A1P1P6[a]
Beet pulp2	Sc16	A1P2P6
Beet pulp3	Sc17	A2P1P6
Beet pulp4	Sc18	A2P2P6
Beet pulp5	Sc19	A3P1P6
Beet pulp6	Sc20	A3P2P6

[a] The production of fermentable sugars from sugar beet pulp has to go through a processing of sugar beet (P1 or P2) first to produce beet pulp and then undergo a pre-treatment and hydrolysis step (P6).

Data on agricultural activities for the cultivation of maize and sugar beet are presented in Tables 6 and 7. All inputs and outputs are related to one crop rotation per hectare of cultivated land.

It is very difficult to assume a generic fraction for stover removal, as each region has different geo-climatic conditions. Therefore, it is ideal to carry out a soil analysis and to identify the maximum recommended values for stover removal so as not to jeopardize soil quality.

There are 5 many variables that must be addressed before considering stover removal (Seamon, 2014): Soil organic matter content, soil slope, soil type, tillage system and soil fertility. Crop residues prevent soil erosion and if the slope of the land is a threat to soil erosion, then a stover mulch should be maintained in the field. In addition, maize stover has a significant amount of nutrients (nitrogen, phosphorus, and potassium). Therefore, their elimination may involve the substitution of nutrients in the form of fertilizers. On the other hand, if a soil is extremely fertile, the elimination of stover can benefit the soil.

As the data on agricultural activities in this study come from the literature, it is not possible to evaluate the ideal amount of stover to be removed for each agricultural field. Original data for maize in the U.S. (Scenario A5) did not consider stover removal. Therefore, the data related to US maize (scenario A4) and BE maize (scenario 8) were modified, assuming that 50% of the maize stover is removed and the rest is left in the field as recommended by the literature (Prasad et al., 2016). The other scenarios Maize in IT (Scenarios 6 and 7) take into consideration two types of maize grains with 100% stover removal. These two scenarios have maintained total removal of stover to give a broad spectrum of maize farms, as some agricultural fields, such as these case studies in Italy, remove all the stover either for animal and/or reintroduce again the stover into the field as a compost, mixed with animal manure, for example.

This study considers the amount of nutrients that should be replaced according to the nutrient content lost due to stover removal. On average, there are about 7.5 kg of nitrogen, 2.5 kg of P2O5 and 8.2 kg of K2O per t of dry stover (David, 2013). Additional energy was assumed for the baling process, using Ecoinvent v3.5 as a parameter, which considers 700 kg of straw for each unit of baling: "Round baler for round bales of 1.4 m3 for silage, bale with wrapping foil" (Ecoinvent database version 3.5, 2018)[a].

Table 6: Life cycle inventory table - maize agriculture

FU: 1 hectare	Unit	Maize US, SR (A4)	Maize US, Non-SR (A5)	Maize IT, SR, LY (A6)	Maize IT, SR, HY (A7)	Maize BE, SR (A8)
Agricultural inputs						
Occupation	ha·year^{-1}	0.67	0.67	0.50	0.50	0.67
Irrigation	m^3	-	-	800	800	-
Seed	kg	17.8	17.8	25	25	27
NPK fertiliser	kg	326	257	757	1074	302
Lime	kg	337	337	-	-	-
Pesticides	kg	2.8	2.8	6	6	1.6
Energy	MJ	5961	5545	4615	4615	2383
Agricultural outputs						

[a] https://v35.ecoquery.ecoinvent.org/Home/Index

FU: 1 hectare	Unit	Maize US, SR (A4)	Maize US, Non-SR (A5)	Maize IT, SR, LY (A6)	Maize IT, SR, HY (A7)	Maize BE, SR (A8)
Maize grain	t	9.1	9.1	6.5	15	10
Maize stover (by-product)	t	4.5	-	8.5	25	5
Maize stover (left on field)	t	4.5	9.1	0	0	5
Field emissions to air						
N_2O	kg	6.06	5.49	9.68	13.2	5.28
NO_2	kg	16	13	32	46	10
NH_3	kg	8.66	7.14	67	74	31
Field emissions to water						
NO_3^- leaching	kg	46	42	104	115	39
P leaching	kg	0.07	0.07	0.08	0.1	0.08
P runoff	kg	0.18	0.18	0.31	0.34	0.20
Transport						
Barge	km	1500	1500	-	-	-
Ship	km	7500	7500	-	-	-
Road	km	300	300	300	300	300

Table 7: Life cycle inventory table - sugar beet agriculture

FU: 1 hectare	Unit	Sugar beet UK (A1)	Sugar beet FR (A2)	Sugar beet DE (A3)
Agricultural inputs				
Occupation	$ha \cdot year^{-1}$	0.50	0.50	0.50
Irrigation	m^3	40	184	200
Seed	kg	1.12	2	3
NPK fertiliser	kg	181	253	458
Lime	kg	1100	0.1	-
Pesticides	kg	8.6	3	2.64
Energy	MJ	8572	6070	7350
Agricultural outputs				
Sugar beet	t	49	84	69
Sugar leaves (left on field)	t	24.5	42	34.5
Field emissions to air				

FU: 1 hectare	Unit	Sugar beet UK (A1)	Sugar beet FR (A2)	Sugar beet DE (A3)
N_2O	kg	6.91	9.60	8.72
NO_2	kg	9.57	8.8	10.87
NH_3	kg	5.03	4.63	5.72
Field emissions to water				
NO_3^- leaching	kg	67	18	17.8
P leaching	kg	0.07	0.07	0.07
P runoff	kg	0.19	0.20	0.29
Transport				
Road	km	300	300	300

Within the European region, the assumptions made for transportation takes into consideration lorry trucks. In addition, there is a distance of 300 km from the farm to the pre-processing plant. Regarding the transport of fermentable sugars to the biorefinery, the factories will be located very close to each other (50 km). Outside Europe, as for maize production in the United States, maize grain is supposed to be transported to Europe from the Corn Belt region in the Midwest of the United States. The grain is transported by barge along the Mississippi River to the Port of New Orleans and transported by ship to Europe. The stover was considered to be processed in the USA as it has a low bulk density and a low price. It is very difficult to find reliable data indicating current information on the production of maize grains, maize stover and sugar beet pulp intended exclusively for glucose production. Therefore, in order to make a fair comparison and from a biorefinery perspective, the same distance is assumed for agricultural products between Europe and the biorefinery is located next to the pre-processing activities.

Agricultural activities are responsible for a variety of field emissions. Most of the emissions considered in the literature are emissions to air and waterbodies due to the use of agricultural machineries, as well as the production and use of nitrogen and phosphorus for agricultural activities. Other considerations, such as land use changes can influence soil carbon stocks, emitting GHG as a result of soil carbon losses (FAO, 2017). In addition to carbon sequestration capacity, soil carbon stocks are crucial for maintaining soil quality, improving soil fertility, preventing soil damage from erosion and extreme weather conditions (Müller et al., 2016). Heavy metals and pesticides emissions from agriculture are also producing negative impacts in the environment.

Table 8 shows the preliminary emissions considered in this report. For a fair comparison, emissions were calculated using the same methods for all agricultural scenarios. The parameters and methods used in this report are presented in Table 8. After revision, it was decided to include pesticides and heavy metals emissions as well as CO_2 emissions from carbon stocks changes, which will be assessed in the next deliverable 2.5.

Table 8: Field emissions calculation

Field emissions	Parameters considered	Method
Field emissions to air		
Nitrous oxide (N_2O)	❖ Nitrogen in mineral or organic fertiliser; ❖ Nitrogen content of maize residues; ❖ NO_x emissions; ❖ NH_3 emissions; ❖ NO_3^- leaching; ❖ Mineralization of organic soil	IPCC 2006, Tier 1(Nemecek et al., 2015)
Nitrogen dioxide (NO_2)	❖ 0.012 kg NO_x-N/kg N applied	Table 3-1. Tier 1 emission factors for NO_x emissions (EEA, 2013)
Ammonia (NH_3)	❖ 0.037 kg NH_3-N/kg N applied for ammonium nitrate fertiliser type	Table 3-2. Tier 2 emission factors for total NH_3 emissions (EEA, 2013)
Field emissions to water		
Nitrate (NO_3^-) leaching (groundwater)	❖ Precipitation and irrigation; ❖ Clay content; ❖ Root depth; ❖ Nitrogen supply; ❖ Organic carbon content; ❖ Nitrogen uptake	EMPA (Faist Emmenegger et al., 2009)
Phosphorus (P) leaching (groundwater)	❖ 0.07 kg P/ha for arable land ❖ If slurry is applied, a correction factor is needed	EMPA (Faist Emmenegger et al., 2009; Nemecek et al., 2015)
Phosphorus (P) runoff (surface water)	❖ 0.175 kg P/ha for arable land + correction factors; ❖ Correction factors are applied for the: • Amount of P_2O_5 in mineral fertiliser; • Amount of P_2O_5 in slurry; • Amount of P_2O_5 in solid manure;	EMPA (Faist Emmenegger et al., 2009; Nemecek et al., 2015)

Tables 9, 10, 11 and 12 show a summary of the main inputs and outputs required for the processing of maize grains, sugar beets, maize stover and sugar beet pulp, respectively. Data concerning the processing of maize stover (Table 11) and sugar beet pulp (Table 12) were modelled and designed by our AUA partners.

As noted, the processing of maize stover and sugar beet pulp into total sugars delivers a considerable amount of residues. For every kg of total sugars produced, an average of 8.5 kg and 5 kg of residues are also generated for maize stover and beet pulp, respectively. However, most of these residues can be valorized. For instance, the water and protein (as nitrogen source) is considered to be used in the fermentation[1] process. Inorganic soluble solids, that is $(NH_4)_2SO_4$ can be recovered as fertiliser. Moreover, xylan, sugar oligomers and furfurals can also be used for anaerobic digestion for biogas production. The acid insoluble lignin and acid soluble lignin can be used for energy production. Ash and organic soluble solids were considered as waste.

Table 9: Life cycle inventory table - maize processing

FU: 1 kg glucose	**Unit**	**Maize processing (P3)**	**Maize processing (P4)**
Main inputs			
Harvested grain	kg	1.50	1.56
Energy	MJ	3.11	2.64
Processed water	kg	4.90	4.4
Sulphuric acid	g	0.45	-
Sulphur dioxide	g	3.06	
Sulphur	g	-	2.79
Enzymes	g	-	8.36
Urea	mg	208	-
Sodium hydroxide	mg	282	-
Sodium chloride	mg	65	-
Cyclohexane	mg	55	-
Chlorine	mg	12	-
Outputs			
Glucose	**kg**	**1**	**1**
Maize gluten feed	g	268	290
Maize gluten meal	g	80	92
Maize oil	g	27	-

[1] The fermentation occurs after enzymatic hydrolysis process. WP3 is responsible for the fermentation step, which is considered as a downstream process.

FU: 1 kg glucose	Unit	Maize processing (P3)	Maize processing (P4)
Maize germ	g	-	106
Wastewater to treatment	kg	3.92	3.52
Transport			
Road	km	50	50

Table 10: Life cycle inventory table – sugar beet processing

FU: 1 kg of sucrose	Unit	Sugar beet processing (P1)	Sugar beet processing (P2)
Main inputs			
Harvested crop	kg	6.5	7.84
Energy	MJ	3.26	7.47
Processed water	kg	-	-
Limestone	g	150	401
Sulphuric acid	g	1.1	5.32
Sulphur dioxide	g	0.85	-
Sodium carbonate	mg	327	-
Formaldehyde	mg	982	-
Outputs			
Sucrose	**kg**	**1**	**1**
Molasses	g	-	335
Beet pulp	g	651	391
Lime fertiliser	g	295	-
Transport			
Road	km	50	50

Table 11: Life cycle inventory table - maize stover processing

FU: 1 kg fermentable sugars	Unit	Maize stover processing (P5)
Main inputs		
Maize stover	kg	2.08
Water	Kg	6.59

FU: 1 kg fermentable sugars	Unit	Maize stover processing (P5)
Sulfuric acid	kg	0.04
Ammonia	kg	0.02
Enzymes	Kg	0.01
Electricity	kWh	0.157
Cooling water	kg	0.018
Steam	kg	0.56
Outputs		
Main output (Total sugars):	**kg**	**1**
Glucose	kg	0.59
Xylose	kg	0.33
Other sugars	kg	0.08
Other outputs:	**kg**	**8.48**
Sugar oligomers	kg	0.03
Organic soluble solids	kg	0.29
Inorganic soluble solids	kg	0.05
Other insoluble solids	kg	0.09
Furfurals	kg	0.01
Cellulose	kg	0.02
Xylan	kg	0.01
Lignin	kg	0.25
Protein	kg	0.06
Water	kg	7.67
Transport		
Road	km	50

Table 12: Life cycle inventory table – sugar beet pulp processing

FU: 1 kg fermentable sugars	Unit	Beet pulp processing (P6)
Main inputs		

FU: 1 kg fermentable sugars	Unit	Beet pulp processing (P6)
Sugar beet pulp	kg	5.096
Water	Kg	0.694
Sulfuric acid	kg	0.023
Ammonia	kg	0.013
Enzymes	Kg	0.008
Electricity	kWh	0.101
Cooling water	kg	0.011
Steam	kg	0.35
Outputs		
Main output (Total sugars):	**kg**	**1**
Glucose	kg	0.374
Arabinose	kg	0.407
Galactose	kg	0.102
Xylose	kg	0.086
Mannose	kg	0.031
Other outputs	**kg**	**4.913**
Acid insoluble lignin	kg	0.018
Acid soluble lignin	kg	0.002
Protein	kg	0.204
Ash	kg	0.043
Others	kg	0.144
Water	kg	4.465
Inorganic soluble solids	kg	0.037
Transport		
Road	km	50

3.3.2 Allocation

Allocation is very important in LCA and should be done with care, since it can completely change the outcomes. When a production renders to valuable by-products, as in the case of wet mills, it is unfair to attribute the results only to the main product (e.g. sucrose), without considering the by-products (e.g. molasses and sugar beet pulp). Therefore, in this case, the allocation of the products must be taken into account in the overall computation. The assignment can be very controversial, as it has many methods and they are not 100% scientifically accepted and are subject to various interpretations. However, we decided to use two of the most common allocation methods (mass and economic). The substitution approach is also a possibility when considering a biologically based product. This involves finding substitute materials to replace the by-products. However, the substitution approach would require more processes and data to consider, such as predicting what would be a possible substitute that could replace maize gluten feeds on the market, and this assessment could lead to greater uncertainty. However, if enough information is available on time, the substitution approach will be used and detailed in the next deliverable 2.4.

Figures 9 and 10 show the average price of maize grain in the USA, Belgium and Italy, as well as the prices of glucose and sucrose in the last three years (2016,2017 and 2018). As shown, maize grain prices in the US are lower than those of the other two countries, as they are the world's main producers. As shown in Figure 10, sucrose prices are higher than glucose prices, making glucose a more interesting raw material to use in industrial fermentation from an economic perspective.

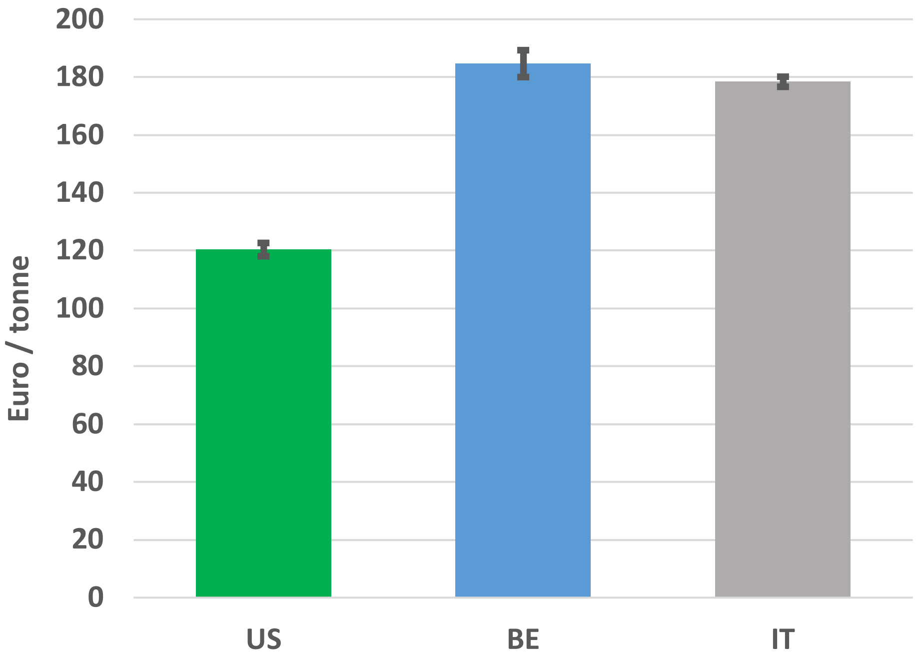

Figure 9: Average price of maize grain (years 2016, 2017 and 2018)

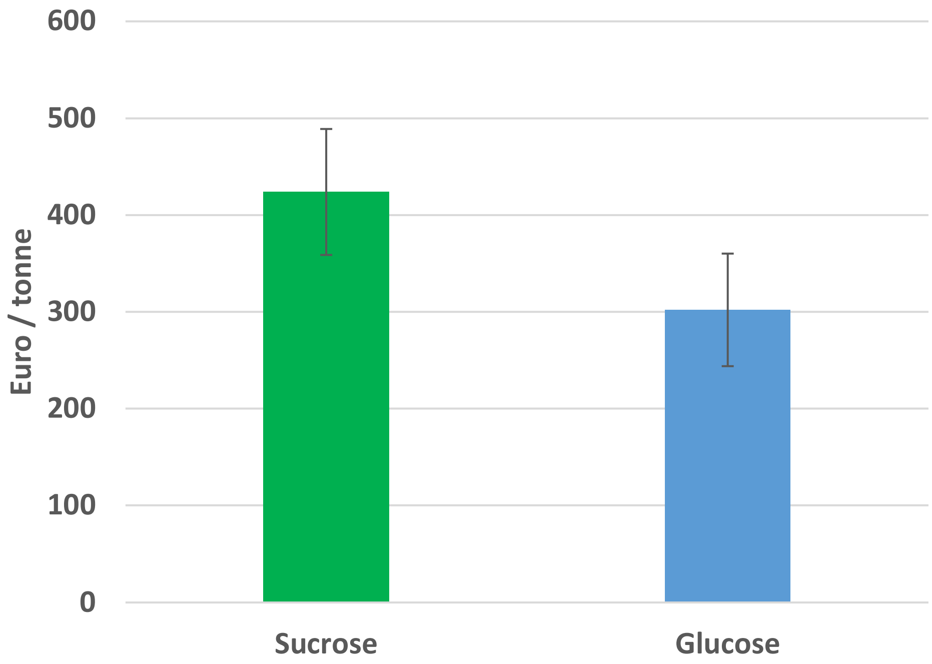

Figure 10: Average price of sucrose and glucose (years 2016, 2017 and 2018)

Table 13 presents the economic values considered for the by-products of fermentable sugar production. The data were gathered through databases and peer-reviewed studies.

Table 13: Economic values for maize grain, maize stover and sugar beet

Maize agriculture	**Maize grain and stover price (€ kg^{-1})**
A4 (US)	0.120[a]; 0.036[b]
A6 (IT)	0.178[c]; 0.051[b]
A7 (IT)	0.178[c]; 0.051[b]
A8 (BE)	0.184[c]; 0.054[b]
Maize processing	**Price (€ kg^{-1})**
Maize germ	0.270[d]
Maize oil	0.910[e]
Maize gluten feed	0.158[d]
Maize gluten meal	0.632[d]
Maize sugar	0.300[d]
Sugar beet processing	**Price (€ kg^{-1})**
Beet pulp	0.156[f]
Calcium carbonate	0.100[e]
Beet sugar	0.423[g]
Molasses	0.105[f]
Maize stover and beet pulp processing	**Price (€ kg^{-1})**
Lignin	0.630[d]
Furfural	0.900[d]

a Source:US Department of Agriculture (USDA, 2019)
b The price of maize stover is assumed to be 30% of the grain according to literature (Noya et al., 2015)
c Source: (EUROSTAT, 2019)
d Source: (Moncada et al., 2018)
e Source: Agri-footprint(Durlinger et al., 2017)
f Source: (Maravíc et al., 2015)
g Source: (European Commission, 2019)

4. Life cycle impact assessment

With the aim to account for the environmental impacts of bio-products, 11 impact categories were chosen. These environmental indicators were selected through a thorough literature review, taking into consideration a set of criteria, such as scientific acceptance, operability, and consistency among indicators. For detailed information on the chosen impact categories, see Deliverable 2.2. The GWPbio factor was not considered in this study since for short-rotation crops (i.e. a one-year period for maize and sugar beet) and a short storage time for fermentable sugars (i.e. one-year storage time), the value of the GWPbio factor is close to zero, therefore it can be disregarded.

Table 14: Chosen impact categories for bio-based products

	Impact category	Acronym	Unit	Source
1	**Acidification**	AC	mol H^+-eq	(Posch et al., 2008; Seppälä et al., 2006)
2	**Particulate matter**	PM	Deaths/kg emitted	(Fantke et al., 2016)
3	**Climate change**	CC	kg CO_2-eq	(IPCC, 2013)
4	**Affected biodiversity**	BIO	$m^2 \cdot$ PAS	(Millenium Ecosystem Assessment, 2005)
5	**Terrestrial eutrophication**	TE	Mol N-eq	(Posch et al., 2008; Seppälä et al., 2006)
6	**Freshwater eutrophication**	FE	Kg P-eq	(Struijs et al., 2013)
7	**Human toxicity, cancer**	HT	CTUh	(Rosenbaum et al., 2008)
8	**Land use, soil quality index**	LU	Pt (Dimensionless)	(Bos et al., 2016)
9	**Soil erosion**	SE	Kg soil erosion	(Borrelli et al., 2017)
10	**Fossil resource depletion**	FD	MJ	(Guinée et al., 2002; Van Oers et al., 2002)
11	**Water scarcity**	WD	m^3 water deprived-eq	(Boulay et al., 2018)

3.1.3 Biodiversity and soil erosion indicators

Two of the environmental indicators (Affected Biodiversity and Soil Erosion) do not have characterization factors in the LCA SimaPro software and cannot be calculated through it. With respect to the biodiversity indicator, the default values of each country were also evaluated, as described in Deliverable D2.2 in the "selection of environmental indicators and impact categories". Since most agricultural scenarios are found in temperate climates, the amount of species richness is not high compared to tropical levels. Again, this indicator leads to high uncertainty, since biodiversity is a multidimensional concept with different interpretations. It can be measured in terms of species numbers, density, rarity and diversity, for example. The most common indicator of biodiversity, however, is species richness (América P et al., 2018). The quantification of the biodiversity indicator is based on the 2005 Millennium Ecosystem Assessment (Millenium Ecosystem Assessment, 2005), related to terrestrial biomes, and only considers amphibians, birds, mammals and reptiles. Despite the complexity of quantifying biodiversity, the presence of endemic species, for example, indicates that the local is preserved as these species are very sensitive to changes in land use.

Biodiversity indicator

With the aim to calculate the biodiversity indicator BIO, the land occupation for each scenario needs to be multiplied by the species richness of each country, as indicated below:

BIO= PAS (potentially affected species) * m^2 * year

According to Deliverable 2.2, the averages of potentially affected species (PAS) for each of the countries under investigation are:

- United Kingdom = 3,237
- France = 3,717
- Germany = 3,202
- United States = 2,519
- Italy = 3,357
- Belgium = 3,602

For instance, for maize grain in the US (scenario A4), the land occupation is 0.66 m^2 * year and for sugar beet in the UK (Scenario A1) is 0.10 m2 * year. Therefore, the results for Bio indicator are:

- Maize grain in the US (scenario A4): 2,519 * 0.66 = 1662.54
- Sugar beet in the UK (Scenario A1): 3,237 * 0.10 = 323.7

That means that the Biodiversity is less affected producing sugar beet in the UK (Scenario A1) than maize grain in the US (Scenario A4).

Soil erosion indicator

Soil erosion, according to Revised Universal Soil Loss Equation (RUSLE) (Panagos et al., 2015d) is the mean annual soil loss:

A = R * K * C * LS * P

Where:

A is the annual soil erosion (t ha^{-1} yr^{-1})

R is the rainfall erosivity factor (MJ mm ha^{-1} h-1 yr^{-1})

K is the soil erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1})

LS is the slope length and steepness factor (no dimension)

C is the cover management factor (no dimension) and is related to the type of crop cultivated

P is the support practice (no dimension)

To calculate soil erosion, default data for countries in Europe can be found in the literature for each variable R (Panagos et al., 2017) , K (Panagos et al., 2014), LS (Panagos et al., 2015a), C (Panagos et al., 2015b) and P (Panagos et al., 2015c). However, for the United States, it was assumed that the agricultural region is located in the Corn Belt in the IOWA region, where data on soil erosion can be found in the literature (Loudis, 2017).

For instance, for maize grain in Belgium (Scenario A8):

- R factor (BE) = 601.5 MJ mm ha^{-1} h^{-1} yr^{-1}
- K factor (BE) = 0.04 t ha h ha^{-1} MJ^{-1} mm^{-1}
- LS factor (BE)= 0.36
- C factor (for maize) = 0.38
- P factor (BE) = 0.95

Therefore, "A" factor for maize grain in BE is:

A = 601.5 * 0.04 * 0.36 * 0.38 * 0.95 = 2.5 t ha^{-1} yr^{-1}

As regards sugar beet in the United Kingdom (Scenario A1):

- R factor (UK) = 746.6 mm ha^{-1} h^{-1} yr^{-1}
- K factor (UK) = 0.027 t ha h ha^{-1} MJ^{-1} mm^{-1}
- LS factor (BE)= 0.53
- C factor (for sugar beet) = 0.34
- P factor (BE) = 0.95

Therefore, "A" factor for sugar beet in the UK is:

A = 746.6 * 0.027 * 0.53 * 0.34 * 0.95 = 3.5 t ha^{-1} yr^{-1}

Comparing annual soil erosion, maize grain in Belgium has a smaller impact than sugar beet cultivation in the UK. The calculation of soil erosion requires very specific data, which implies local measurements and observations. In this case, since most of the agriculture and pre-processing data are derived from the literature and databases, it was not possible to quantify this indicator with in situ data and default values were applied in this report. However, this leads to great uncertainty, as soil erosion figures may have very different values within the same region, depending on soil type, climate and agricultural management category. However, these results can serve as a basis for further evaluation.

3.1.4 Preliminary results

The outcomes of life cycle impact assessment will be reported in Deliverable 2.4, due by month 35. However, work is underway on Task 2.5 "Major environmental impacts associated with feedstock production and upstream processing" and some preliminary results of agricultural activities for sugar beet in the UK (scenario A1) and maize grain in the US (Scenario A4) are already available and displayed in Figures 11 and 12, respectively. As shown, fertilisation and field emissions play a major role for sugar beet cultivation (Figure 11) and maize grain (Figure 12). Economic allocation was performed to assess the environmental burdens of maize grain and stover production.

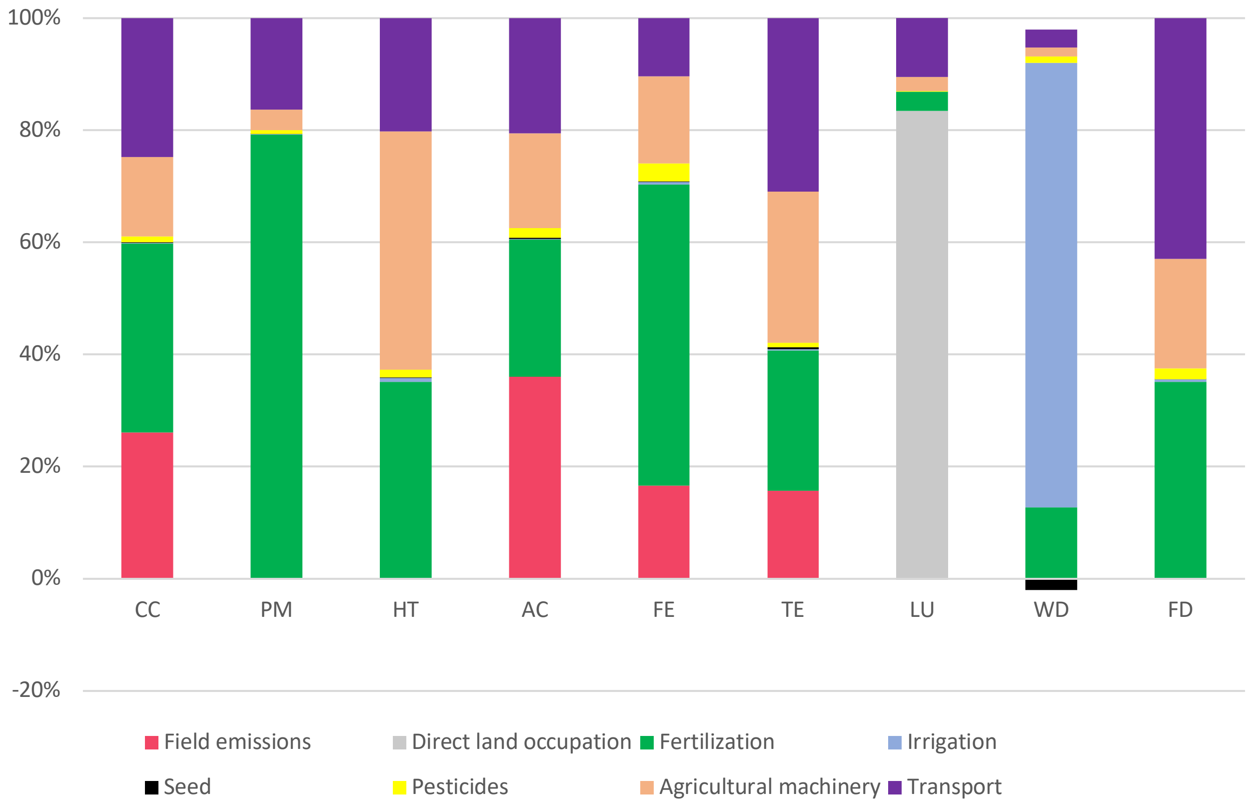

Figure 11: Environmental hotspot analysis of sugar beet production (Scenario A1). Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; WD – Water Depletion and FE – Fossil Depletion

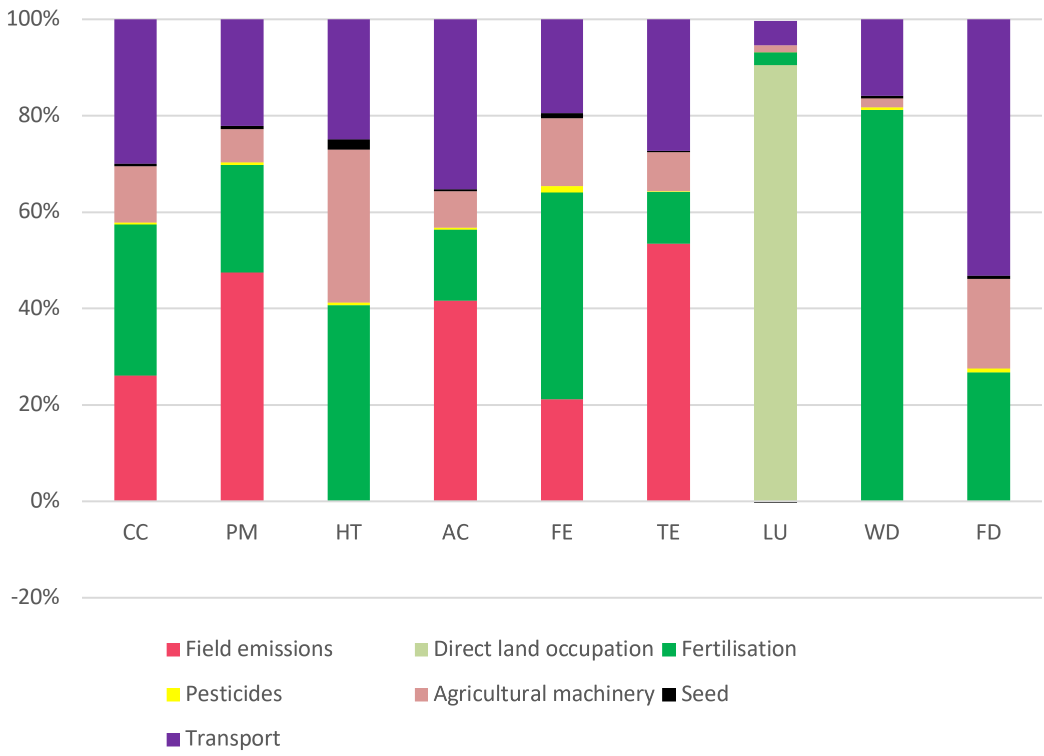

Figure 12: Environmental hotspot analysis of maize grain production (Scenario A4). Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; WD – Water Depletion and FE – Fossil Depletion

4. Hybridised indicators

Novel indicators were proposed to fill the gap in environmental indicators and provide a circular economy perspective. For further clarification on hybrid indicators, see Deliverable 3.1. This section presents the results of the hybrid indicators for the upstream environmental assessment.

5. Hazardous chemical use

Hazardous chemical use is a qualitative parameter that identifies the use of hazardous substances (e.g. additives, solvents, catalysts), according to the classification of "Substitute It Now" (SIN) list - SINLIST[1] and SUBSPORT[2]. These databases provide information on carcinogenic, mutagenic and toxic to reproduction (CMR), bioaccumulative and persistent toxic substances (PBT) and endocrine disruptors. This indicator is for information only to ask questions about the possible replacement of less harmful materials. The use of hazardous substances is analysed for the production of fermentable sugars from maize grain, maize stover and sugar beet pulp, as follows. Three substances were identified as hazardous chemicals and should be replaced by less harmful substances:

- Glyphosate in agricultural activities
- Cyclohexane in maize processing
- Formaldehyde in sugar beet processing

[1] https://chemsec.org/sin-list/
[2] Schmitz-Felten et al., "SUBSPORT – Substitution Support Portal- Moving towards Safer Alternatives".

6. Feedstock efficiency

Feedstock efficiency is a quantitative indicator, which assesses the total amount of feedstocks needed to produce a bio-product.

$$Feedstock\ efficiency = \frac{M_{raw.mat}}{M_{main.prod}+M_{co.prod}} \quad \text{Eq 1a}$$

$M_{main.prod}$ =*Total mass of target products synthesised in a process (kg)*
$M_{main.prod}$ = *Total mass of useful co-products synthesised in a process (kg)*
$M_{raw.mat}$ =*Total mass of main feedstock fed into the process (kg)*

Table 15: Summary hybridized indicators results for feedstock efficiency (F_e)

Feedstock efficiency (F_e)	Maize grain	Maize stover	Sugar beet pulp
1 kg fermentable sugar	1.13	1.49	9.4
PLA packaging film	8.5×10^{-3}	1.03×10^{-2}	7×10^{-2}
PLA agricultural mulch	249	328	2064
PBS	3.11	4.11	26

7. Waste-factor

This quantitative indicator is the total mass generated as waste divided by the total mass of the bio-product and co-products generated.

$$Waste - factor = \frac{M_{TotW}}{M_{Prod} + M_{co.\ prod}} \quad \text{Eq 2a}$$

M_{TotW} =*Total mass of waste generated from the production process (kg)*
$M_{co.\ prod}$ =*Total mass of useful co-products generated (kg)*
M_{Prod} =*Total mass of target product generated from the process (kg)*

Table 16: Summary hybridized indicators results for waste factor (W_f)

Waste factor W_f	Maize grain	Maize stover	Sugar beet pulp
1 kg fermentable sugar	6.35×10^{-3}	0.27	0.31
PLA packaging film	4.73×10^{-5}	2.06×10^{-3}	2.33×10^{-3}
PLA agricultural mulch	1.4	60.7	68.3
PBS	1.75×10^{-2}	0.76	0.77

8. Energy intensity

Energy intensity is a qualitative indicator which is the ratio of the total amount of energy (fossil-derived, renewable and internally derived energy) to the total amount of bio-products and co-products generated within the process.

$$Energy\ intensity = \frac{E_{FosD} + E_{RenD} + E_{IntD}}{M_{Prod} + M_{Co.prod}} \quad \text{Eq 3a}$$

E_{FosD} = *Fossil-derived energy used (kWh)*

E_{RenD} = *Renewable energy used (kWh)*

E_{IntD} = *Internally derived energy used (kWh)*

M_{Prod} = *Total mass of target product generated (kg)*

$M_{Co.prod}$ =*Total mass of co-product generated (kg)*

Table 17: Summary hybridized indicators results for energy intensity (E_i)

Energy intensity E_i	Maize grain	Maize stover	Sugar beet pulp
1 kg fermentable sugar	0.74	0.93	1.94
PLA packaging film	5.5×10^{-3}	6.9×10^{-3}	14.47×10^{-3}
PLA agricultural mulch	162.8	204.6	494.4
PBS	2.04	2.57	5.33

As can be seen from the figures in the hybrid indicators, glucose production from maize grain showed a better performance in all indicators (raw material efficiency, waste factor and energy intensity). On the other hand, sugar beet pulp is by far the biomass that has a less circular economic outlook. This is because the technology has not achieved stability for processing lignocellulosic materials compared to starch crops. In addition, beet pulp must undergo three different processes (agriculture, processing of beet sugar and processing of beet pulp) to become fermentable sugars, while maize stover requires only two steps (agriculture and processing of maize stover). In addition, about 2 kg of stover and 5 kg of beet pulp are required to produce 1 kg of fermentable sugars.

5. Conclusions

It is essential to take into account the environmental sustainability aspects of upstream activities, as they represent a very different and independent stage in the bioproducts supply chain. An important way to produce biological products is through a fermentable sugar platform. These sugars are produced from raw materials rich in carbohydrates, either from starch or sugar crops (e.g. maize and sugar beet) or from lignocellulosic biomass (e.g. maize residues and beet pulp).

This report is part of Task 2.4, which concerns the inventory phase of the production of fermentable sugars. The quantity of fermentable sugars, from maize grain, maize stover and sugar beet pulp, needed to produce the three case studies is: 1 PLA packaging film 350 mm x 250 mm (7.5 g fermentable sugars); 1 ha PLA agricultural mulch (220 kg fermentable sugars) and 1 kg PBS (2.77 kg fermentable sugars). PLA and PBS are the main polymers used in the downstream environmental assessment (in WP3).

Data on the agricultural activities of sugar beet, maize and stover as well as the pre-processing of maize grains into glucose were collected through peer-reviewed studies and databases. On the other hand, information on lignocellulosic processing (maize stover and sugar beet pulp) was collected in collaboration with our AUA partners. As pretreatment processes, especially of starch crops, generate valuable by-products (e.g. maize oil), data on the mass and prices of these by-products were collected to apply a mass and economic allocation. The results of the hybrid indicators were also evaluated in this report as a complement to WP3 Deliverable 3.1.

As Task 2.5 has already started, related to life cycle impact assessment, preliminary results of agricultural activities are presented in this report. It shows that in the case of sugar beet (scenario A1) and grain maize (scenario A4), field emissions and fertilization are the main critical points for the environment. In addition, hybrid indicator figures show that glucose production from maize grain has the best performance for all indicators.

6. References

ABSugar, 2018. An introduction to the global sugar markets 2019.

Adom, F., Dunn, J.B., Han, J., 2014. GREET Pretreatment Module. Chicago.

América P, D., Jonathan MH, G., Christopher D, W., Piero, V., Neil D, B., Malika, V.-S., Andrew, B., Https://doi.org/10.1101/447, bioRxiv 447466; doi:, 2018. Putting species back on the map: devising a robust method for quantifying the biodiversity impacts of land conversion. bioRxiv 447466. https://doi.org/https://doi.org/10.1101/447466

Boone, L., Van, V., Meester, S. De, Vandecasteele, B., Muylle, H., Roldán-ruiz, I., Nemecek, T., Dewulf, J., 2016. Environmental life cycle assessment of grain maize production : An analysis of factors causing variability. Science of the Total Environment 553, 551–564. https://doi.org/10.1016/j.scitotenv.2016.02.089

Borrelli, P., Robinson, D.A., Fleischer, L.R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schütt, B., Ferro, V., Bagarello, V., Oost, K. Van, Montanarella, L., Panagos, P., 2017. An assessment of the global impact of 21st century land use change on soil erosion. Nature Communications 8, 13. https://doi.org/10.1038/s41467-017-02142-7

Bos, U., Horn, R., Beck, T., Lindner, jan P., Fischer, M., 2016. LANCA - Characterization Factors for Life Cycle Impact Assessment - v2.0.

Bosco, S., Di Bene, C., Galli, M., Remorini, D., Massai, R., Bonari, E., 2013. Soil organic matter accounting in the carbon footprint analysis of the wine chain. International Journal of Life Cycle Assessment 18, 973–989. https://doi.org/10.1007/s11367-013-0567-3

Boulay, A.M., Bare, J., Benini, L., Berger, M., Lathuillière, M.J., Manzardo, A., Margni, M., Motoshita, M., Núñez, M., Pastor, A.V., Ridoutt, B., Oki, T., Worbe, S., Pfister, S., 2018. The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). International Journal of Life Cycle Assessment 23, 368–378. https://doi.org/10.1007/s11367-017-1333-8

Cherubini, F., Strømman, A.H., 2011. Life cycle assessment of bioenergy systems: State of the art and future challenges. Bioresource Technology 102, 437–451. https://doi.org/10.1016/j.biortech.2010.08.010

David, E., 2013. Sustainable Corn Stover Harvest. Iowa.

De Matos, C.T., Garcia, J.C., Aurambout, J.-P., Kavalov, B., Manfredi, S., 2015. Environmental Sustainability Assessment of Bioeconomy Products and Processes – Progress Report 1. https://doi.org/10.2788/708144

Díaz, A.B., Marzo, C., Caro, I., de Ory, I., Blandino, A., 2017. Valorization of exhausted sugar beet cossettes by successive hydrolysis and two fermentations for the production of bio-products. Bioresource Technology 225, 225–233. https://doi.org/10.1016/j.biortech.2016.11.024

Draycott, A.P., 2006. Sugar Beet, Blackwell Publishing. Blackwell Publishing. https://doi.org/10.1002/9780470751114

Duraisam, R., Salelgn, K., Berekete, A.K., 2017. Production of Beet Sugar and Bio-ethanol from Sugar beet and it Bagasse: A Review. International Journal of Engineering Trends and Technology 43, 222–233. https://doi.org/10.14445/22315381/IJETT-V43P237

Durlinger, B., Koukouna, E., Broekema, R., Van Paassen, M., Scholten, J., 2017. Agri-footprint 4.0. Gouda.

Ecoinvent database®, 2015. Ecoinvent database® [WWW Document]. URL http://www.ecoinvent.org/database

EEA, 2013. Crop production and agricultural soils, in: EMEP/EEA Emission Inventory Guidebook. pp. 1–43.

Eerhart, A.J.J.E., Faaij, A.P.C., Patel, M.K., 2012. Replacing fossil based PET with biobased PEF; process analysis, energy and GHG balance. Energy & Environmental Science 5, 6407. https://doi.org/10.1039/c2ee02480b

Faist Emmenegger, M., Reinhard, J., Zah, R., 2009. Sustainability Quick Check for Biofuels. Intermediate background report. Dübendorf.

Fantin, V., Righi, S., Rondini, I., Masoni, P., 2017. Environmental assessment of wheat and maize production in an Italian farmers' cooperative. Journal of Cleaner Production 140, 631–643. https://doi.org/10.1016/j.jclepro.2016.06.136

Fantke, P., Evans, J., Hodas, N., Joshua, A., Jantunen, M., Jolliet, O., Mckone, T.E., 2016. Health impacts of fine particulate matter, in: Global Guidance for Life Cycle Impact Assessment Indicators. p. 166.

FAO, 2017. Global database of GHG emissions related to feed crops: Methodology. Version 1. Livestock Environmental Assessment and Performance Partnership. Rome.

FAO, 2009. Sugar Beet White Sugar, Agribusiness Handbooks.

FAOSTAT, 2017. Crop statistics [WWW Document]. URL http://www.fao.org/faostat/en/#data (accessed 1.10.19).

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., Van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.., De Bruijn, J.A., Van Duin, R., Huijbregts, M.A.J., 2002. Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards.

Habeeb, A.A.M., Gad, A.E., EL-Tarabany, A.A., Mustafa, M.M., Atta, M.A.A., 2017. Using of Sugar Beet Pulp By-Product in Farm Animals Feeding. International Journal of Scientific Research in Science and Technology 3, 107–120.

IfBB, 2018. Biopolymers facts and statistics. Production capacities, processing routes, feedstock, land and water use. Hannover. https://doi.org/10.1002/adfm.200600816

IPCC, 2013. Anthropogenic and natural radiative forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. https://doi.org/10.1017/CBO9781107415324.018

ISO 14040, 2006. Environmental Management-Life Cycle Assessment- Principles and Framework, Geneve, Switzerland.

ISO14044, 2006. ISO 14044, Environmental management — Life cycle assessment — Requirements and guidelines 2006, 54.

Kathage, J., Gómez-barbero, M., Rodríguez-cerezo, E., 2016. Framework for assessing the socio-economic impacts of Bt maize cultivation. https://doi.org/10.2788/739670

Loudis, C., 2017. Losing Ground: Soil Erosion in the Upper Iowa Watersheed. Medford, MA.

Maravíc, N., Kiss, F., Seres, L., Bogdanovic, Branislav, Bogdanovic, Biljana, Seres, Z., 2015. Economic analysis and LCA of an advanced industrial-scale raw sugar juice purification procedure. Food and Bioproducts Processing 5, 19–26. https://doi.org/10.1016/j.fbp.2015.02.004

Millenium Ecosystem Assessment, 2005. Ecosystems and Human Well-Being: Synthesis. Washington, DC.

Modelska, M., Berlowska, J., Kregiel, D., Cieciura, W., Antolak, H., Tomaszewska, J., Binczarski, M., Szubiakiewicz, E., Witonska, I.A., 2017. Concept for recycling waste biomass from the sugar industry for chemical and biotechnological purposes. Molecules 22, 1–26. https://doi.org/10.3390/molecules22091544

Moncada, J., Vural Gursel, I., Huijgen, W.J.J., Dijkstra, J.W., Ramírez, A., 2018. Techno-economic and ex-ante environmental assessment of C6 sugars production from spruce and corn. Comparison of organosolv and wet milling technologies. Journal of Cleaner Production 170, 610–624. https://doi.org/10.1016/j.jclepro.2017.09.195

Müller, A., Bautze, L., Meier, M., Gattinger, A., Gall, E., Chatzinikolaou, Effimia Meredith, S., Tonći, U., Ullmann, L., Tonći, U., 2016. Organic farming , climate change mitigation and beyond. Reducing the environmental impacts of EU agriculture. Brussels.

Muñoz, I., Flury, K., Jungbluth, N., Rigarlsford, G., I Canals, L.M., King, H., 2014. Life cycle assessment of bio-based ethanol produced from different agricultural feedstocks. International Journal of Life Cycle Assessment 19, 109–119. https://doi.org/10.1007/s11367-013-0613-1

Nemecek, T., Bengoa, X., Lansche, J., Mouron, P., Riedener, E., Rossi, V., Humbert, S., 2015. Methodological Guidelines for the Life Cycle Inventory of Agricultural Products. Version 3.0. Lausanne and Zurich.

Noya, I., González-García, S., Bacenetti, J., Arroja, L., Moreira, M.T., 2015. Comparative life cycle assessment of three representative feed cereals production in the Po Valley (Italy). Journal of Cleaner Production 99, 250–265. https://doi.org/10.1016/j.jclepro.2015.03.001

Nwaneshiudu, I.C., Ganguly, I., Pierobon, F., Bowers, T., Eastin, I., 2016. Environmental assessment of mild bisulfite pretreatment of forest residues into fermentable sugars for biofuel production. Biotechnology for Biofuels 1–10. https://doi.org/10.1186/s13068-016-0433-1

Panagos, P., Ballabio, C., Meusburger, K., Spinoni, J., Alewell, C., Borrelli, P., 2017. Towards estimates of future rainfall erosivity in Europe based on REDES and WorldClim datasets 548, 251–262. https://doi.org/10.1016/j.jhydrol.2017.03.006

Panagos, P., Borrelli, P., Meusburger, K., 2015a. A New European Slope Length and Steepness Factor (LS-Factor) for Modeling Soil Erosion by Water 117–126. https://doi.org/10.3390/geosciences5020117

Panagos, P., Borrelli, P., Meusburger, K., Alewell, C., Lugato, E., Montanarella, L., 2015b. Land Use Policy Estimating the soil erosion cover-management factor at the European scale. Land Use Policy 48, 38–50. https://doi.org/10.1016/j.landusepol.2015.05.021

Panagos, P., Borrelli, P., Meusburger, K., Zanden, E.H. Van Der, Poesen, J., Alewell, C., 2015c. ScienceDirect Modelling the effect of support practices (P -factor) on the reduction of soil erosion by water at European scale. Environmental Science and Policy 51, 23–34. https://doi.org/10.1016/j.envsci.2015.03.012

Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L., Alewell, C., 2015d. The new assessment of soil loss by water erosion in Europe. Environmental Science and Policy 54, 438–447. https://doi.org/10.1016/j.envsci.2015.08.012

Panagos, P., Meusburger, K., Ballabio, C., Borrelli, P., Alewell, C., 2014. Science of the Total Environment Soil erodibility in Europe : A high-resolution dataset based on LUCAS. Science of the Total Environment, The 479–480, 189–200. https://doi.org/10.1016/j.scitotenv.2014.02.010

Papageorgiou, M., Skendi, A., 2018. Introduction to cereal processing and by-products. Sustainable Recovery and Reutilization of Cereal Processing By-Products 1–25. https://doi.org/10.1016/B978-0-08-102162-0.00001-0

Posch, M., Seppälä, J., Hettelingh, J.P., Johansson, M., Margni, M., Jolliet, O., 2008. The role of atmospheric dispersion models and ecosystem sensitivity in the determination of characterisation factors for acidifying and eutrophying emissions in LCIA. International Journal of Life Cycle Assessment 13, 477–486. https://doi.org/10.1007/s11367-008-0025-9

Prasad, A., Sotenko, M., Blenkinsopp, T., Coles, S.R., 2016. Life cycle assessment of lignocellulosic biomass pretreatment methods in biofuel production. International Journal of Life Cycle Assessment 21, 44–50. https://doi.org/10.1007/s11367-015-0985-5

Renouf, M.A., Wegener, M.K., Nielsen, L.K., 2008. An environmental life cycle assessment comparing Australian sugarcane with US corn and UK sugar beet as producers of sugars for fermentation. Biomass and Bioenergy 32, 1144–1155. https://doi.org/10.1016/j.biombioe.2008.02.012

Rosenbaum, R.K., Bachmann, T.M., Gold, L.S., Huijbregts, M.A.J., Jolliet, O., Juraske, R., Koehler, A., Larsen, H.F., MacLeod, M., Margni, M., Mackone, T.E., Payet, J., Schuhmacher, M., Van De Meent, D., Hauschild, M.Z., 2008. USEtox - The UNEP-SETAC toxicity model: Recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. International Journal of Life Cycle Assessment 13, 532–546. https://doi.org/10.1007/s11367-008-0038-4

Rüdelsheim, P.L.J., Smets, G., 2011. Baseline information on agricultural practices in the EU Maize (Zea mays L .). Brussels.

Salim, I., González-García, S., Feijoo, G., Moreira, M.T., 2019. Assessing the environmental sustainability of glucose from wheat as a fermentation feedstock. Journal of Environmental Management 247, 323–332. https://doi.org/10.1016/j.jenvman.2019.06.016

Seamon, M., 2014. Corn stover: When does removal make sense? [WWW Document]. Michigan State University Extension. URL https://www.canr.msu.edu/news/corn_stover_when_does_removal_make_sense (accessed 7.2.19).

Seppälä, J., Posch, M., Johansson, M., Hettelingh, J.P., 2006. Country-dependent characterisation factors for acidification and terrestrial eutrophication based on accumulated exceedance as an impact category indicator. International Journal of Life Cycle Assessment 11, 403–416. https://doi.org/10.1065/lca2005.06.215

Struijs, J., Beusen, A., van Jaarsveld, H., Huijbregts, M.A.., 2013. Eutrophication, in: ReCiPe 2008. A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and Endpoint Level. pp. 58–66. https://doi.org/10.2307/40184439

Tao, L., Tan, E.C.D., Aden, A., Elander, R.T., 2014. Techno-Economic Analysis and Life-Cycle Assessment of Lignocellulosic Biomass to Sugars Using Various Pretreatment Technologies, in: Biological Conversion of Biomass for Fuels and Chemicals: Explorations from Natural Utilization Systems. pp. 358–380.

Thomas, V.M., Choi, D.G., Luo, D., Realff, M., 2012. A supercritical Water Approach to Cellulosic Sugars: Lifecycle Energy, Greenhouse Gas and Water Implications.

Tomaszewska, J., Bieliński, D., Binczarski, M., Berlowska, J., Dziugan, P., Piotrowski, J., Stanishevsky, A., Witońska, I.A., 2018. Products of sugar beet processing as raw materials for chemicals and biodegradable polymers. RSC Advances 8, 3161–3177. https://doi.org/10.1039/C7RA12782K

Van Oers, L., De Koning, A., Guinée, J.B., Huppes, G., 2002. Abiotic resource depletion in LCA. Improving characterisation factors for abiotic resource depletion as recommended in the new Dutch LCA handbook., Aviation Week and Space Technology (New York). Delft, The Netherlands.

Vargas-Ramirez, J.M., Wiesenborn, D.P., Ripplinger, D.G., Pryor, S.W., 2017. Carbon footprint of industrial-beet sugars stored as raw thick juice for use as a fermentation feedstock. Journal of Cleaner Production 162, 1418–1429. https://doi.org/10.1016/j.jclepro.2017.06.153

Vercalsteren, A., Boonen, K., 2015. Life Cycle Assessment study of starch products for the European starch industry association (AAF): sector study.

Wood, D., Rourke, T.O., 1995. Glucose syrups in the fermentation industries, in: Handbook of Starch Hydrolysis Products and Their Derivatives. pp. 230–244. https://doi.org/10.1007/978-1-4615-2159-4_8

Notes on references and style:

In large reports, in which individual chapters are written more or less autonomously by one or more authors, the reference list should be placed as the last section in each chapter.

Reference style to be used: "European Union Interinstitutional Style Guide", which is the common style guide that is used by the different branches of the European Union. It is available in most bibliographic management tools and compatible with http://citationstyles.org/ See also http://www.citationmachine.net/european-union-interinstitutional-style-guide/cite-a-other for simple automated citation formatting.

The European Union Interinstitutional Style Guide[1] also provides detailed guidance on Punctuation, Singular or plural, Tenses of minutes, Spelling, Upper and lower case, Numbers, dates and time, Gender-neutral language, Italics and on Abbreviations and symbols: http://publications.europa.eu/code/pdf/en-PIV-rev2105.pdf

Due to the diverse nature of the consortium, we cannot use bibliographic software. References should be manually added in-line as a footnote (see example on this page). Further guidance on citations will be provided in a separate document.

[1] European Union Interinstitutional Style Guide. European Union. 2011

Information Sheet STAR-ProBio

STAR-ProBio supports the European Commission in the full implementation of European policy initiatives, including the Lead Market Initiative in bio-based products, the industrial policy and the European Bio-economy Strategy.

STAR-ProBio does so by developing sustainability assessment tools for bio-based products, and by developing credible cases for bio-based products with the highest actual market penetration and highest potential for the future markets.

STAR-ProBio integrates scientific and engineering approaches with social sciences and humanities-based approaches to formulate guidelines for a common framework promoting the development of regulations and standards supporting the adoption of business innovation models in the bio-based products sector.

The aim of STAR-ProBio is to cover gaps in the existing framework for sustainability assessment of bio-based products and improve consumer acceptance for bio-based products by identifying the critical sustainability issues in their value chains.

STAR-ProBio constitutes a multidisciplinary project that will:

- meet environmental, social and economic challenges, paving the way for a much-needed sustainability transition towards a bio-based economy;
- promote a more efficient and harmonized policy regulation framework;
- boost the market-pull of bio-based products within the context on a sustainable 21st Century.

The overall objective of the project is to promote a more efficient and harmonized policy regulation framework for the market-pull of bio-based products. This will be achieved by developing a fit-for-purpose sustainability scheme, including standards, labels and certifications.

An integral part of STAR-ProBio is the adoption of life-cycle methodologies to measure Environmental, techno-economic and social impacts, and comprehensively assess the roll-out of bio-based products. The analysis of selected case studies on construction materials, bio-based polymers, and fine chemicals, will ensure that the approach is not too broad and theoretic, allowing the benchmarking against non-bio-based products.

The specific objectives of STAR-ProBio are to:

- Develop a fit-for-purpose sustainability scheme;
- Identify gaps regarding sustainability indicators, requirements and criteria;
- Develop a sound and harmonised approach for environmental LCA, Social-LCA and techno-economic LCC assessment of bio-based products;
- Enhance the reliability of sustainability certifications and standards;
- Assess the effectiveness of the proposed sustainability scheme for selected case studies;
- Develop an approach to identify and mitigate the risk of negative ILUC effects;
- Encourage market pull for bio-based products through the assessment of consumers' preferences and acceptance;
- Spread awareness about sustainable production of bio-based products among farmer associations, industries, EU bodies, entrepreneurs and stakeholders from the civil society.

The STAR-ProBio consortium is integrated by:

- UNITELMA Sapienza University of Rome, Italy (Consortium leader)
- University of York, United Kingdom
- Technische Universität Berlin, Germany
- Agricultural University of Athens, Greece
- DBFZ, Germany
- SQ Consult B.V., The Netherlands
- University of Bologna, Italy
- Uniwersytet Warminsko Mazurski W Olsztynie, Poland
- ChemProf, Poland
- Quantis SARL, Switzerland
- Novamont SPA, Italy
- Naturvardsverket, Sweden
- Universidad de Santiago de Compostela, Spain
- European Environmental Citizens Organisation for Standardisation, Belgium
- agroVet GmbH, Austria

STAR-ProBio receives funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 727740, Work Programme BB-01-2016: Sustainability schemes for the bio-based economy.

Additional information can be found here: www.star-probio.eu

Annex1

The detailed calculation for each hybridised indicator is assessed in this section.

9. Feedstock efficiency

Feedstock efficiency is a quantitative indicator, which assesses the total amount of feedstocks needed to produce a bio-product.

$$Feedstock\ efficiency = \frac{M_{raw.mat}}{M_{main.prod}+M_{co.prod}} \quad \text{Eq 1a}$$

$M_{main.prod}$ =*Total mass of target products synthesised in a process (kg)*

$M_{main.prod}$ = *Total mass of useful co-products synthesised in a process (kg)*

$M_{raw.mat}$ =*Total mass of main feedstock fed into the process (kg)*

2.1 Maize grain

Agriculture

Reference: 1.51 kg maize grain produces 1 kg of fermentable sugars

- 1 kg of glucose

F_e = 0.11 kg agricultural inputs /(1.51 kg maize grain +0.755 maize stover)
F_e = 0.04

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

F_e = 0.04 x 0.0075
$F_e = 3 \times 10^{-4}$

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

F_e = 0.04 x 220
F_e = 8.8

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

F_e = 0.04 x 2.77
F_e = 0.11

Processing

- 1 kg of glucose

F_e = 1.51 kg maize grain / (1 kg of sugar + 0.375 kg co-products)
F_e = 1.09 kg raw material/ kg sugar

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

$F_e = 1.09 \times 0.0075$
$F_e = 8.2 \times 10^{-3}$

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

$F_e = 1.09 \times 220$
$F_e = 240$

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

$F_e = 1.09 \times 2.77$
$F_e = 3$

Total (Agriculture + Processing)

- 1 kg of glucose

$F_e = 0.04 + 1.09$
$F_e = 1.13$

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

$F_e = 3 \times 10^{-4} + 8.2 \times 10^{-3}$
$F_e = 8.5 \times 10^{-3}$

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

$F_e = 8.8 + 240$
$F_e = 248.8$

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

$F_e = 0.11 + 3$
$F_e = 3.11$

2.2 Maize stover

Agriculture

Reference: 2.08 kg maize stover produces 1 kg of fermentable sugars

- 1 kg of fermentable sugars

F_e = 0.30 kg (agricultural inputs) /(2.08 stover + 4.16 maize grain)
F_e = 0.04

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

F_e = 0.04 x 0.0075
$F_e = 3 \times 10^{-4}$

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

F_e = 0.04 x 220
F_e = 8.8

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

F_e = 0.04 x 2.77
F_e = 0.11

Processing

Reference: 2.08 kg maize stover produces 1 kg of fermentable sugars

- 1 kg of fermentable sugars

F_e = 2.08 kg maize stover / (1 kg of sugar + 0.43 kg co-products)
F_e = 1.45 kg raw material/ kg sugar

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

F_e = 1.45 x 0.0075
F_e = 0.01

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

F_e = 1.45 x 220
F_e = 319

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

F_e = 1.43 x 2.77
F_e = 4

Total (Agriculture + Processing)

- 1 kg of fermentable sugars

F_e = 0.04 + 1.45
F_e = 1.49

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

F_e = 3×10^{-4} + 0.01
F_e = 0.0103

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

F_e = 8.8 + 319
F_e = 327.8

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

F_e = 0.11 + 4
F_e = 4.11

2.3 Sugar beet pulp

Agriculture

Reference: 102.31 kg beet sugar to produce 5.096 kg beet pulp that leads to 1 kg of fermentable sugars

- 1 kg of fermentable sugars

F_e = 0.33 kg (agricultural inputs) /102.31
F_e = 0.003

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

F_e = 0.003 x 0.0075
F_e = 2.2×10^{-5}

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

$F_e = 0.003 \times 220$
$F_e = 0.66$

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

$F_e = 0.003 \times 2.77$
$F_e = 8.31 \times 10^{-3}$

Processing 1

Reference: 102.31 kg beet sugar to produce 5.096 kg beet pulp that leads to 1 kg of fermentable sugars

- 1 kg of fermentable sugars

F_e = 102.31 (harvested beet) / 5.096 (bee pulp) + 4.33 (molasse) + 13 (sucrose)
F_e = 4.56 kg raw material/ kg sugar

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

$F_e = 4.56 \times 0.0075$
$F_e = 0.034$

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

$F_e = 4.56 \times 220$
$F_e = 1003$

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

$F_e = 4.56 \times 2.77$
$F_e = 12.63$

Processing 2

Reference: 102.31 kg beet sugar to produce 5.096 kg beet pulp that leads to 1 kg of fermentable sugars

- 1 kg of fermentable sugars

F_e = 5.096 (beet pulp)/ (1 (sugar) + 0.057)
F_e = 4.82 kg raw material/ kg sugar

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

$F_e = 4.82 \times 0.0075$
$F_e = 0.036$

- ❖ PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

$F_e = 4.82 \times 220$
$F_e = 1060.4$

- ❖ PBS (2.77 kg of glucose to produce 1 kg of PBS)

$F_e = 4.82 \times 2.77$
$F_e = 13.35$

Total (Agriculture + Processing)

- ❖ 1 kg of fermentable sugars

$F_e = 0.003 + 4.56 + 4.82$
$F_e = 9.4$

- ❖ PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

$F_e = 2.2 \times 10^{-5} + 0.034 + 0.036$
$F_e = 0.07$

- ❖ PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

$F_e = 0.66 + 1003 + 1060.4$
$F_e = 2383$

- ❖ PBS (2.77 kg of glucose to produce 1 kg of PBS)

$F_e = 8.31 \times 10^{-3} + 12.63 + 13.35$
$F_e = 26$

Summary

Feedstock efficiency F_e	Maize grain	Maize stover	Sugar beet pulp
1 kg fermentable sugar	1.13	1.49	9.4
PLA packaging film	8.5×10^{-3}	1.03×10^{-2}	7×10^{-2}
PLA agricultural mulch	249	328	2064
PBS	3.11	4.11	26

10.Waste-factor

This quantitative indicator is the total mass generated as waste divided by the total mass of the bio-product and co-products generated.

$$Waste - factor = \frac{M_{TotW}}{M_{Prod} + M_{co.\,prod}} \quad \text{Eq 2a}$$

M_{TotW} =*Total mass of waste generated from the production process (kg)*

$M_{co.\,prod}$ =*Total mass of useful co-products generated (kg)*

M_{Prod} =*Total mass of target product generated from the process (kg)*

3.1 Maize grain

Agriculture

Reference: 1.51 kg maize grain produces 1 kg of glucose

- 1 kg of glucose

W_f = 0.014 kg waste /(1.51 kg maize grain +0.755 maize stover)
$W_f = 6.18 \times 10^{-3}$

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

$W_f = 6.18 \times 10^{-3} \times 0.0075$
$W_f = 0.046 \times 10^{-3}$

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

$W_f = 6.18 \times 10^{-3} \times 220$
$W_f = 1.36$

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

$W_f = 6.18 \times 10^{-3} \times 2.77$
$W_f = 0.017$

Processing

- 1 kg of glucose

$W_f = 2.4 \times 10^{-4}$ / (1 kg of sugar + 0.375 kg co-products)
$W_f = 1.7 \times 10^{-4}$ / kg sugar

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

$W_f = 1.7 \times 10^{-4} \times 0.0075$
$W_f = 1.3 \times 10^{-6}$

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

$W_f = 1.7 \times 10^{-4} \times 220$
$W_f = 0.0374$

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

$W_f = 1.7 \times 10^{-4} \times 2.77$
$W_f = 4.7 \times 10^{-4}$

Total (Agriculture + Processing)

- 1 kg of glucose

$W_f = 6.18 \times 10^{-3} + 1.7 \times 10^{-4}$
$W_f = 6.35 \times 10^{-3}$

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

$W_f = 4.6 \times 10^{-5} + 1.3 \times 10^{-6}$
$W_f = 4.73 \times 10^{-5}$

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

$W_f = 1.36 + 0.0374$
$W_f = 1.4$

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

$W_f = 0.017 + 4.7 \times 10^{-4}$
$W_f = 1.75 \times 10^{-2}$

3.2 Maize stover

Agriculture

Reference: 2.08 kg maize stover produces 1 kg of fermentable sugars

- 1 kg of fermentable sugar

$W_f = 0.03831 / (2.08 \text{ stover} + 4.16 \text{ maize grain})$
$W_f = 6.18 \times 10^{-3}$

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

$W_f = 6.18 \times 10^{-3} \times 0.0075$
$W_f = 0.046 \times 10^{-3}$

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

$W_f = 6.18 \times 10^{-3} \times 220$
$W_f = 1.36$

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

$W_f = 6.18 \times 10^{-3} \times 2.77$
$W_f = 0.017$

Processing

Reference: 2.08 kg maize stover produces 1 kg of fermentable sugars

- 1 kg of fermentable sugars

$W_f = 0.38 / (1 \text{ kg of sugar} + 0.43 \text{ kg co-products})$
$W_f = 0.27$ kg waste/ kg sugar

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

$W_f = 0.27 \times 0.0075$
$W_f = 2.02 \times 10^{-3}$

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

$W_f = 0.27 \times 220$
$W_f = 59.4$

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

$W_f = 0.27 \times 2.77$
$W_f = 0.75$

Total (Agriculture + Processing)

- 1 kg of glucose

$W_f = 6.18 \times 10^{-3} + 0.27$
$W_f = 0.27618$

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

$W_f = 0.046 \times 10^{-3} + 2.02 \times 10^{-3}$
$W_f = 2.066 \times 10^{-3}$

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

$W_f = 1.36 + 59.4$
$W_f = 60.76$

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

$W_f = 0.017 + 0.75$
$W_f = 0.767$

3.3 Sugar beet pulp

Agriculture

Reference: 102.31 kg sugar beet to produce 5.096 kg beet pulp that leads to 1 kg of fermentable sugars

- 1 kg of fermentable sugars

W_f = 0.050 kg waste /102.31
$W_f = 4.80 \times 10^{-4}$

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

$W_f = 4.80 \times 10^{-4} \times 0.0075$
$W_f = 3.6 \times 10^{-6}$

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

$W_f = 4.80 \times 10^{-4} \times 220$
$W_f = 0.1056$

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

$W_f = 4.80 \times 10^{-4} \times 2.77$
$W_f = 1.32 \times 10^{-3}$

Processing 1

Reference: 102.31 kg beet sugar to produce 5.096 kg beet pulp that leads to 1 kg of fermentable sugars

- 1 kg of fermentable sugars

W_f = 3.06 / 5.096 (bee pulp) + 4.33 (molasse) + 13 (sucrose)
W_f = 0.13 kg waste / kg sugar

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

$W_f = 0.13 \times 0.0075$
$W_f = 9.75 \times 10^{-4}$

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

$W_f = 0.13 \times 220$
$W_f = 28.6$

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

$W_f = 0.13 \times 2.77$
$W_f = 0.36$

Processing 2

Reference: 102.31 kg beet sugar to produce 5.096 kg beet pulp that leads to 1 kg of fermentable sugars

- 1 kg of fermentable sugars

W_f = 0.187 kg waste/ (1 (sugar) + 0.057)
W_f = 0.18 kg / kg sugar

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

W_f = 0.18 x 0.0075
$W_f = 1.35 \times 10^{-3}$

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

W_f = 0.18 x 220
W_f = 39.6

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

W_f = 0.18 x 2.77
W_f = 0.41

Total (Agriculture + Processing)

- 1 kg of fermentable sugars

$W_f = 4.80 \times 10^{-4} + 0.13 + 0.18$
W_f = 0.31

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

$W_f = 3.6 \times 10^{-6} + 9.75 \times 10^{-4} + 1.35 \times 10^{-3}$
$W_f = 2.33 \times 10^{-3}$

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

W_f = 0.1056 + 28.6 +39.6
W_f = 68.3

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

$W_f = 1.32 \times 10^{-3} + 0.36 + 0.41$
W_f = 0.77

Summary

Waste factor W_f	Maize grain	Maize stover	Sugar beet pulp
1 kg fermentable sugar	6.35×10^{-3}	0.27	0.31
PLA packaging film	4.73×10^{-5}	2.06×10^{-3}	2.33×10^{-3}
PLA agricultural mulch	1.4	60.7	68.3
PBS	1.75×10^{-2}	0.76	0.77

11.Energy intensity

Energy intensity is a qualitative indicator which is the ratio of total amount of energy (fossil-derived, renewable and internally derived energy) to the total amount of bio-products and co-products generated within the process.

$$Energy\ intensity = \frac{E_{FosD}+E_{RenD}+E_{IntD}}{M_{Prod}+M_{Co.prod}} \qquad \text{Eq 3a}$$

E_{FosD} = *Fossil-derived energy used (kWh)*
E_{RenD} = *Renewable energy used (kWh)*
E_{IntD} = *Internally derived energy used (kWh)*
M_{Prod} = *Total mass of target product generated (kg)*
$M_{Co.prod}$ =*Total mass of co-product generated (kg)*

4.1 Maize grain

Reference: 1.51 kg maize grain produces 1 kg of glucose

<u>Agriculture</u>

- 1 kg of glucose

E_i = 0.27 kWh /(1.51 kg maize grain +0.755 maize stover)
E_i = 0.12

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

E_i = 0.12 x 0.0075
$E_i = 9 \times 10^{-4}$

- ❖ PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

$E_i = 0.12 \times 220$
$E_i = 26.4$

- ❖ PBS (2.77 kg of glucose to produce 1 kg of PBS)

$E_i = 0.12 \times 2.77$
$E_i = 0.33$

Processing

- ❖ 1 kg of glucose

E_i = 0.86 kWh / (1 kg of sugar + 0.375 kg co-products)
E_i = 0.62 kWh/ kg sugar

- ❖ PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

$E_i = 0.62 \times 0.0075$
$E_i = 4.6 \times 10^{-3}$

- ❖ PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

$E_i = 0.62 \times 220$
$E_i = 136.4$

- ❖ PBS (2.77 kg of glucose to produce 1 kg of PBS)

$E_i = 0.62 \times 2.77$
$E_i = 1.71$

Total (Agriculture + Processing)

- ❖ 1 kg of glucose

$E_i = 0.12 + 0.62$
$E_i = 0.74$

- ❖ PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

$E_i = 9 \times 10^{-4} + 4.6 \times 10^{-3}$
$E_i = 5.5 \times 10^{-3}$

- ❖ PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

$E_i = 26.4 + 136.4$

$E_i = 162.8$

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

$E_i = 0.33 + 1.71$
$E_i = 2.04$

4.2 Maize stover

Agriculture

Reference: 2.08 kg maize stover produces 1 kg of fermentable sugars

- 1 kg of fermentable sugar

$E_i = 0.74$ kWh /(2.08 stover + 4.16 maize grain)
$E_i = 0.12$

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

$E_i = 0.12 \times 0.0075$
$E_i = 9 \times 10^{-4}$

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

$E_i = 0.12 \times 220$
$E_i = 26.4$

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

$E_i = 0.12 \times 2.77 = 0.33$

Processing

Reference: 2.08 kg maize stover produces 1 kg of fermentable sugars

- 1 kg of fermentable sugars

E_i = 1.156 kWh / (1 kg of sugar + 0.43 kg co-products)
E_i = 0.81 kg kWh/ kg sugar

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

$E_i = 0.81 \times 0.0075$
$E_i = 6 \times 10^{-3}$

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

$E_i = 0.81 \times 220$
$E_i = 178.2$

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

$E_i = 0.81 \times 2.77$
$E_i = 2.24$

Total (Agriculture + Processing)

- 1 kg of fermentable sugars

$E_i = 0.12 + 0.81$
$E_i = 0.93$

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

$E_i = 9 \times 10^{-4} + 6 \times 10^{-3}$
$E_i = 6.9 \times 10^{-3}$

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

$E_i = 26.4 + 178.2$
$E_i = 204.6$

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

$E_i = 0.33 + 2.24$
$E_i = 2.57$

4.3 Sugar beet pulp

Agriculture

Reference: 102.31 kg sugar beet to produce 5.096 kg beet pulp that leads to 1 kg of fermentable sugars

- 1 kg of fermentable sugars

$E_i = 2.05$ kWh /102.31
$E_i = 0.02$

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

E_i = 0.02 x 0.0075
E_i = 1.5 x 10^{-4}

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

E_i = 0.02 x 220
E_i = 4.4

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

E_i = 0.02 x 2.77
E_i = 5.54 x 10^{-2}

Processing 1

Reference: 102.31 kg beet sugar to produce 5.096 kg beet pulp that leads to 1 kg of fermentable sugars

- 1 kg of fermentable sugars

E_i = 28 kWh / 5.096 (bee pulp) + 4.33 (molasse) + 13 (sucrose)
E_i = 1.24 kWh / kg sugar

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

E_i = 1.24 x 0.0075
E_i = 9.3 x 10^{-3}

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

E_i = 1.24 x 220
E_i = 273

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

E_i = 1.24 x 2.77
E_i = 3.43

Processing 2

Reference: 102.31 kg beet sugar to produce 5.096 kg beet pulp that leads to 1 kg of fermentable sugars

- 1 kg of fermentable sugars

E_i = 0.711 kWh/ (1 (sugar) + 0.057)
E_i = 0.67 kWh / kg sugar

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

E_i = 0.67 x 0.0075
E_i = 5.02 x 10^{-3}

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

E_i = 0.67 x 220
E_i = 147.4

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

E_i = 0.67 x 2.77
E_i = 1.85

Total (Agriculture + Processing)

- 1 kg of fermentable sugars

E_i = 0.02 + 1.24 + 0.67
E_i = 1.94

- PLA packaging film (7.5 g of glucose to produce 5.58 g of PLA)

E_i = 1.5 x 10^{-4}+ 9.3 x 10^{-3}+ 5.02 x 10^{-3}
E_i = 14.47 x 10^{-3}

- PLA agricultural mulch (220 kg of glucose to produce 152 kg of PLA per ha)

E_i = 4.4+ 273+220
E_i = 494.4

- PBS (2.77 kg of glucose to produce 1 kg of PBS)

E_i = 5.54 x 10^{-2}+ 3.43+1.85
E_i = 5.33

Summary

Energy intensity Ei	Maize grain	Maize stover	Sugar beet pulp
1 kg fermentable sugar	0.74	0.93	1.94
PLA packaging film	5.5×10^{-3}	6.9×10^{-3}	14.47×10^{-3}
PLA agricultural mulch	162.8	204.6	494.4
PBS	2.04	2.57	5.33