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Abstract

This report investigates the environmental impacts of feedstock production and upstream processing, as regards the STAR-ProBio case studies. The feedstocks considered for the production of the case studies are fermentable sugars from sugar beet pulp, maize grain and maize stover. Fermentable sugars (e.g. glucose) are interesting renewable materials to produce a variety of bio-products, for instance, polylactic acid (PLA) and polybutylene succinate (PBS). Maize grain is a starch-rich crop, which goes through an enzymatic hydrolysis process to obtain glucose. On the other hand, sugar beet pulp and maize stover are abundant in ligno-hemicellulose, which is transformed into a variety of sugars (glucose, xylose, arabinose, galactose…) by first carrying out a pretreatment process and then, enzymatic hydrolysis.

This assessment considers 20 different scenarios of fermentable sugars, 10 for maize grain, 4 for maize stover and 6 for sugar beet pulp. Two main processes are taken into consideration: agricultural activities and the pre-processing of feedstock. In addition, the environmental burdens of agricultural activities alone were also evaluated, since this process plays a fundamental role in the global impacts of fermentable sugars and also it will allow different agricultural systems to be compared.

With the aim to perform the upstream LCA, 11 impact categories were considered as proposed in Deliverable 2.2: acidification (mol H+-eq); particulate matter (deaths/kg emitted); climate change (kg CO_2-eq); affected biodiversity ($m^2 \cdot$ PAS); terrestrial eutrophication (Mol N-eq); freshwater eutrophication (Kg P-eq); human toxicity, cancer (CTUh); land use, soil quality index (Pt); soil erosion (Kg soil erosion); fossil resource depletion (MJ); and water scarcity (m^3 water deprived-eq). The functional units are the amount of fermentable sugars necessary to produce the bio-based case studies (downstream processes of WP3): 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 and 2.77 kg of fermentable sugars to produce 1 kg of PBS. Moreover, 1 kg of agricultural maize production (maize grain, stover and sugar beet) was also selected as a functional unit to compare the different agricultural systems. Economic allocation was performed to distribute the environmental impacts of the by-products maize stover and sugar beet pulp. Moreover, a sensitivity analysis was performed comparing mass and economic allocations.

Overall, field emissions, chemical fertilization and agricultural activities are critical factors for the environmental impacts in all the agricultural scenarios. With regard to the production of fermentable sugars, the contribution analysis shows that agricultural activities play a key role in the total impacts of sugars from maize and stover. However, in the sugars from beet pulp scenarios, agriculture and beet pulp production have a small contribution, due to its low market value.

The average values from the 20 scenarios for the production of 1 kg of fermentable sugars emit about 0.5 kg of CO_2 eq and 6 MJ of energy. However, standard variation values are very high due to the different agricultural systems considered in this study. In this upstream LCA, the outcomes showed that the use of fermentable sugars from beet pulp has less impact than maize grain and stover, consequently reducing the global impacts of the three STAR-ProBio case studies. The sensitivity analysis comparing economic and mass allocation indicates that the figures for maize grain are not as sensitive, when compared with maize stover or beet pulp. Both showed an extremely high sensitivity in the results.

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Executive summary

Given the current bioeconomy framework, the use of renewable biomass for the production of biobased products has grown interest. Feedstocks that are rich in carbohydrates can be interesting renewable materials to be processed into bio-based products. They may include first generation feedstocks that compete with food markets such as maize and wheat grains; second generation feedstocks, which are residues from agricultural activities (e.g. maize stover and wheat straw); third generation feedstocks (i.e. macro and microalgae) and fourth generation feedstocks such as residues from industrial operations (e.g. sugar beet pulp). These raw materials can be starch, sugar and lignocellulosic rich biomass. The use of first-generation biomass, however, may undermine food demand as the population continues to grow. On the other hand, technology for processing second, third and fourth generation raw materials into bio-based products is still in its infancy.

This report is part of Task 2.5 and the main objective of this deliverable D2.4 is to perform a life cycle assessment of the upstream processing of bio-based products. More specifically, this report evaluates the environmental burdens of producing fermentable sugars from maize grain, maize stover and sugar beet pulp. This assessment is the result and complement of a robust work carried out in the previous Tasks and Deliverables of WP2, where a review of environmental indicators related to bio-based products (Task 2.1 and Deliverable D2.1), system boundaries for WP2 (Task 2.2), a selection of environmental indicators and impact methods for bio-based products (Task 2.3 and Deliverable D2.2) and life cycle inventory for WP2 (Task 2.4 and Deliverable D2.3) were carried out (Figure 1).

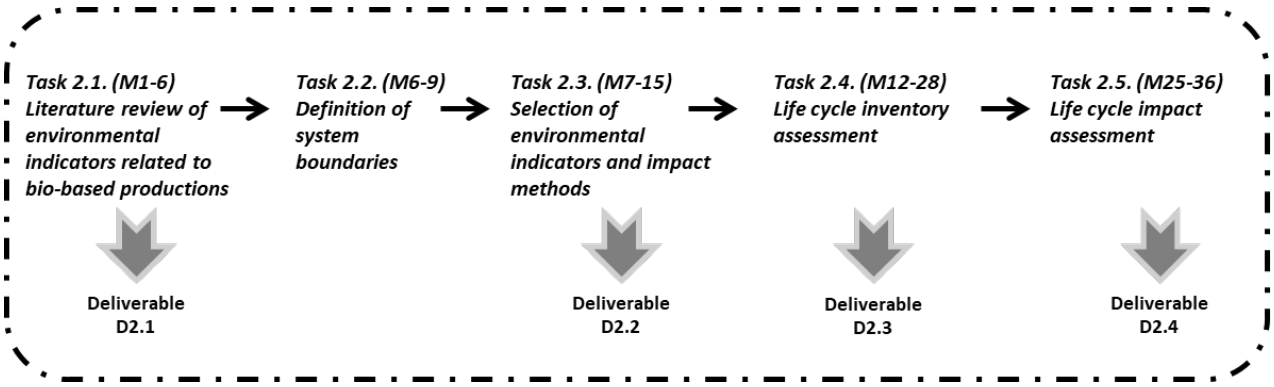

Figure 1: Work carried out in WP2

The previous works (Task 2.4 and deliverable D2.3) were fundamental to identify the inputs and outputs of materials and energy needed to produce fermentable sugars from the three raw materials (sugar beet pulp, maize grain and maize stover). The quality and accuracy of the data collected were essential to carry out this report and deliver a sound evaluation and interpretation of the environmental impacts. Additionally, the cooperation with STAR-ProBio partners, in special from AUA (Agricultural University of Athens), was crucial in providing data from raw materials pre-processing activities, as well as QUANTIS, by planning a strategy to select environmental indicators and methods to carry out this LCA and UNIBO (University of Bologna), with their thorough insights to improve this study after reviewing WP2 work. Although not involved in this Work Package, the University of York, which is WP3 leader, helped WP2 mainly with the clarification of a functional unit and system boundaries for the case studies between WP2 and WP3.

Overview of main considerations

Table 1: Overview of main considerations

Topic	Main considerations
Main objective of this report	Life cycle impact assessment and interpretation 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 piece of PLA packaging film measuring 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
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, NH_3 and pesticides 2) Field emissions to water: N and P leaching, P run-off, pesticides and heavy metals 3) Field emissions to soil: heavy metals and pesticides.
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.

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).
Results (LCIA)	The average values from the 20 scenarios for the production of 1 kg of fermentable sugars emit about 0.50 kg of CO_2 eq and 6 MJ of energy. However, standard variation values are very high due to the different agricultural systems considered in this study. In this upstream LCA, the outcomes showed that the use of fermentable sugars from beet pulp has less impact than maize grain and stover, consequently reducing the global impacts of the three STAR-ProBio case studies. The sensitivity analysis comparing economic and mass allocation indicates that the figures for maize grain do not vary considerably with the changes in the parameter's values, when compared with maize stover or beet pulp. Both showed an extremely high sensitivity in the results.

Background and introduction

One of the routes to boost the bioeconomy and reduce the use of fossil fuels is through the production of bio-products, made from renewable raw materials. However, bio-products must be produced responsibly, taking into account, from the first stage of development, their environmental, techno-economic and social viability. The production of bio-products may also involve competition with food and feed markets, as well as land use issues.

As aforementioned, WP2 is responsible to provide the environmental impacts of fermentable sugar production, from an LCA approach. A variety of raw materials can be used to produce fermentable sugars that will later become a bio-product. Biomass rich in carbohydrates can comprise starch crops (e.g. wheat and maize grains); sugar crops (e.g. sugar beet and sugarcane), lignocellulosic crops (e.g. wheat straw and maize stover), as well as residues of industrial side streams that are rich in lignocellulose (e.g. sugar beet pulp and municipal solid waste). With this purpose, three feedstocks (maize grain, maize stover and sugar beet pulp) were selected to investigate the environmental impacts of fermentable sugars production. This selection was made based on the importance of these raw materials as biomass rich in carbohydrates and their availability in the world, mainly in Europe. The rationale of this selection is summarized in the "Internal Report on Feedstock Selection Criteria for the Development of Case Studies", performed by AUA.

There are many LCA studies whose interest in agricultural and pre-processing systems are mainly concerned to food production (Klenk et al., 2012; Liang et al., 2018; Noya et al., 2015). With regard to inedible products, various LCA studies are related to the production of biofuels, using fermentable sugars as an intermediate product (Buratti et al., 2008; Rocha et al., 2014; Tsiropoulos et al., 2014). Although interest has increased in the last decade, few studies have investigated the environmental impacts of fermentable sugars for the production of bio-products (Moncada et al., 2018; Renouf et al., 2008).

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 2 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.

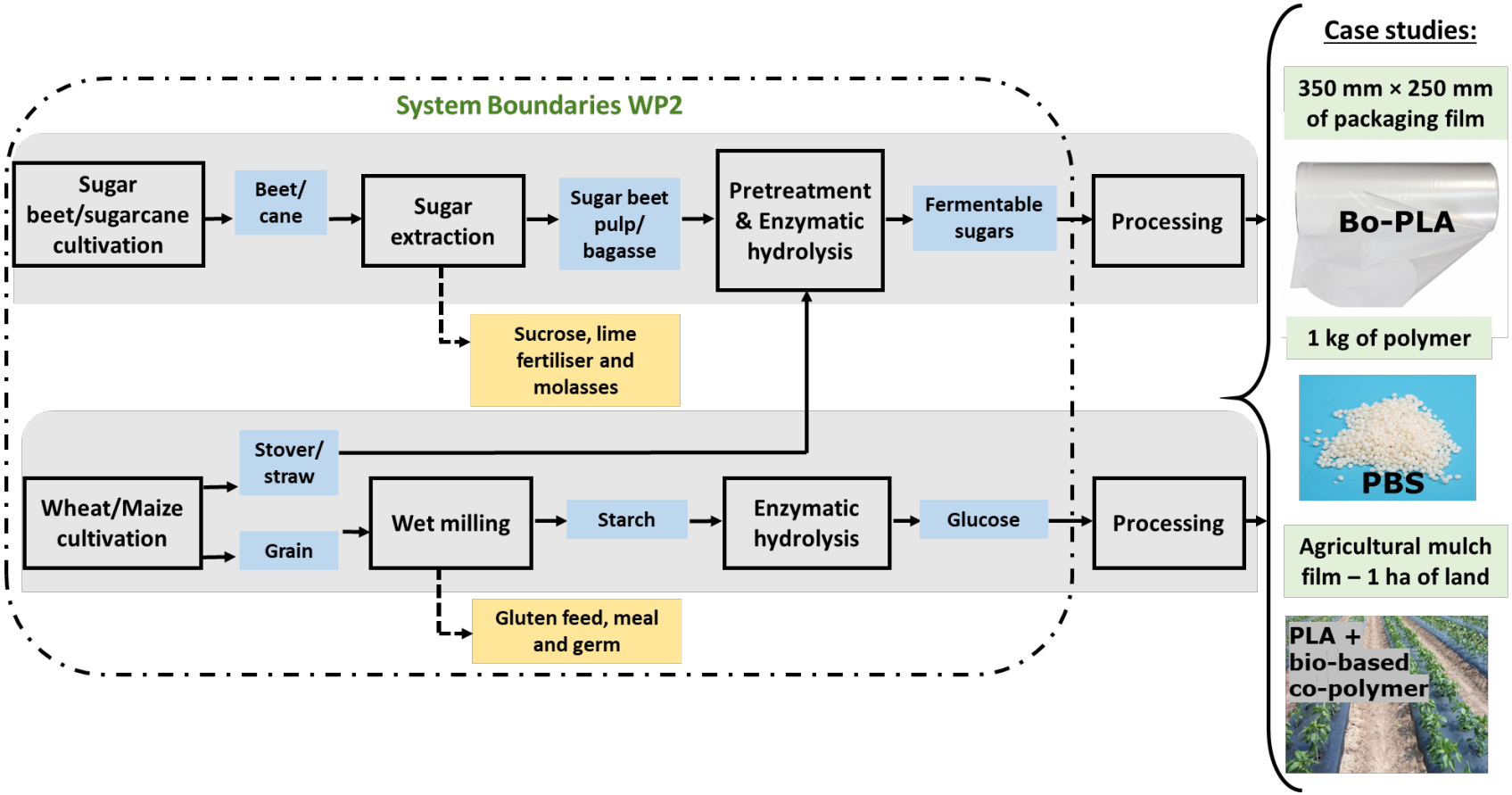

Figure 2: Generic overview of the system boundaries for WP2

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 case studies (Figure 3):

- 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

In the processing routes of PBS and PLA production, three intermediates biochemicals are required: lactic acid (LA), 1.4 butanediol (1.4 BDO) and succinic acid (SA). It is necessary approximately 1.1 kg, 2.8 kg and 1.3 kg of fermentable sugars to produce 1 kg of LA, 1.4 BDO and SA, respectively. Moreover, it is required the amount of 1.3 kg of LA to produce 1 kg of PLA. To produce 1 kg of PBS, it is needed 0.68 kg of SA and 0.68 kg of 1.4 BDO.

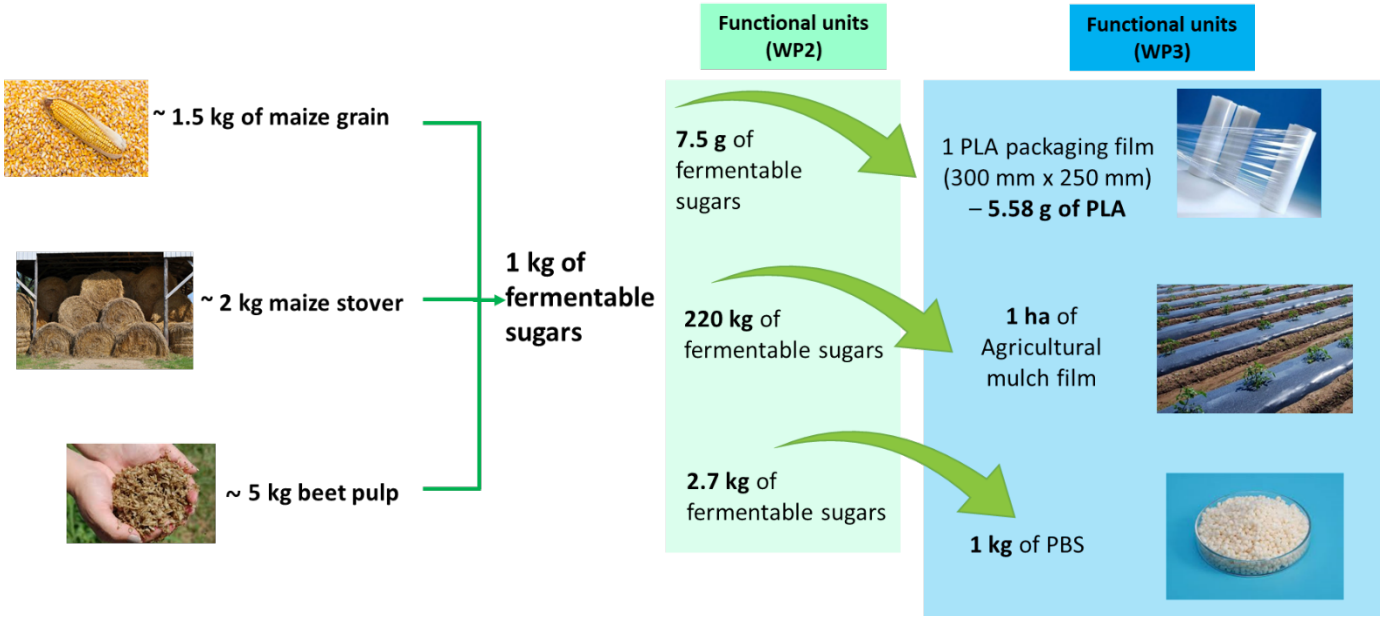

Figure 3: Amounts of feedstocks needed to produce the three case studies (PLA packaging film, PLA mulch film and PBS resin)

An additional functional unit was chosen to investigate only the environmental burdens of agricultural activities. That is, 1 kg of maize grain, stover and sugar beet production in 6 different countries: Italy, Belgium and United States for maize grain and stover; and Germany, France and United Kingdom for sugar beet.

3. Life cycle inventory (LCI) phase

The inventory phase of this LCA was carried out during Task 2.4 and the outcomes can be found in the Deliverable D2.3. After the reviewing process from STAR-ProBio partners, small changes were carried out with respect to the inventory data:

- Pesticides and heavy metals emissions are now taken into consideration in this assessment (see Annex 1).
- Prices of products and by-products were also updated and can be depicted in the Annex 2.
- It was decided to decrease the stover removal rate to 30%, as it is an acceptable quantity of stover that can be removed from maize agricultural systems without jeopardizing soil quality (Khanna and Paulson, 2016).

The updated scenarios are depicted in Table 2 and 3.

Table 2: 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 30% 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 30% SR, low yield (LY), IT	A6	(Noya et al., 2015)
Maize grain and 30 % SR, high yield (HY), IT	A7	(Noya et al., 2015)
Maize grain and 30% 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 3: 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).

Field emissions from direct land use change (LUC) were not taken into account as no significant changes in land use have been reported during the past 20 years in the countries and crops evaluated. In order to determine if land use changes occur, the three-step approach was used as recommended (Milà I Canals et al., 2013) as exemplified in the decision tree underneath (Figure 4):

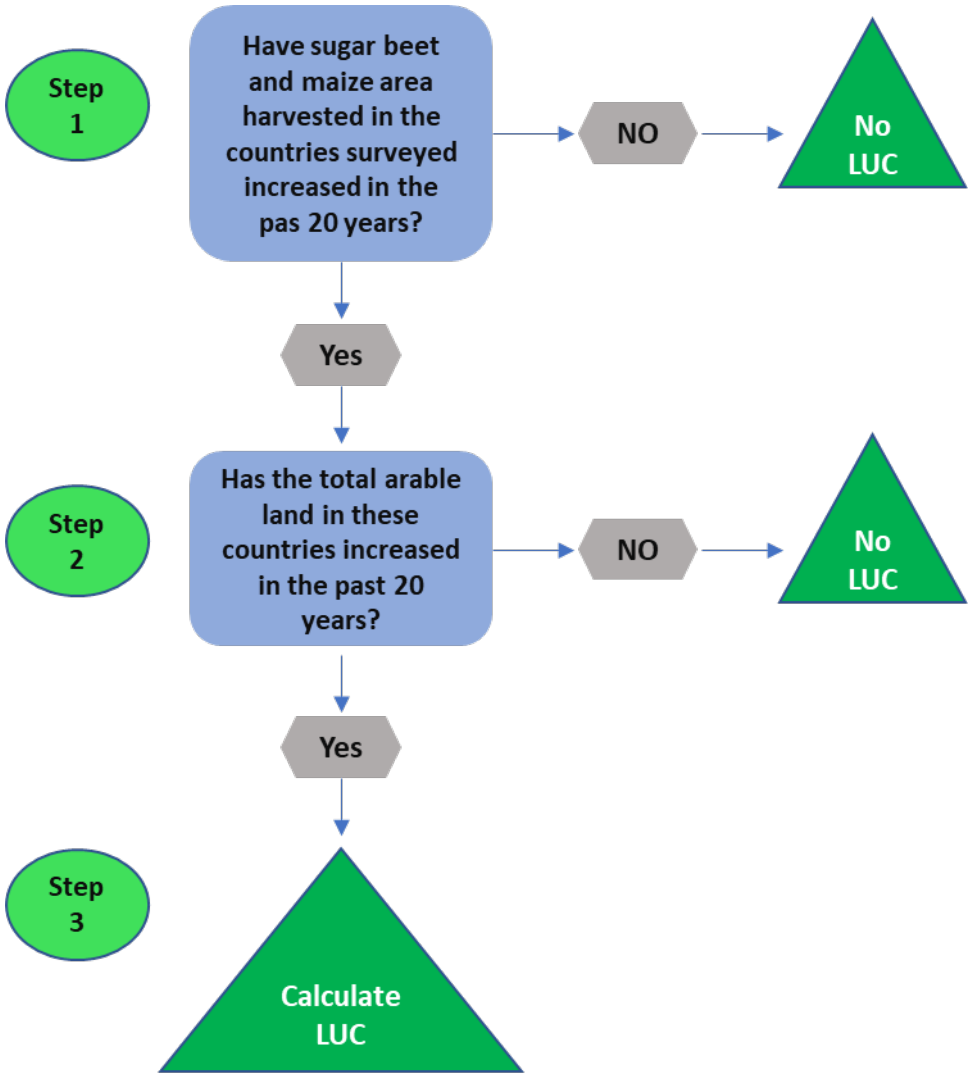

Figure 4: Decision tree to evaluate the occurrence of land use change (LUC). Adapted from: (Milà I Canals et al., 2013)

The harvested area[b] of sugar beet in the three countries France, Germany and the United Kingdom can be depicted in Figure 5. As observed, there has been a decrease in the harvested area of sugar beet in the last 20 years. Similarly, the area used for sugar beet has decreased in Europe and the world in 20 years (Figure 6). On the other hand, sugar cane, one of the main substitutes of sugar beet, in addition to having a considerably larger amount of harvested area, also shows a great increase in these areas in the last two decades (Figure 6).

[b] According to FAOSTAT, data for harvested area is: "refer to the area from which a crop is gathered. Area harvested, therefore, excludes the area from which, although sown or planted, there was no harvest due to damage, failure, etc. If the crop under consideration is harvested more than once during the year as a consequence of successive cropping (i.e., the same crop is sown or planted more than once in the same field during the year), the area is counted as many times as harvested. On the contrary, area harvested will be recorded only once in the case of successive gathering of the crop during the year from the same standing crops." Retrieved from FAO: http://www.fao.org/waicent/faostat/agricult/pr_ele-e.htm

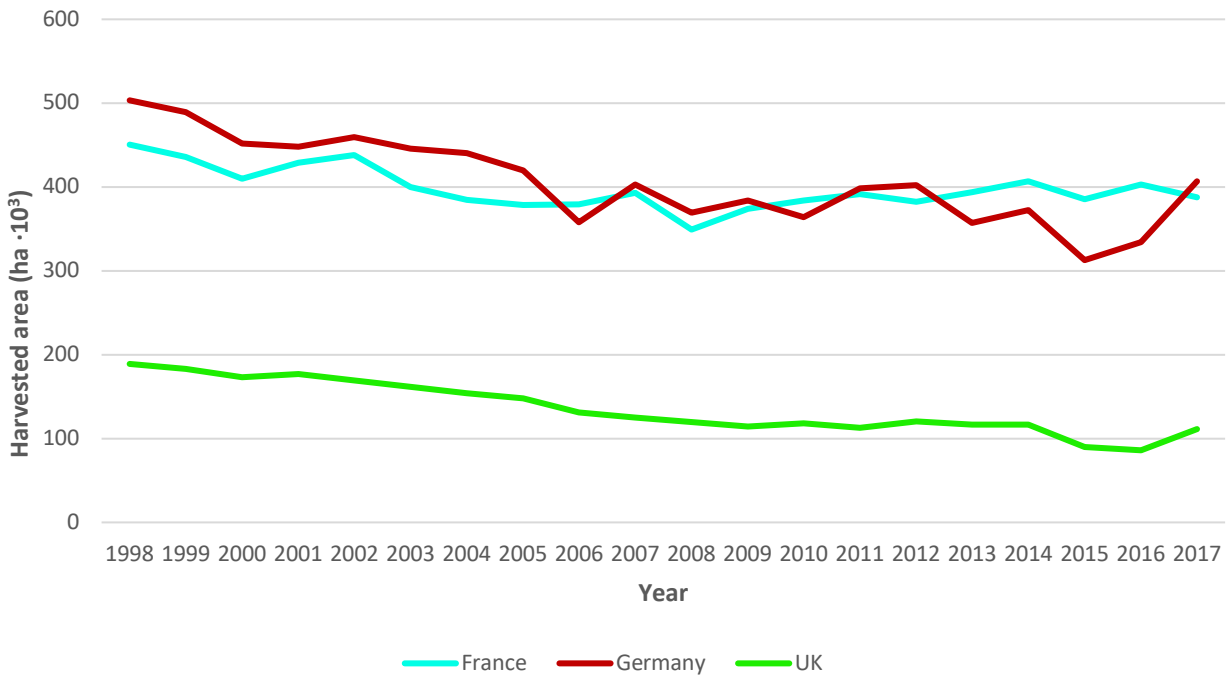

Figure 5: Harvested area (ha) of sugar beet crop in France, Germany and the United Kingdom (UK) over the last 20 years. Source: (FAOSTAT, 2019)

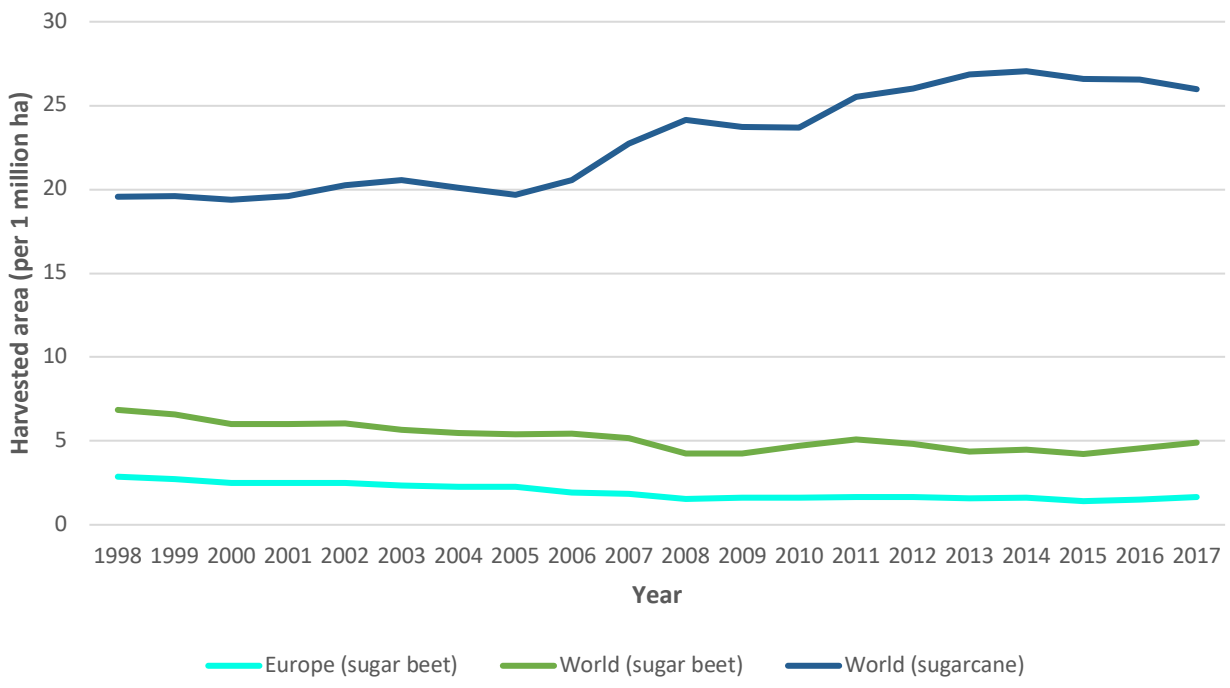

Figure 6: Harvested area (ha) of sugar beet crops in Europe and the world and area harvested (ha) for sugarcane production in the world over the last 20 years. Source: (FAOSTAT, 2019)

The area used for maize production in the three countries Belgium, Italy and the United States (USA) is depicted in Figure 7. As observed, the harvested area of Italy shows a slight drop, while areas in Belgium and the USA have slightly increased. It is also clear that the harvested area of maize in the world is increasing but decreasing in Europe (Figure 8). The area used for harvesting wheat in the world has not shown significant changes in the last 20 years (Figure 8). Wheat is also an important starch crop to produce fermentable sugars. Although the area used for harvesting maize in Belgium and the USA has slightly grown, the arable land[1] in those countries has decreased (Figure 9).

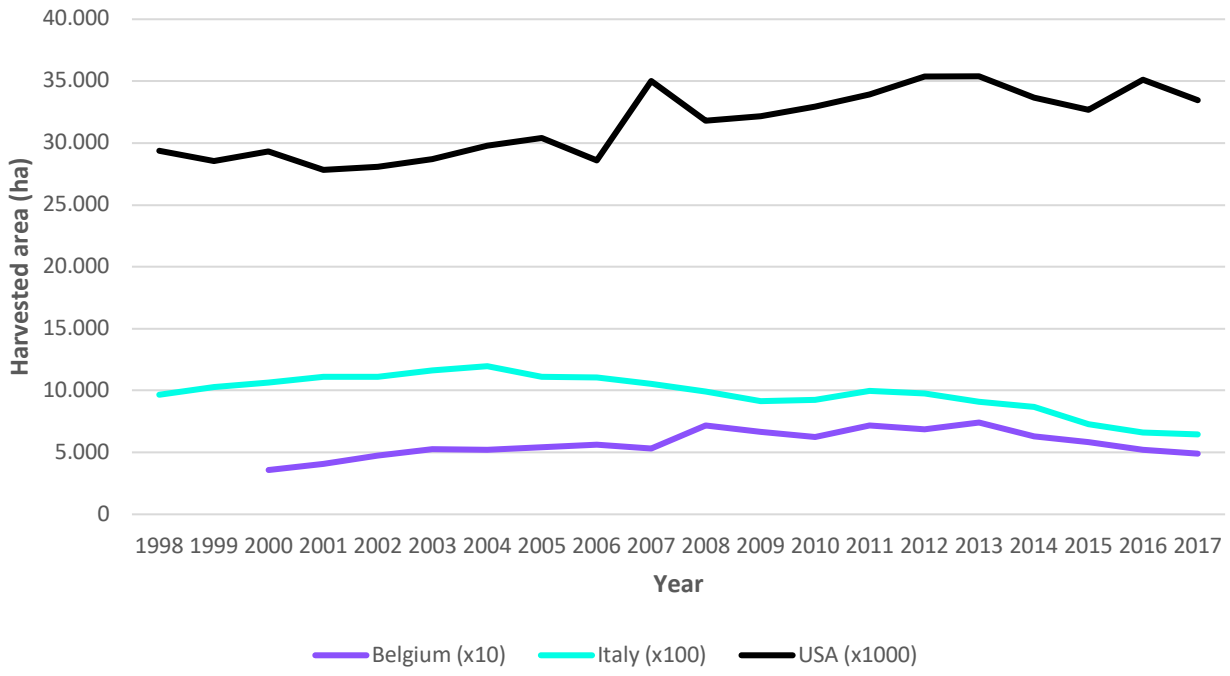

Figure 7: Harvested area (ha) of maize production in Belgium [a], Italy and United States (USA) over the last 20 years. Source: (FAOSTAT, 2019)

[a] No data is available for Belgium for 1998 and 1999.

[1] According to FAOSTAT, arable land is: "The total of areas under temporary crops, temporary meadows and pastures, and land with temporary fallow. Arable land does not include land that is potentially cultivable but is not normally cultivated." Retrieved from FAO: http://www.fao.org/faostat/en/#data/RL

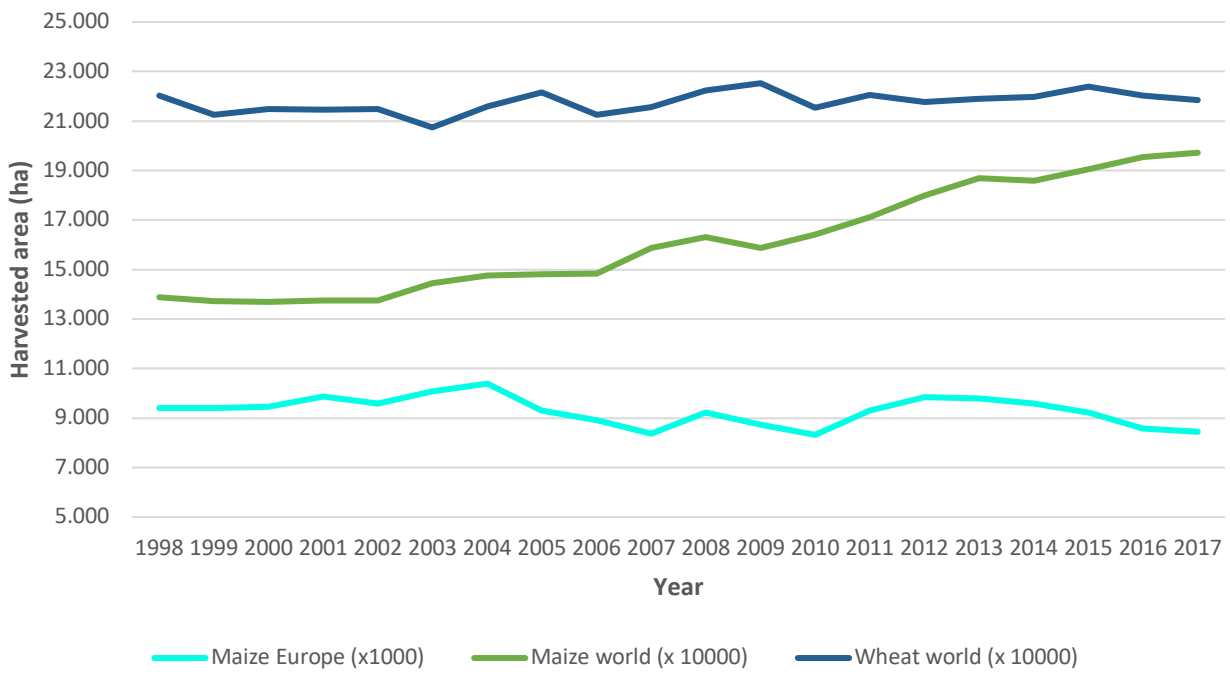

Figure 8: Harvested area (ha) of maize production in Europe and the world and area harvested (ha) for wheat production in the world over the last 20 years. Source: (FAOSTAT, 2019)

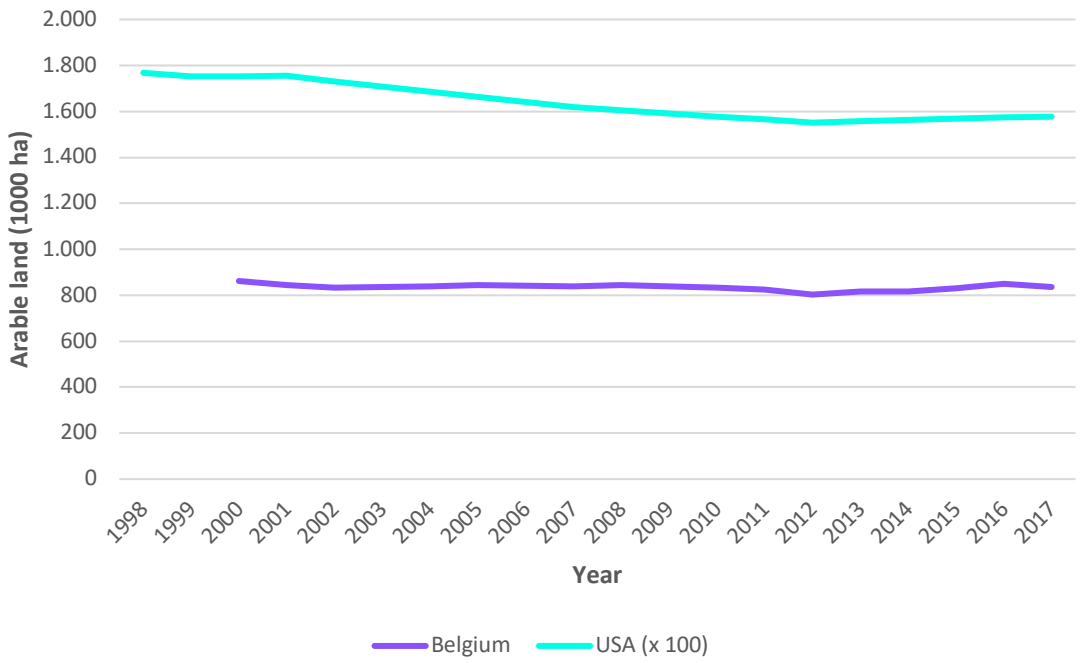

Figure 9: Area used for arable land (ha) in Belgium [a] and United States (USA) over the last 20 years. Source: (FAOSTAT, 2019).

[a] No data is available for Belgium in the years 1998 and 1999.

4. Impact categories

With the aim to evaluate the environmental burdens of the bio-based case studies, 11 impact categories were chosen (see Deliverable D2.2) as depicted in Table 4.

Table 4: 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 (or incidence)	(Fantke et al., 2016)
3	**Climate change**	CC	kg CO_2-eq	(IPCC, 2013)
4	**Affected biodiversity**	BIO	m^2.year.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)

The environmental indicators affected biodiversity (BIO) and soil erosion (SE) must be calculated manually, as they do not have characterization factors in LCA software. Regarding the biodiversity indicator, the agricultural areas used in this report have a temperate climate, therefore, the species richness factor is considerably lower when compared to tropical areas. Yet, this impact category leads to high uncertainty, as biodiversity is an intricate concept with various interpretations. It can be evaluated in terms of species numbers, density, rarity and diversity, for instance. The most common indicator of biodiversity, however, is species richness (Durán 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 region is preserved as these species are very sensitive to changes in land use.

With the objective 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

The soil erosion (SE) indicator , according to Revised Universal Soil Loss Equation (RUSLE) (Panagos et al., 2015) 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)

The calculation of soil erosion requires very specific data, which implies local measurements and observations. In this case, since most of the agricultural 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.

Both impact categories (BIO and SE) have default values which can be assessed in the Deliverable D2.2. Land occupation plays an important role in these two indicators. The values for each country assessed in this report for BIO and SE indicators are shown in Table 5.

Table 5: Soil erosion (SE) and Potential affected species (PAS) values for UK, FR, DE, US, IT and BE.

Countries	Soil erosion ($t\ ha^{-1}\ yr^{-1}$)	Potential Affected species (PAS)
UK (Beet)	3.14	3237
FR (Beet)	0.73	3714
DE (Beet)	0.37	3202
US (Maize)	17.53	2519
IT (Maize)	1.25	3357
BE (Maize)	0.95	3602

5. Results

The results of this life cycle assessment are focused on the production of raw materials and the upstream processing of fermentable sugars from maize grains, maize stover and sugar beet pulp. As a first step, economic allocation was carried out to assess the environmental burden of by-products, then mass allocation was performed to compare the outcomes. The Deliverable D2.3 explores in more detail the processes and limits of this upstream LCA. The Annexes 3 and 4 present a general description of the system for maize and sugar beet feedstocks.

5.1.1 Agriculture

An environmental assessment of agricultural activities was evaluated for maize and sugar beet crops. As it can be observed from Figures 10, 11, 12 and 13, agricultural machinery, transportation, field emissions and fertilisation play an important role in the global environmental burdens. To see all the agricultural scenarios, see Annexes 5,6,7 and 8.

The field emissions to air, water and soil (i.e. CO_2, N_2O, NH_3, heavy metals, pesticides, phosphorus and nitrogen) are great contributor mainly for CC, HT, AC and TE. In scenarios where irrigation is carried out, it was considered that the use of water comes from a natural source, which reduces the results of water depletion. Therefore, most of the contribution of water depletion comes from background processes, such as fertilizer production and agricultural machineries. The negative values for water depletion are due to background processes of seed production and agricultural machinery which considered that water is brought to the surface. Pesticides and seed production have very low contribution in all the agricultural scenarios.

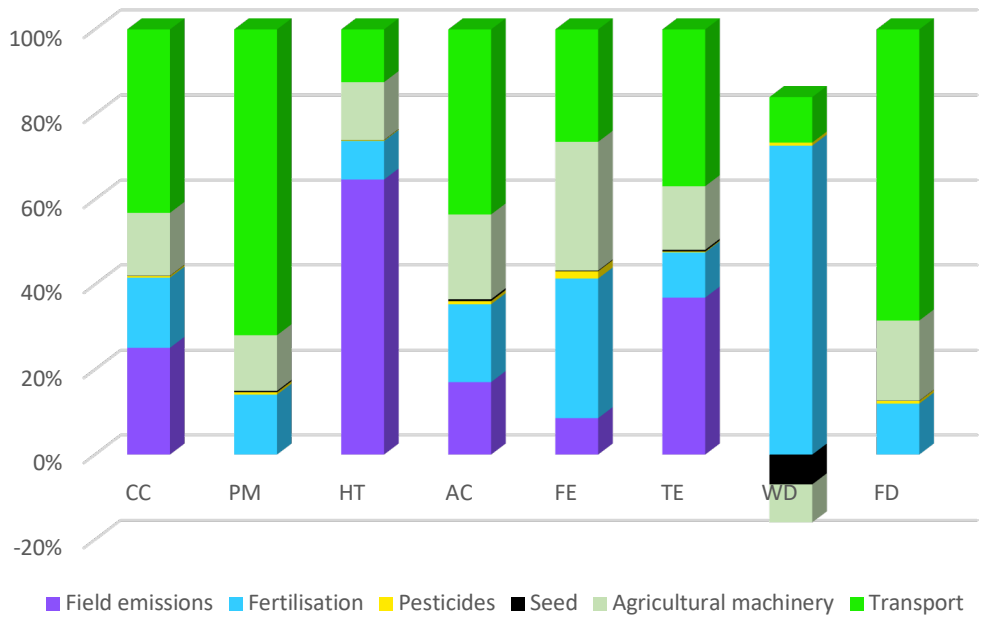

Figure 10: Process contribution for the production of sugar beet in France (FR) (scenario A2). Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; WD – Water Depletion and FE – Fossil Depletion

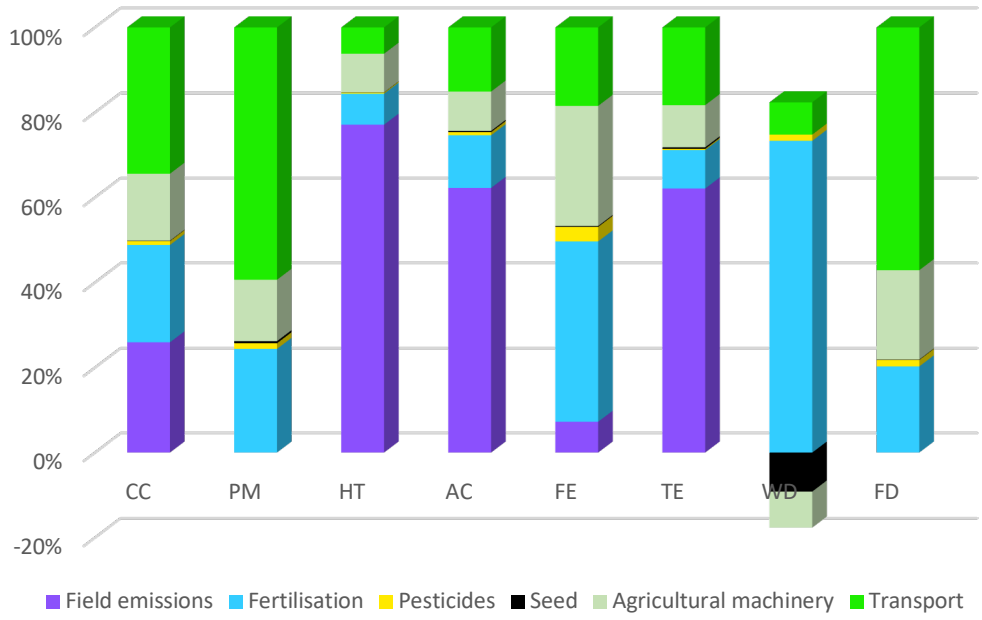

Figure 11: Process contribution for the production of sugar beet in Germany (DE) (scenario A3). Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; WD – Water Depletion and FE – Fossil Depletion

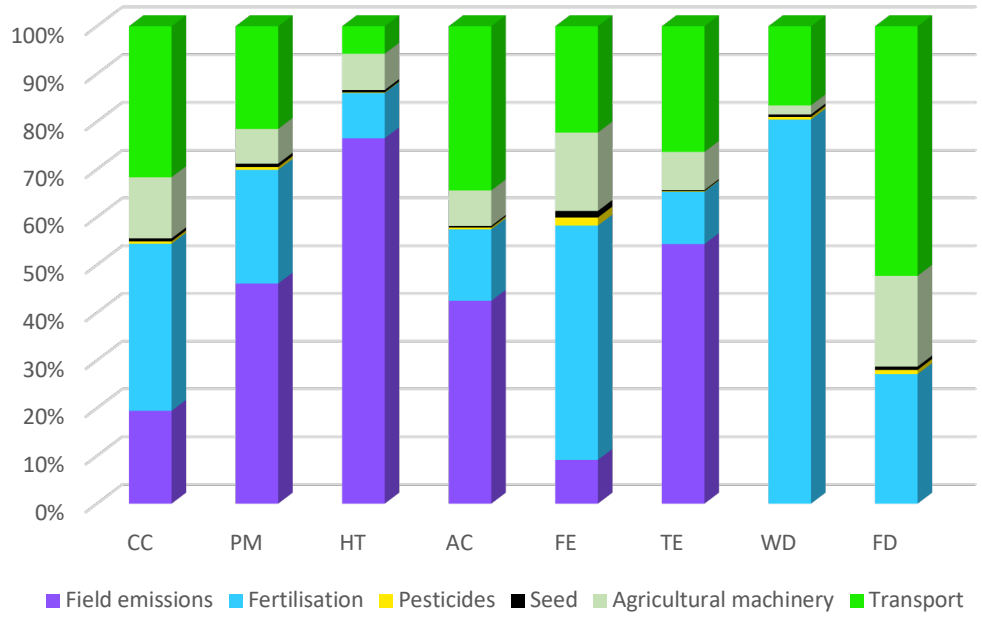

Figure 12: Process contribution for the production of maize grain in the USA (scenario A4). Economic allocation. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; WD – Water Depletion and FE – Fossil Depletion

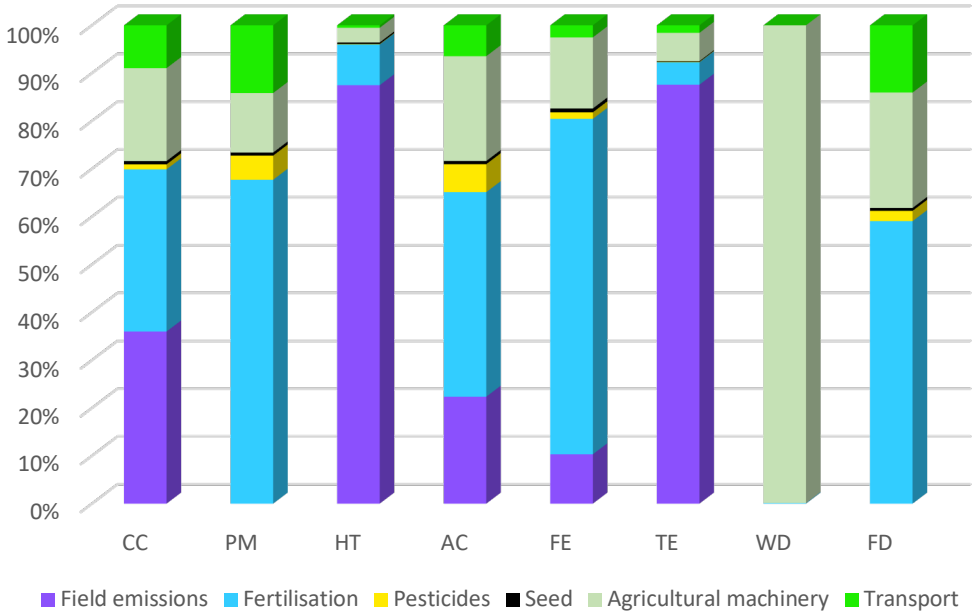

Figure 13: Process contribution for the production of maize grain in Italy (scenario A6). Economic allocation. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; WD – Water Depletion and FE – Fossil Depletion

The results from land use (LU), biodiversity (BIO) and soil erosion (SE) were not included in Figures 10, 11, 12 and 13 as most of the contribution derives from direct land occupation, making the other processes contribution insignificant. However, their absolute values are depicted in Tables 6 and 7. The absolute values of all scenarios are shown in Table 6 (economic allocation) and Table 7 (mass allocation) using 1 kg of raw material as a functional unit. As noted, the numbers are considerably different for each scenario, both for mass and economic allocation. This is because agriculture is a complex system that involves many anthropogenic and non-anthropogenic variables. These variables can include yields, land occupation, geoclimatic conditions, type of agrochemicals used, type of machinery, tillage methods, residues removal rate, etc. It must be kept in mind that the yield is very different for maize and sugar beet. The average world yield of sugar beet in 2017 was about 61 t, compared to 5.7 t for maize grain (FAOSTAT, 2019). Therefore, crops with high yields have less environmental burden if the functional unit considered is per kg of biomass produced.

Table 6: Environmental impacts for 1 kg of feedstock production. Economic allocation. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; WD – Water Depletion; FE – Fossil Depletion; BIO – affected Biodiversity; SE – Soil Erosion

Impact categories	A1 Beet	A2 Beet	A3 Beet	A4 - Grain	A4 - Stover	A5 - Grain	A6 - Grain	A6 - Stover	A7 - Grain	A7 - Stover	A8 - Grain	A8 - Stover
CC	0.155	0.091	0.114	0.581	0.251	0.608	0.547	0.158	0.186	0.057	0.187	0.054
PM	$2.25 \cdot 10^{-08}$	$4.96 \cdot 10^{-09}$	$6.01 \cdot 10^{-09}$	$3.63 \cdot 10^{-08}$	$1.57 \cdot 10^{-08}$	$3.65 \cdot 10^{-08}$	$3.13 \cdot 10^{-08}$	$9.10 \cdot 10^{-09}$	$9.67 \cdot 10^{-09}$	$2.99 \cdot 10^{-09}$	$6.81 \cdot 10^{-09}$	$1.9 \cdot 10^{-09}$
HT	$4.91 \cdot 10^{-09}$	$2.43 \cdot 10^{-09}$	$4.80 \cdot 10^{-09}$	$2.67 \cdot 10^{-08}$	$1.15 \cdot 10^{-08}$	$2.68 \cdot 10^{-08}$	$7.26 \cdot 10^{-08}$	$2.10 \cdot 10^{-08}$	$8.86 \cdot 10^{-09}$	$2.74 \cdot 10^{-09}$	$1.29 \cdot 10^{-08}$	$3.74 \cdot 10^{-09}$
AC	$1.16 \cdot 10^{-03}$	$5.16 \cdot 10^{-04}$	$1.49 \cdot 10^{-03}$	$8.17 \cdot 10^{-03}$	$3.54 \cdot 10^{-03}$	$8.47 \cdot 10^{-03}$	$4.33 \cdot 10^{-03}$	$1.26 \cdot 10^{-03}$	$1.23 \cdot 10^{-03}$	3.82E-04	$6.56 \cdot 10^{-03}$	$1.90 \cdot 10^{-03}$
FE	$3.20 \cdot 10^{-05}$	$1.24 \cdot 10^{-05}$	$1.78 \cdot 10^{-05}$	$9.8 \cdot 10^{-05}$	$4.24 \cdot 10^{-05}$	$1.02 \cdot 10^{-04}$	$1.63 \cdot 10^{-04}$	$4.72 \cdot 10^{-05}$	$2.80 \cdot 10^{-05}$	8.69E-06	$3.14 \cdot 10^{-05}$	$9.11 \cdot 10^{-06}$
TE	$2.92 \cdot 10^{-03}$	$2.38 \cdot 10^{-03}$	$4.79 \cdot 10^{-03}$	$3.11 \cdot 10^{-02}$	$1.35 \cdot 10^{-02}$	$3.19 \cdot 10^{-02}$	$6.91 \cdot 10^{-02}$	$2.00 \cdot 10^{-02}$	$1.39 \cdot 10^{-02}$	$4.30 \cdot 10^{-03}$	2.19E-02	$6.33 \cdot 10^{-03}$
LU	13.91	8.26	20.34	62.29	26.98	48.07	102	29.63	5.30	1.64	55.18	15.99
WD	$7.09 \cdot 10^{-05}$	$2.21 \cdot 10^{-04}$	$2.97 \cdot 10^{-04}$	$3.27 \cdot 10^{-03}$	$1.42 \cdot 10^{-03}$	$3.26 \cdot 10^{-03}$	18.45	5.35	12.55	3.88	$5.12 \cdot 10^{-04}$	$1.49 \cdot 10^{-04}$
FD	1.63	0.948	1.13	5.31	2.30	5.43	5.75	1.6	1.97	0.609	1.56	0.454
BIO	690	462	492	2517	1090	1924	4899	1420	195	60.56	3272	948
SE	$6.70 \cdot 10^{-02}$	$9.10 \cdot 10^{-03}$	$5.69 \cdot 10^{-03}$	1.75	0.758	1.33	0.182	$5.29 \cdot 10^{-02}$	$7.29 \cdot 10^{-03}$	$2.26 \cdot 10^{-03}$	$8.63 \cdot 10^{-02}$	$2.50 \cdot 10^{-02}$

Table 7: Environmental impacts for 1 kg of feedstock production. Mass allocation. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; WD – Water Depletion; FE – Fossil Depletion; BIO – affected Biodiversity; SE – Soil Erosion

Impact categories	A1 Beet	A2 Beet	A3 Beet	A4 - Grain	A4 - Stover	A5 - Grain	A6 - Grain	A6 - Stover	A7 - Grain	A7 - Stover	A8 - Grain	A8 - Stover
CC	0.155	0.091	0.114	0.505	0.503	0.608	0.438	0.444	0.149	0.161	0.156	0.156
PM	$2.26 \cdot 10^{-08}$	$4.96 \cdot 10^{-09}$	$6.01 \cdot 10^{-09}$	$3.17 \cdot 10^{-08}$	$3.15 \cdot 10^{-08}$	$3.66 \cdot 10^{-08}$	$2.51 \cdot 10^{-08}$	$2.55 \cdot 10^{-08}$	$7.74 \cdot 10^{-09}$	$8.38 \cdot 10^{-09}$	$5.70 \cdot 10^{-09}$	$5.68 \cdot 10^{-09}$
HT	$4.92 \cdot 10^{-09}$	$2.44 \cdot 10^{-09}$	$4.88 \cdot 10^{-09}$	$2.33 \cdot 10^{-08}$	$2.32 \cdot 10^{-08}$	$2.69 \cdot 10^{-08}$	$5.81 \cdot 10^{-08}$	$5.89 \cdot 10^{-08}$	$7.09 \cdot 10^{-09}$	$7.68 \cdot 10^{-09}$	$1.08 \cdot 10^{-08}$	$1.08 \cdot 10^{-08}$
AC	$1.16 \cdot 10^{-03}$	$5.16 \cdot 10^{-04}$	$1.49 \cdot 10^{-03}$	$7.11 \cdot 10^{-03}$	$7.08 \cdot 10^{-03}$	$8.47 \cdot 10^{-03}$	$3.47 \cdot 10^{-03}$	$3.52 \cdot 10^{-03}$	$9.87 \cdot 10^{-04}$	$1.07 \cdot 10^{-03}$	$5.49 \cdot 10^{-03}$	$5.47 \cdot 10^{-03}$
FE	$3.21 \cdot 10^{-05}$	$1.25 \cdot 10^{-05}$	$1.79 \cdot 10^{-05}$	$8.53 \cdot 10^{-05}$	$8.49 \cdot 10^{-05}$	$1.02 \cdot 10^{-04}$	$1.30 \cdot 10^{-04}$	$1.32 \cdot 10^{-04}$	$2.25 \cdot 10^{-05}$	$2.43 \cdot 10^{-05}$	$2.63 \cdot 10^{-05}$	$2.62 \cdot 10^{-05}$
TE	$2.92 \cdot 10^{-03}$	$2.38 \cdot 10^{-03}$	$4.79 \cdot 10^{-03}$	$2.71 \cdot 10^{-02}$	$2.69 \cdot 10^{-02}$	$3.19 \cdot 10^{-02}$	$5.53 \cdot 10^{-02}$	$5.61 \cdot 10^{-02}$	$1.11 \cdot 10^{-02}$	$1.20 \cdot 10^{-02}$	$1.83 \cdot 10^{-02}$	$1.82 \cdot 10^{-02}$
LU	13.91	8.26	20.35	54.20	53.97	48.08	81.74	82.96	4.25	4.60	46.19	45.99
WD	$7.09 \cdot 10^{-05}$	$2.21 \cdot 10^{-04}$	$2.97 \cdot 10^{-04}$	$2.85 \cdot 10^{-03}$	$2.83 \cdot 10^{-03}$	$3.26 \cdot 10^{-03}$	14.76	14.99	10.04	10.88	$4.29 \cdot 10^{-04}$	$4.27 \cdot 10^{-04}$
FD	1.64	0.95	1.14	4.62	4.60	5.44	4.61	4.67	1.58	1.71	1.31	1.31
BIO	690	462	492	2190	2180	1924	3919	3977	156	169	2738	2726
SE	$6.70 \cdot 10^{-02}$	$9.10 \cdot 10^{-03}$	$5.69 \cdot 10^{-03}$	1.52	1.52	1.34	0.145	0.148	$5.83 \cdot 10^{-03}$	$6.31 \cdot 10^{-03}$	$7.22 \cdot 10^{-02}$	$7.19 \cdot 10^{-02}$

Table 8 shows the average values of the 11 impact indicators and their respective standard deviations taking into consideration 1 kg of feedstock production as functional unit (sugar beet, maize grain and stover). Standard deviations are considerably high since agricultural systems are very different for each scenario. As regards sugar beet, there is no need for allocation as the beet leaves are left in the field after the harvest process. On the other hand, as 30% of maize stover is harvested in almost all the scenarios, apart from scenario A5 (see Table 2), economic and mass allocations were performed. As seen in Table 8, economic allocation significantly reduces the environmental results for maize stover, due to the low price of this biomass. On the other hand, mass allocation slightly benefits the results for maize grain.

Table 8: Environmental impacts 1 kg of feedstock production. Average impacts and standard deviation of the different feedstocks from Table 4 (mass allocation) and Table 5 (economic allocation). Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; WD – Water Depletion; FE – Fossil Depletion; BIO – affected Biodiversity; SE – Soil Erosion

Impact categories	Sugar beet	Maize grain		Maize stover	
		Economic allocation	Mass allocation	Economic allocation	Mass allocation
CC	0.12 ± 0.03	0.42 ± 0.21	0.37 ± 0.20	0.13 ± 0.09	0.31 ± 0.18
PM	$(1.11 \pm 0.98) \cdot 10^{-08}$	$(2.41 \pm 1.47) \cdot 10^{-08}$	$2.13 \pm 1.39 \cdot 10^{-08}$	$7.71 \pm 6.08 \cdot 10^{-09}$	$1.77 \pm 1.26 \cdot 10^{-08}$
HT	$(4.07 \pm 1.42) \cdot 10^{-09}$	$(2.95 \pm 2.53) \cdot 10^{-08}$	$2.52 \pm 2.01 \cdot 10^{-08}$	$9.53 \pm 8.73 \cdot 10^{-09}$	$2.51 \pm 2.35 \cdot 10^{-08}$
AC	$(1.05 \pm 0.49) \cdot 10^{-03}$	$(5.75 \pm 3.01) \cdot 10^{-03}$	$5.11 \pm 2.96 \cdot 10^{-03}$	$1.39 \pm 1.49 \cdot 10^{-03}$	$4.28 \pm 2.59 \cdot 10^{-03}$
FE	$(2.08 \pm 1.01) \cdot 10^{-05}$	$(8.44 \pm 5.61) \cdot 10^{-05}$	$7.32 \pm 4.74 \cdot 10^{-05}$	$2.67 \pm 2.09 \cdot 10^{-05}$	$6.69 \pm 5.18 \cdot 10^{-05}$
TE	$(3.36 \pm 1.27) \cdot 10^{-03}$	$(3.36 \pm 2.12) \cdot 10^{-02}$	$2.87 \pm 1.69 \cdot 10^{-02}$	$1.05 \pm 0.76 \cdot 10^{-02}$	$2.83 \pm 1.95 \cdot 10^{-02}$
LU	14.17 ± 6.04	54.60 ± 34.62	46.89 ± 27.78	14.97 ± 15.43	46.88 ± 32.35
WD	$(1.96 \pm 1.15) \cdot 10^{-04}$	6.20 ± 8.74	4.96 ± 6.99	3.28 ± 2.29	6.46 ± 7.65
FD	1.24 ± 0.35	4.00 ± 2.05	3.51 ± 1.91	1.29 ± 0.83	3.07 ± 1.81
BIO	548 ± 123	2561 ± 1730	2185 ± 1368	658 ± 702	2263 ± 1585
SE	$(2.72 \pm 3.44) \cdot 10^{-02}$	0.67 ± 0.81	0.61 ±0.74	0.20 ± 0.37	0.43 ± 0.72

The outcomes from land use (LU) biodiversity (BIO) and soil erosion (SE) indicators are highly dependent on the area occupied for the agricultural activities. In addition, and not surprisingly, environmental results are highly dependent on yields. In general, the higher the yield, the lower the environmental impact tends to be. In some scenarios, for instance, sugar beet, can yield about 80 t against 9 t for maize.

5.1.2 Agriculture + Processing

This section assesses the environmental burdens of producing fermentable sugars from three types of biomass (beet pulp, maize grain and stover). These renewable carbohydrate materials are used as intermediate sources on the path to bio-based production. More specifically, they are the sources of input for producing the selected STAR-ProBio case studies, whose environmental impacts are assessed by WP3. Firstly, the results are presented with a functional unit of 1 kg of fermentable sugars using economic (Tables 9 and 10) and mass (Tables 11 and 12) allocations from the 20 scenarios. The average impacts of all scenarios and their corresponding standard variations are summarized in Table 13.

As the aim of this report is to assess the outcomes from upstream processes of the case studies, the environmental impacts of fermentable sugars needed to produce the case studies BoPLA packaging film (FU: 7.5 g of fermentable sugars), PLA mulch film (220 kg of fermentable sugars) and PBS (2.7 kg of fermentable sugars) are summarized in Tables 14, 15 and 16, respectively. The results for each functional unit will then be combined with the ones from WP3 (downstream processes of the case studies) to perform the global LCA.

Table 9: Environmental impacts of 1 kg of fermentable sugar from the different scenarios (economic allocation)

Impact category	Sc1	Sc2	Sc3	Sc4	Sc5	Sc6	Sc7	Sc8	Sc9	Sc10
CC	0.759	0.710	0.788	0.739	0.722	0.675	0.335	0.301	0.336	0.302
PM	$4.55 \cdot 10^{-08}$	$4.10 \cdot 10^{-08}$	$4.57 \cdot 10^{-08}$	$4.11 \cdot 10^{-08}$	$4.01 \cdot 10^{-08}$	$3.58 \cdot 10^{-08}$	$1.68 \cdot 10^{-08}$	$1.33 \cdot 10^{-08}$	$1.38 \cdot 10^{-08}$	$1.03 \cdot 10^{-08}$
HT	$2.95 \cdot 10^{-08}$	$2.83 \cdot 10^{-08}$	$2.97 \cdot 10^{-08}$	$2.84 \cdot 10^{-08}$	$7.88 \cdot 10^{-08}$	$7.58 \cdot 10^{-08}$	$1.04 \cdot 10^{-08}$	$9.73 \cdot 10^{-09}$	$1.47 \cdot 10^{-08}$	$1.39 \cdot 10^{-08}$
AC	$9.92 \cdot 10^{-03}$	$9.04 \cdot 10^{-03}$	$1.02 \cdot 10^{-02}$	$9.35 \cdot 10^{-03}$	$5.80 \cdot 10^{-03}$	$5.07 \cdot 10^{-03}$	$2.48 \cdot 10^{-03}$	$1.85 \cdot 10^{-03}$	$8.20 \cdot 10^{-03}$	$7.38 \cdot 10^{-03}$
FE	$1.34 \cdot 10^{-04}$	$1.19 \cdot 10^{-04}$	$1.38 \cdot 10^{-04}$	$1.22 \cdot 10^{-04}$	$2.04 \cdot 10^{-04}$	$1.86 \cdot 10^{-04}$	$5.94 \cdot 10^{-05}$	$4.61 \cdot 10^{-05}$	$6.30 \cdot 10^{-05}$	$4.96 \cdot 10^{-05}$
TE	$3.65 \cdot 10^{-02}$	$3.39 \cdot 10^{-02}$	$3.74 \cdot 10^{-02}$	$3.47 \cdot 10^{-02}$	$7.73 \cdot 10^{-02}$	$7.33 \cdot 10^{-02}$	$1.81 \cdot 10^{-02}$	$1.61 \cdot 10^{-02}$	$2.66 \cdot 10^{-02}$	$2.43 \cdot 10^{-02}$
LU	67.60	66.09	52.33	51.35	110	107	6.43	7.02	59.97	58.72
WD	0.118	$3.04 \cdot 10^{-02}$	0.118	$3.04 \cdot 10^{-02}$	19.92	19.15	13.58	13.04	0.115	$2.75 \cdot 10^{-02}$
FD	7.84	7.21	7.98	7.34	8.32	7.67	4.26	3.74	3.83	3.33
BIO	2721	2619	2085	2005	5284	5091	236	216	3540	3406
SE	1.89	1.82	1.45	1.39	0.196	0.189	$8.82 \cdot 10^{-03}$	$8.06 \cdot 10^{-03}$	$9.34 \cdot 10^{-02}$	$8.98 \cdot 10^{-02}$

Table 10: (Cont.) Environmental impacts of 1 kg of fermentable sugar from the different scenarios (economic allocation)

Impact category	Sc11	Sc12	Sc13	Sc14	Sc15	Sc16	Sc17	Sc18	Sc19	Sc20
CC	0.893	0.700	0.490	0.482	0.328	0.343	0.330	0.309	0.309	0.321
PM	$5.12 \cdot 10^{-08}$	$3.74 \cdot 10^{-08}$	$2.47 \cdot 10^{-08}$	$2.25 \cdot 10^{-08}$	$2.29 \cdot 10^{-08}$	$2.5 \cdot 10^{-08}$	$1.7 \cdot 10^{-08}$	$1.55 \cdot 10^{-08}$	$1.55 \cdot 10^{-08}$	$1.61 \cdot 10^{-08}$
HT	$2.7 \cdot 10^{-08}$	$4.67 \cdot 10^{-08}$	$8.57 \cdot 10^{-09}$	$1.07 \cdot 10^{-08}$	$4.34 \cdot 10^{-09}$	$4.77 \cdot 10^{-09}$	$4.26 \cdot 10^{-09}$	$3.43 \cdot 10^{-09}$	$4.32 \cdot 10^{-09}$	$4.75 \cdot 10^{-09}$
AC	$9.77 \cdot 10^{-03}$	$5.03 \cdot 10^{-03}$	$3.21 \cdot 10^{-03}$	$6.37 \cdot 10^{-03}$	$2.20 \cdot 10^{-03}$	$2.29 \cdot 10^{-03}$	$2.10 \cdot 10^{-03}$	$1.95 \cdot 10^{-03}$	$2.35 \cdot 10^{-03}$	$2.47 \cdot 10^{-03}$
FE	$2.31 \cdot 10^{-04}$	$2.41 \cdot 10^{-04}$	$1.60 \cdot 10^{-04}$	$1.61 \cdot 10^{-04}$	$1.15 \cdot 10^{-04}$	$1.17 \cdot 10^{-04}$	$1.09 \cdot 10^{-04}$	$1.07 \cdot 10^{-04}$	$1.09 \cdot 10^{-04}$	$1.10 \cdot 10^{-04}$
TE	$3.28 \cdot 10^{-02}$	$4.65 \cdot 10^{-02}$	$1.37 \cdot 10^{-02}$	$1.80 \cdot 10^{-02}$	$4.87 \cdot 10^{-03}$	$5.13 \cdot 10^{-03}$	$5.61 \cdot 10^{-03}$	$4.85 \cdot 10^{-03}$	$5.72 \cdot 10^{-03}$	$6.16 \cdot 10^{-03}$
LU	51.90	57.40	-0.805	29.05	2.84	4.05	3.90	0.996	5.73	7.54
WD	$1.30 \cdot 10^{-02}$	11.10	8.09	$1.04 \cdot 10^{-02}$	$6.91 \cdot 10^{-03}$	$6.90 \cdot 10^{-03}$	$7.11 \cdot 10^{-03}$	$6.98 \cdot 10^{-03}$	$7.01 \cdot 10^{-03}$	$7.02 \cdot 10^{-03}$
FD	11.04	9.73	7.53	7.20	5.09	5.24	5.03	4.89	4.87	5.00
BIO	2441	3186	357	2221	487	547	614	450	396	438
SE	1.69	0.118	$1.33 \cdot 10^{-02}$	0.154	$4.73 \cdot 10^{-02}$	$5.31 \cdot 10^{-02}$	$1.21 \cdot 10^{-02}$	$8.85 \cdot 10^{-03}$	$4.58 \cdot 10^{-03}$	$5.07 \cdot 10^{-03}$

Table 11: Environmental impacts of 1 kg of fermentable sugar from the different scenarios (mass allocation)

Impact category	Sc1	Sc2	Sc3	Sc4	Sc5	Sc6	Sc7	Sc8	Sc9	Sc10
CC	0.689	0.640	0.801	0.748	0.615	0.569	0.300	0.266	0.308	0.273
PM	$4.11 \cdot 10^{-08}$	$3.65 \cdot 10^{-08}$	$4.64 \cdot 10^{-08}$	$4.17 \cdot 10^{-08}$	$3.39 \cdot 10^{-08}$	$2.96 \cdot 10^{-08}$	$1.5 \cdot 10^{-08}$	$1.14 \cdot 10^{-08}$	$1.28 \cdot 10^{-08}$	$9.27 \cdot 10^{-09}$
HT	$2.62 \cdot 10^{-08}$	$2.5 \cdot 10^{-08}$	$3.02 \cdot 10^{-08}$	$2.88 \cdot 10^{-08}$	$6.42 \cdot 10^{-08}$	$6.15 \cdot 10^{-08}$	$8.59 \cdot 10^{-09}$	$7.99 \cdot 10^{-09}$	$1.26 \cdot 10^{-08}$	$1.19 \cdot 10^{-08}$
AC	$8.92 \cdot 10^{-03}$	$8.04 \cdot 10^{-03}$	$1.04 \cdot 10^{-02}$	$9.47 \cdot 10^{-03}$	$4.95 \cdot 10^{-03}$	$4.22 \cdot 10^{-03}$	$2.25 \cdot 10^{-03}$	$1.62 \cdot 10^{-03}$	$7.17 \cdot 10^{-03}$	$6.35 \cdot 10^{-03}$
FE	$1.23 \cdot 10^{-04}$	$1.07 \cdot 10^{-04}$	$1.41 \cdot 10^{-04}$	$1.24 \cdot 10^{-04}$	$1.72 \cdot 10^{-04}$	$1.54 \cdot 10^{-04}$	$5.43 \cdot 10^{-05}$	$4.08 \cdot 10^{-05}$	$5.84 \cdot 10^{-05}$	$4.48 \cdot 10^{-05}$
TE	$3.27 \cdot 10^{-02}$	$3.01 \cdot 10^{-02}$	$3.80 \cdot 10^{-02}$	$3.52 \cdot 10^{-02}$	$6.35 \cdot 10^{-02}$	$5.97 \cdot 10^{-02}$	$1.53 \cdot 10^{-02}$	$1.34 \cdot 10^{-02}$	$2.32 \cdot 10^{-02}$	$2.09 \cdot 10^{-02}$
LU	59.88	58.44	53.20	52.01	89.92	87.35	5.38	5.99	51.14	50.03
WD	0.120	$3.03 \cdot 10^{-02}$	0.120	$3.07 \cdot 10^{-02}$	16.22	15.52	11.07	10.57	0.117	$2.78 \cdot 10^{-02}$
FD	7.22	6.57	8.11	7.43	7.20	6.56	3.90	3.38	3.61	3.10
BIO	2409	2309	2120	2031	4302	4128	197	178	3016	2889
SE	1.67	1.60	1.47	1.41	0.160	0.153	$7.37 \cdot 10^{-03}$	$6.63 \cdot 10^{-03}$	$7.96 \cdot 10^{-02}$	$7.62 \cdot 10^{-02}$

Table 12: (Cont.) Environmental impacts of 1 kg of fermentable sugar from the different scenarios (mass allocation)

Impact category	Sc11	Sc12	Sc13	Sc14	Sc15	Sc16	Sc17	Sc18	Sc19	Sc20
CC	1.41	1.29	0.706	0.694	1.23	1.29	0.875	0.913	1.00	1.05
PM	$8.4 \cdot 10^{-08}$	$7.14 \cdot 10^{-08}$	$3.59 \cdot 10^{-08}$	$3.02 \cdot 10^{-08}$	$1.42 \cdot 10^{-07}$	$1.5 \cdot 10^{-07}$	$4.31 \cdot 10^{-08}$	$4.55 \cdot 10^{-08}$	$4.9 \cdot 10^{-08}$	$5.18 \cdot 10^{-08}$
HT	$5.1 \cdot 10^{-08}$	$1.25 \cdot 10^{-07}$	$1.88 \cdot 10^{-08}$	$2.53 \cdot 10^{-08}$	$3.03 \cdot 10^{-08}$	$3.17 \cdot 10^{-08}$	$1.64 \cdot 10^{-08}$	$1.69 \cdot 10^{-08}$	$3.01 \cdot 10^{-08}$	$3.15 \cdot 10^{-08}$
AC	$1.71 \cdot 10^{-02}$	$9.74 \cdot 10^{-03}$	$4.64 \cdot 10^{-03}$	$1.38 \cdot 10^{-02}$	$8.70 \cdot 10^{-03}$	$8.85 \cdot 10^{-03}$	$5.11 \cdot 10^{-03}$	$5.03 \cdot 10^{-03}$	$1.06 \cdot 10^{-02}$	$1.08 \cdot 10^{-02}$
FE	$3.19 \cdot 10^{-04}$	$4.17 \cdot 10^{-04}$	$1.93 \cdot 10^{-04}$	$1.97 \cdot 10^{-04}$	$3.12 \cdot 10^{-04}$	$3.12 \cdot 10^{-04}$	$2.02 \cdot 10^{-04}$	$1.96 \cdot 10^{-04}$	$2.33 \cdot 10^{-04}$	$2.28 \cdot 10^{-04}$
TE	$6.08 \cdot 10^{-02}$	0.121	$2.98 \cdot 10^{-02}$	$4.27 \cdot 10^{-02}$	$2.10 \cdot 10^{-02}$	$2.18 \cdot 10^{-02}$	$1.79 \cdot 10^{-02}$	$1.86 \cdot 10^{-02}$	$3.15 \cdot 10^{-02}$	$3.30 \cdot 10^{-02}$
LU	108	168	5.34	91.43	75.89	79.66	44.16	45.98	111	117
WD	$1.60 \cdot 10^{-02}$	31.17	22.63	$1.09 \cdot 10^{-02}$	$6.84 \cdot 10^{-03}$	$6.75 \cdot 10^{-03}$	$7.69 \cdot 10^{-03}$	$7.64 \cdot 10^{-03}$	$8.11 \cdot 10^{-03}$	$8.09 \cdot 10^{-03}$
FD	15.83	15.98	9.81	8.98	15.59	16.14	11.73	12.04	12.79	13.17
BIO	4709	8505	584	5920	4094	4291	2851	2963	2979	3108
SE	3.27	0.316	$2.18 \cdot 10^{-02}$	0.410	0.397	0.416	$5.60 \cdot 10^{-02}$	$5.83 \cdot 10^{-02}$	$3.44 \cdot 10^{-02}$	$3.59 \cdot 10^{-02}$

Table 13: Environmental impacts 1 kg of fermentable sugars production. Average impacts and standard deviation of the different feedstocks from Table 9 and 10 (economic allocation) and Table 11 and 12 (mass allocation). Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; WD – Water Depletion; FE – Fossil Depletion; BIO – affected Biodiversity; SE – Soil Erosion

Impact categories	Average	Standard deviation	Maximum	Minimum	Average	Standard deviation	Maximum	Minimum
	(Economic allocation)				(Mass allocation)			
CC	0.508	0.210	0.893	0.301	0.785	0.354	1.41	0.266
PM	$2.76 \cdot 10^{-08}$	$1.32 \cdot 10^{-08}$	$5.12 \cdot 10^{-08}$	$1.03 \cdot 10^{-08}$	$4.91 \cdot 10^{-08}$	$3.81 \cdot 10^{-08}$	$1.5 \cdot 10^{-07}$	$9.27 \cdot 10^{-09}$
HT	$2.19 \cdot 10^{-08}$	$2.24 \cdot 10^{-08}$	$7.88 \cdot 10^{-08}$	$3.43 \cdot 10^{-09}$	$3.27 \cdot 10^{-08}$	$2.68 \cdot 10^{-08}$	$1.25 \cdot 10^{-07}$	$7.99 \cdot 10^{-09}$
AC	$5.35 \cdot 10^{-03}$	$3.17 \cdot 10^{-03}$	$1.02 \cdot 10^{-02}$	$1.85 \cdot 10^{-03}$	$7.89 \cdot 10^{-03}$	$3.80 \cdot 10^{-03}$	$1.71 \cdot 10^{-02}$	$1.62 \cdot 10^{-03}$
FE	$1.29 \cdot 10^{-04}$	$5.54 \cdot 10^{-05}$	$2.41 \cdot 10^{-04}$	$4.61 \cdot 10^{-05}$	$1.81 \cdot 10^{-04}$	$1.02 \cdot 10^{-04}$	$4.17 \cdot 10^{-04}$	$4.08 \cdot 10^{-05}$
TE	$2.61 \cdot 10^{-02}$	$2.13 \cdot 10^{-02}$	$7.73 \cdot 10^{-02}$	$4.85 \cdot 10^{-03}$	$3.65 \cdot 10^{-02}$	$2.49 \cdot 10^{-02}$	$1.21 \cdot 10^{-01}$	$1.34 \cdot 10^{-02}$
LU	37.50	35.55	110	-0.805	68.11	40.84	168	5.34
WD	4.27	7.04	19.92	$6.90 \cdot 10^{-03}$	5.38	9.29	31.17	$6.75 \cdot 10^{-03}$
FD	6.36	2.11	11.04	3.33	9.46	4.45	16.14	3.10
BIO	1917	1619	5284	216	3179	1935	8505	178
SE	0.463	0.714	1.89	$4.58 \cdot 10^{-03}$	0.584	0.863	3.27	$6.63 \cdot 10^{-02}$

Table 14: Environmental impacts 7.5 g of fermentable sugars to produce 1 PLA packaging film. Average impacts and standard deviation of the different feedstocks from Annexes 9 and 10 (economic allocation) and Annexes 11 and 12 (mass allocation). Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; WD – Water Depletion; FE – Fossil Depletion; BIO – affected Biodiversity; SE – Soil Erosion

Impact categories	Average	Standard deviation	Maximum	Minimum	Average	Standard deviation	Maximum	Minimum
	(Economic allocation)				(Mass allocation)			
CC	$3.82 \cdot 10^{-03}$	$1.58 \cdot 10^{-03}$	$6.70 \cdot 10^{-03}$	$2.26 \cdot 10^{-03}$	$5.89 \cdot 10^{-03}$	$2.66 \cdot 10^{-03}$	$1.06 \cdot 10^{-02}$	$2.00 \cdot 10^{-03}$
PM	$2.07 \cdot 10^{-10}$	$9.88 \cdot 10^{-11}$	$3.84 \cdot 10^{-10}$	$7.73 \cdot 10^{-11}$	$3.68 \cdot 10^{-10}$	$2.86 \cdot 10^{-10}$	$1.13 \cdot 10^{-09}$	$6.95 \cdot 10^{-11}$
HT	$1.64 \cdot 10^{-10}$	$1.68 \cdot 10^{-10}$	$5.91 \cdot 10^{-10}$	$2.57 \cdot 10^{-11}$	$2.45 \cdot 10^{-10}$	$2.01 \cdot 10^{-10}$	$9.41 \cdot 10^{-10}$	$6 \cdot 10^{-11}$
AC	$4.02 \cdot 10^{-05}$	$2.38 \cdot 10^{-05}$	$7.68 \cdot 10^{-05}$	$1.39 \cdot 10^{-05}$	$5.92 \cdot 10^{-05}$	$2.85 \cdot 10^{-05}$	$1.28 \cdot 10^{-04}$	$1.21 \cdot 10^{-05}$
FE	$9.68 \cdot 10^{-07}$	$4.16 \cdot 10^{-07}$	$1.80 \cdot 10^{-06}$	$3.46 \cdot 10^{-07}$	$1.36 \cdot 10^{-06}$	$7.68 \cdot 10^{-07}$	$3.13 \cdot 10^{-06}$	$3.06 \cdot 10^{-07}$
TE	$1.96 \cdot 10^{-04}$	$1.60 \cdot 10^{-04}$	$5.80 \cdot 10^{-04}$	$3.63 \cdot 10^{-05}$	$2.74 \cdot 10^{-04}$	$1.87 \cdot 10^{-04}$	$9.11 \cdot 10^{-04}$	$1.00 \cdot 10^{-04}$
LU	$2.81 \cdot 10^{-01}$	0.266	$8.28 \cdot 10^{-01}$	$-6.04 \cdot 10^{-03}$	0.510	0.306	1.26	$4.01 \cdot 10^{-02}$
WD	$3.20 \cdot 10^{-02}$	$5.28 \cdot 10^{-02}$	$1.49 \cdot 10^{-01}$	$5.18 \cdot 10^{-05}$	$4.04 \cdot 10^{-02}$	$6.97 \cdot 10^{-02}$	0.233	$5.06 \cdot 10^{-05}$
FD	$4.77 \cdot 10^{-02}$	$1.59 \cdot 10^{-02}$	$8.29 \cdot 10^{-02}$	$2.50 \cdot 10^{-02}$	$7.10 \cdot 10^{-02}$	$3.34 \cdot 10^{-02}$	0.121	$2.33 \cdot 10^{-02}$
BIO	14.40	12.14	39.60	1.62	23.84	14.51	63.79	1.33
SE	$3.48 \cdot 10^{-03}$	$5.36 \cdot 10^{-03}$	$1.42 \cdot 10^{-02}$	$3.44 \cdot 10^{-05}$	$4.38 \cdot 10^{-03}$	$6.48 \cdot 10^{-03}$	$2.46 \cdot 10^{-02}$	$4.97 \cdot 10^{-05}$

Table 15: Environmental impacts 220 kg of fermentable sugars to produce 1 ha of mulch film. Average impacts and standard deviation of the different feedstocks from Annexes 13 and 14(economic allocation) and Annexes 15 and 16 (mass allocation). Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; WD – Water Depletion; FE – Fossil Depletion; BIO – affected Biodiversity; SE – Soil Erosion

Impact categories	Average	Standard deviation	Maximum	Minimum	Average	Standard deviation	Maximum	Minimum
	(Economic allocation)				(Mass allocation)			
CC	111.97	46.41	196.57	66.33	172.80	77.98	311.77	58.54
PM	$6.06 \cdot 10^{-06}$	$2.9 \cdot 10^{-06}$	$1.13 \cdot 10^{-05}$	$2.27 \cdot 10^{-06}$	$1.08 \cdot 10^{-05}$	$8.38 \cdot 10^{-06}$	$3.31 \cdot 10^{-05}$	$2.04 \cdot 10^{-06}$
HT	$4.82 \cdot 10^{-06}$	$4.93 \cdot 10^{-06}$	$1.73 \cdot 10^{-05}$	$7.54 \cdot 10^{-07}$	$7.2 \cdot 10^{-06}$	$5.91 \cdot 10^{-06}$	$2.76 \cdot 10^{-05}$	$1.76 \cdot 10^{-06}$
AC	1.17	0.698	2.25	0.407	1.73	0.834	3.76	0.355
FE	$2.84 \cdot 10^{-02}$	$1.22 \cdot 10^{-02}$	$5.29 \cdot 10^{-02}$	$1.01 \cdot 10^{-02}$	$3.99 \cdot 10^{-02}$	$2.25 \cdot 10^{-02}$	$9.18 \cdot 10^{-02}$	$8.98 \cdot 10^{-03}$
TE	5.73	4.69	17.00	1.06	8.03	5.48	26.72	2.94
LU	8,250	7,822	24,288	-177	14,984	8,984	37,035	1,175
WD	939	1,550	4,382	1.51	1,185	2,045	6,859	1.48
FD	1,399	465	2,430	733	2,081	980	3,552	683
BIO	421,862	356,321	1,162,582	47,599	699,548	425,858	1,871,298	39,164
SE	101	157	416	1.00	128	189	721	1.45

Table 16: Environmental impacts 2.7 kg of fermentable sugars to produce 1 kg of PBS. Average impacts and standard deviation of the different feedstocks from Annexes 17 and 18 (economic allocation) and Annexes 19 and 20 (mass allocation). Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; LU – Land Use; WD – Water Depletion; FE – Fossil Depletion; BIO – affected Biodiversity; SE – Soil Erosion

Impact categories	Average	Standard deviation	Maximum	Minimum	Average	Standard deviation	Maximum	Minimum
	(Economic allocation)				(Mass allocation)			
CC	1.37	0.569	2.41	0.814	2.12	0.957	3.82	0.718
PM	$7.44 \cdot 10^{-08}$	$3.56 \cdot 10^{-08}$	$1.38 \cdot 10^{-07}$	$2.78 \cdot 10^{-08}$	$1.32 \cdot 10^{-07}$	$1.03 \cdot 10^{-07}$	$4.06 \cdot 10^{-07}$	$2.5 \cdot 10^{-08}$
HT	$5.91 \cdot 10^{-08}$	$6.05 \cdot 10^{-08}$	$2.13 \cdot 10^{-07}$	$9.25 \cdot 10^{-09}$	$8.84 \cdot 10^{-08}$	$7.25 \cdot 10^{-08}$	$3.38 \cdot 10^{-07}$	$2.16 \cdot 10^{-08}$
AC	$1.45 \cdot 10^{-02}$	$8.57 \cdot 10^{-03}$	$2.77 \cdot 10^{-02}$	$5.00 \cdot 10^{-03}$	$2.13 \cdot 10^{-02}$	$1.02 \cdot 10^{-02}$	$4.63 \cdot 10^{-02}$	$4.36 \cdot 10^{-03}$
FE	$3.48 \cdot 10^{-04}$	$1.50 \cdot 10^{-04}$	$6.49 \cdot 10^{-04}$	$1.25 \cdot 10^{-04}$	$4.90 \cdot 10^{-04}$	$2.76 \cdot 10^{-04}$	$1.13 \cdot 10^{-03}$	$1.10 \cdot 10^{-04}$
TE	$7.04 \cdot 10^{-02}$	$5.76 \cdot 10^{-02}$	0.209	$1.31 \cdot 10^{-02}$	$9.86 \cdot 10^{-02}$	$6.73 \cdot 10^{-02}$	0.328	$3.61 \cdot 10^{-02}$
LU	101.25	96.00	298.08	-2.17	183.90	110.27	454.53	14.42
WD	11.53	19.02	53.78	$1.86 \cdot 10^{-02}$	14.54	25.10	84.18	$1.82 \cdot 10^{-02}$
FD	17.17	5.71	29.82	9.00	25.54	12.03	43.60	8.39
BIO	5,177	4,373	14,268	584	8,585	5,226	22,965	480
SE	1.25	1.92	5.11	$1.24 \cdot 10^{-02}$	1.57	2.33	8.85	$1.79 \cdot 10^{-02}$

As observed in Table 13, from a global point of view, the results of economic allocation have less environmental impacts, due to the low economic value of second-generation raw materials. For instance, the average value of all the 20 scenarios for climate change (CC) is about 0.50 kg (economic allocation), compared to 0.78 kg CO_2 eq (mass allocation) for the production of 1 kg of fermentable sugars. The standard variation values, however, are relatively high mainly due to the different types of agricultural systems.

A different approach to understanding the system and its environmental impacts is to identify the environmental hotspots through LCA. The hotspots analysis for each scenario is depicted in Figures 14, 15 and 16 (economic allocation) and Figures 17, 18 and 19 (mass allocation). As depicted in the figures, the agricultural phase plays a key role in the overall results of maize grains and stover, whether applying economic or mass allocation. However, for the beet pulp scenarios, the processing phase, more specifically the "TS production" process, is the main contributor when economic allocation is applied (Figure 16). This is because the raw beet pulp is practically priceless. Pulp prices start to appear when beet pulp pellets are produced, because additional energy is needed to dry the pulp, with almost 30% of all energy used in a sugar mill. On the other hand, if mass allocation is applied (Figure 19), the agricultural phase is now the main contributor, given the high amount of raw beet pulp produced.

The comparison between mass and economic allocation shows that, for fermentable sugars from maize grain, the differences on the results are not as sensitive as those compared to maize stover and sugar beet pulp. For instance, when switching from economic to mass allocations, for the climate change (CC) indicator, maize grain dropped to approximately 8%, while stover and beet pulp increased about 60% and 220%, respectively (see Table 17 and 18). The environmental indicators Land use (LU), soil erosion (SE) and biodiversity (BIO) were not included in the global LCA, as these impact categories are not fair to be compared with fossil-based alternatives. Furthermore, it is not appropriate to compare, for instance, land use in the agricultural phase with land use in manufacturing or end-of-life processes of biobased products.

The LCA outcomes show that the valorisation of the by-products as renewable fermentation materials is very sensitive to allocation. In addition, the prices of these products are not as stable as first-generation raw materials, such as maize grain, which benefits from technological development (for instance, pre-treatment process to glucose production) and economic support (for instance, subsidies). That is why an early techno-economic evaluation of these raw materials must be carried out. The Work Package 4 (WP4) evaluates the techno-economic evaluation of the bioproducts of the case studies.

Tables 17 and 18 show the main results of this deliverable D2.4 for the case studies BoPLA (Table 17) and PLA mulch film (Table 18). These outcomes are the combination of the upstream and downstream processes. The environmental impacts of the downstream processes (manufacturing and end-of-life) are evaluated by the Work Package 3 (WP3). WP3 have also proposed alternative end-of-life scenarios for the case studies (BoPLA and mulch film). For clarification, see D3.3 "Report on sustainability criteria that describes the end-of-life options for biologically based products". Only the global LCA for BoPLA packaging film and agricultural PLA mulch films are depicted in this report because no end-of-life processes were performed for the PBS case study.

It is clear that upstream processes (agriculture and pre-treatment) have a considerable contribution to the global LCA (agricultural, pre-treatment, manufacturing and end of life). In addition, it was observed that choosing the type of raw material and methods used in LCA can alter considerably the results. Therefore, it is very important to investigate aspects of sustainability at a very early stage in the development of a new product or process to help the decision-making process and avoid wrong decisions. In general, the use of fermentable sugar from beet pulp through economic allocation will have a lower environmental impact of the global LCA.

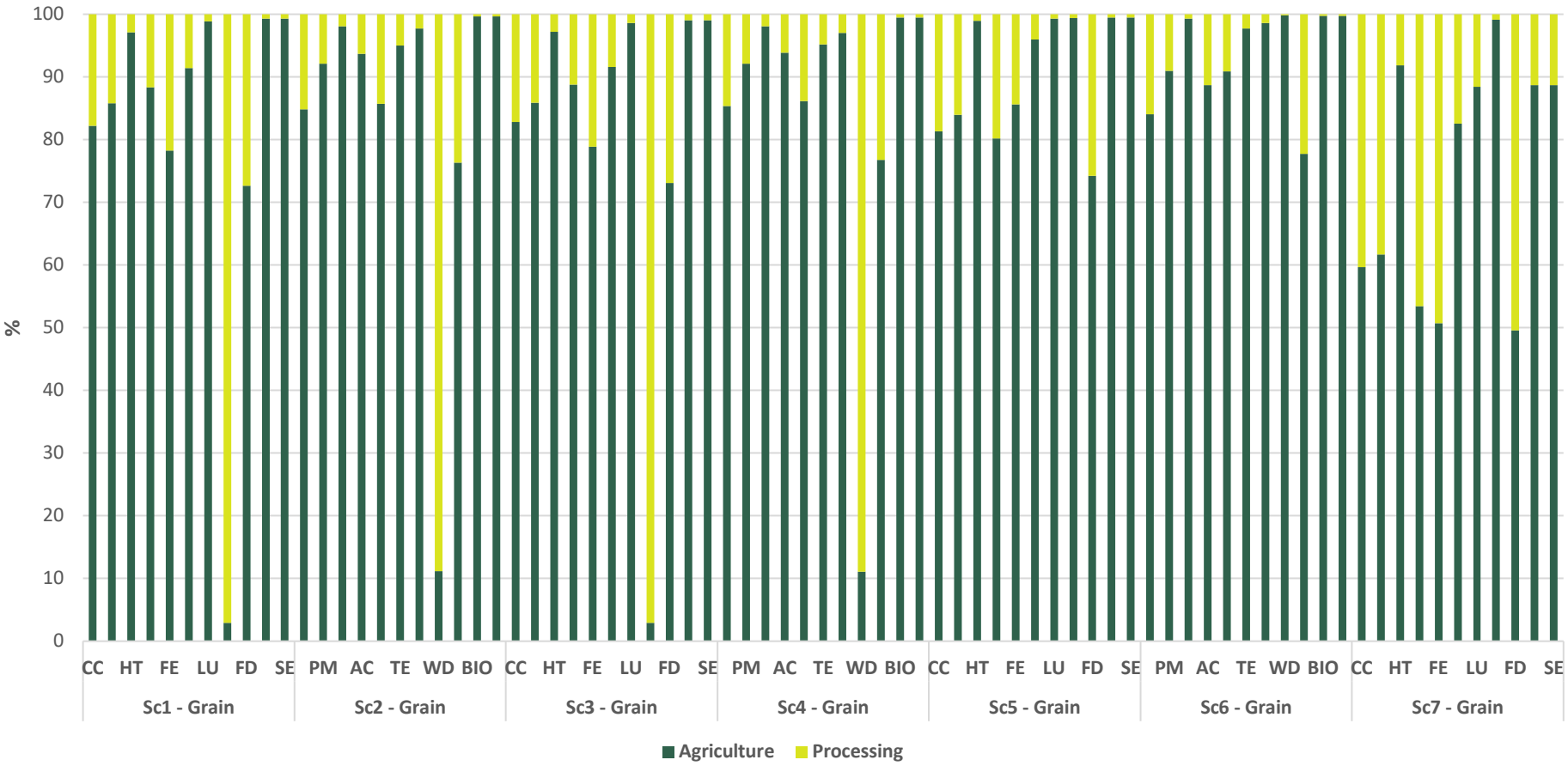

Figure 14: Comparative profile of fermentable sugars production from different scenarios using economic allocation. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; WD – Water Depletion; FE – Fossil Depletion

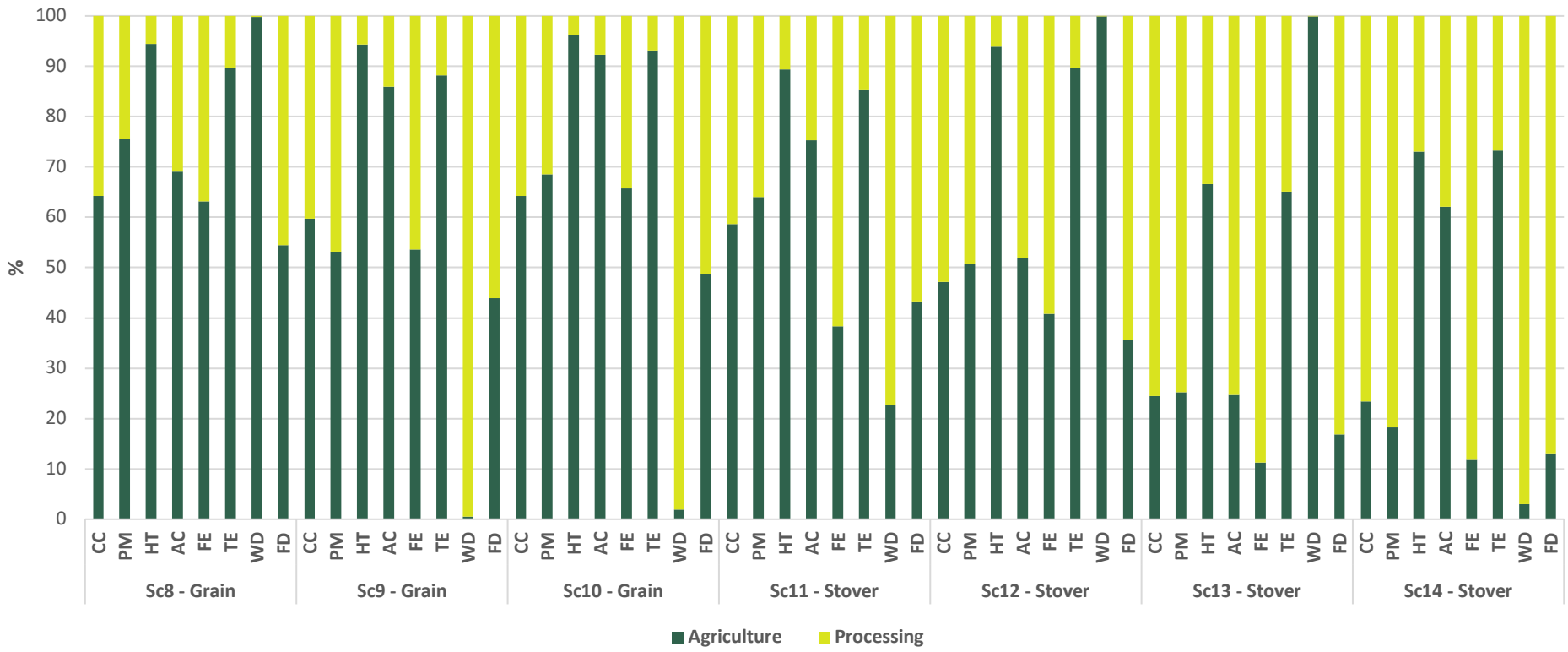

Figure 15: (Cont.) Comparative profile of fermentable sugars production from different scenarios using economic allocation. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; WD – Water Depletion; FE – Fossil Depletion

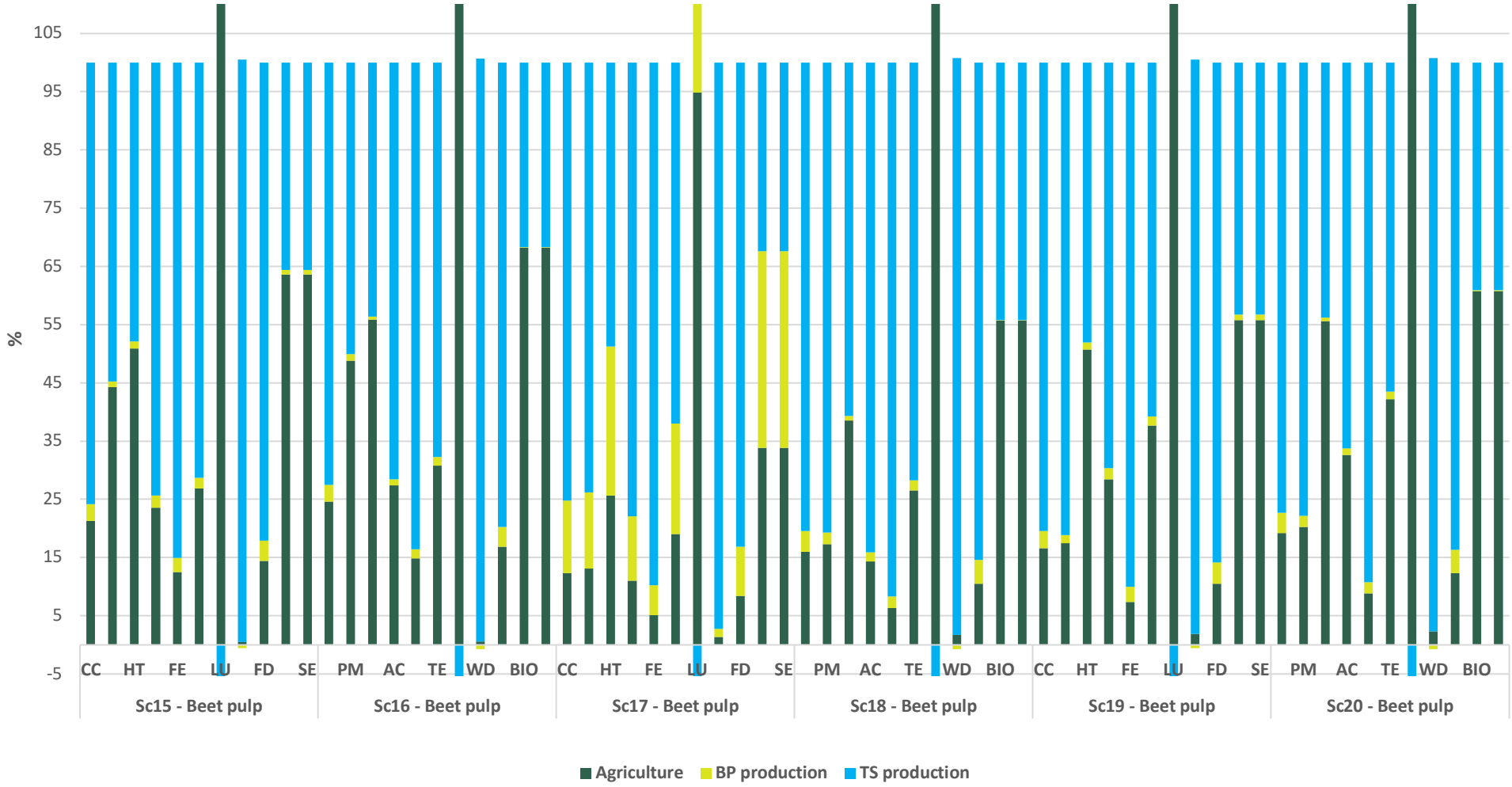

Figure 16: (Cont.) Comparative profile of fermentable sugars production from different scenarios using economic allocation. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; WD – Water Depletion; FE – Fossil Depletion; BP process – Beet pulp processing; TS processing – Total Sugars processing

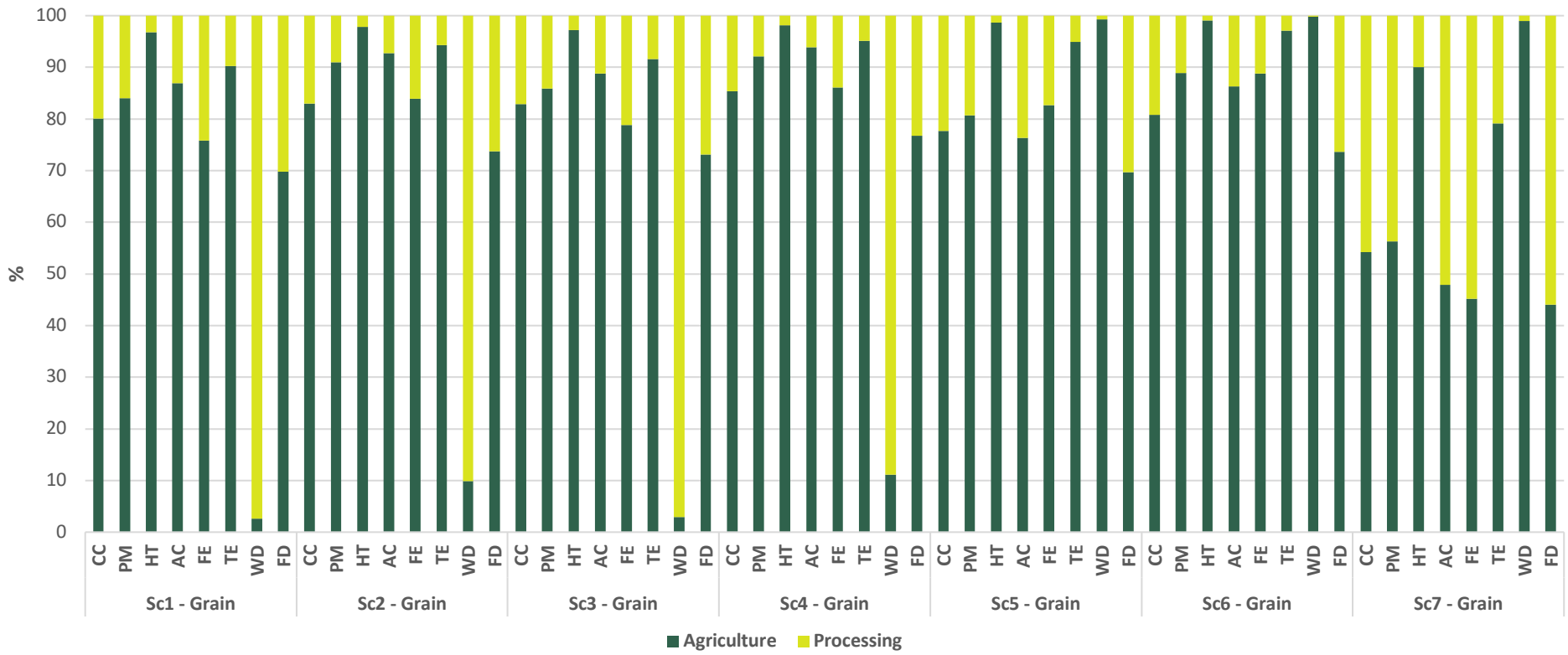

Figure 17: Comparative profile of fermentable sugars production from different scenarios using mass allocation. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; WD – Water Depletion; FE – Fossil Depletion

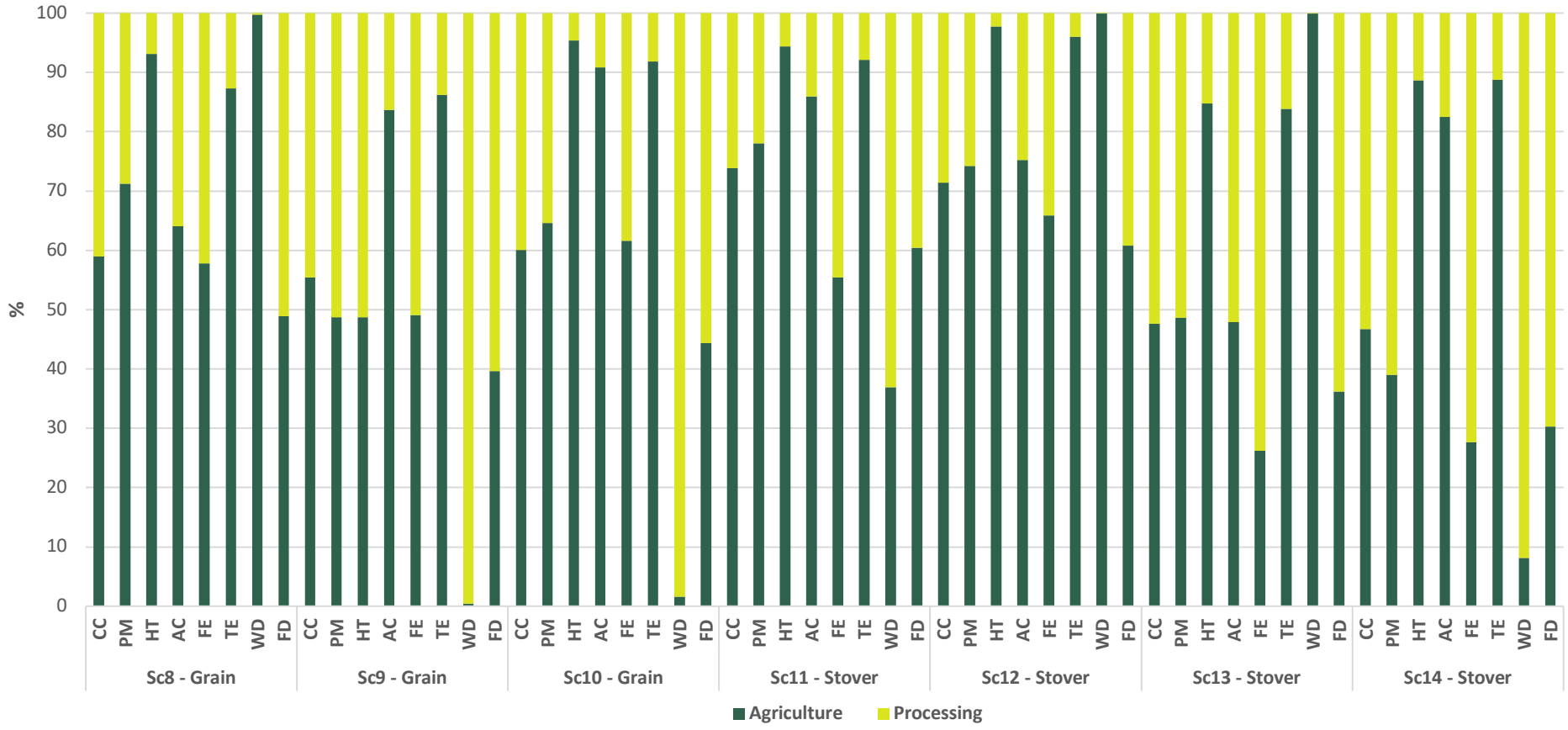

Figure 18: (Cont.) Comparative profile of fermentable sugars production from different scenarios using mass allocation. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; WD – Water Depletion; FE – Fossil Depletion

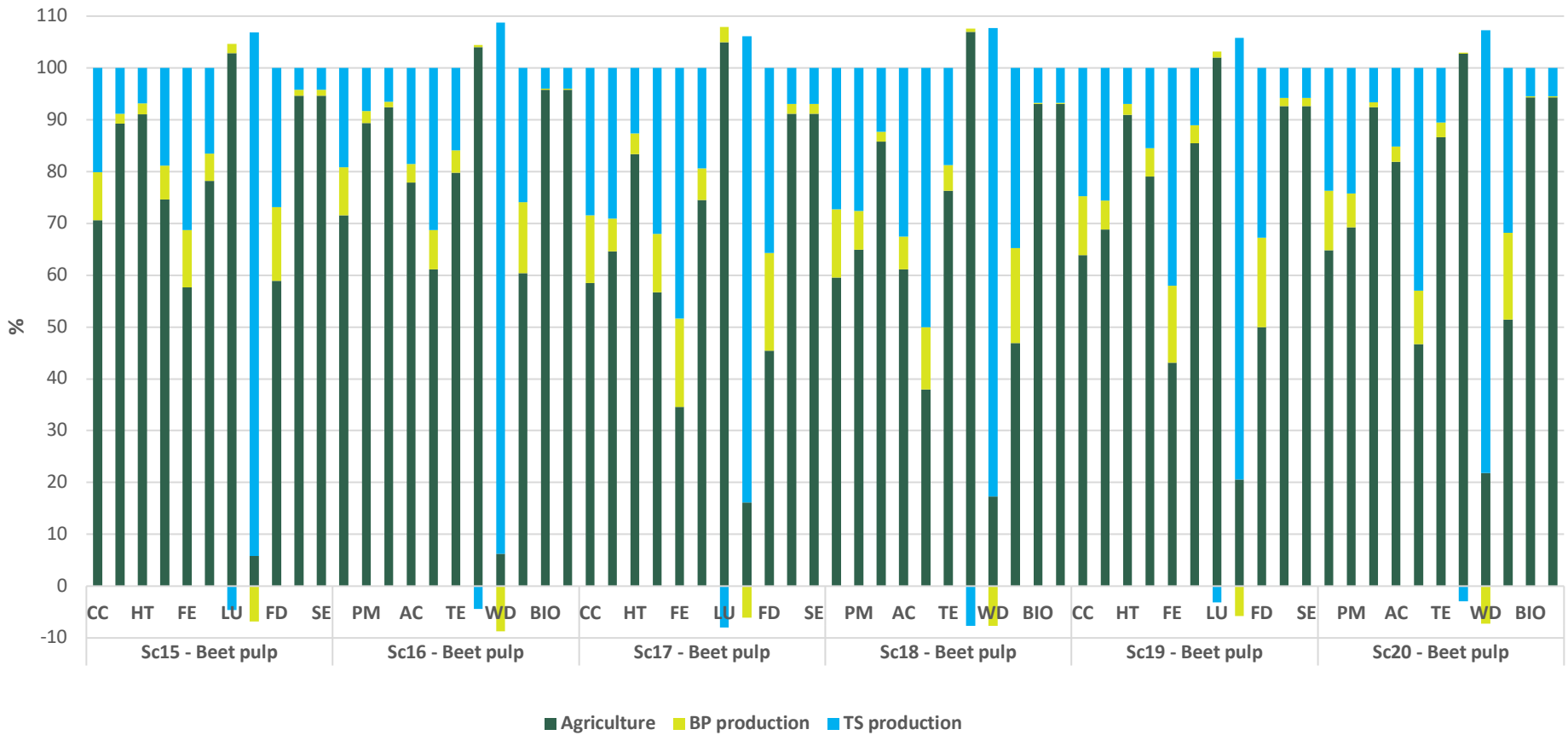

Figure 19: (Cont.) Comparative profile of fermentable sugars production from different scenarios using mass allocation. Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; WD – Water Depletion; FE – Fossil Depletion; BP process – Beet pulp processing; TS processing – Total Sugars processing

Table 17: Global LCA of 1 packaging film production (economic and mass allocation) – BoPLA packaging film

Impact category	Upstream processes (Maize grain)		Upstream processes (Maize stover)		Upstream processes (Beet pulp)		Production and distribution	Intended EoL (Aerobic composting)
	Economic	Mass	Economic	Mass	Economic	Mass		
CC	$(4.25 \pm 1.62) \cdot 10^{-03}$	- 8.07 %	$(4.81 \pm 1.47) \cdot 10^{-03}$	+ 60.25 %	$(2.43 \pm 0.09) \cdot 10^{-03}$	+ 228 %	$4.46 \cdot 10^{-03}$	$-4.50 \cdot 10^{-03}$
PM	$(2.27 \pm 1.11) \cdot 10^{-10}$	- 8.44 %	$(2.55 \pm 0.99) \cdot 10^{-10}$	+ 63.15 %	$(1.40 \pm 0.31) \cdot 10^{-10}$	+ 330 %	$1.67 \cdot 10^{-09}$	$6.33 \cdot 10^{-11}$
HT	$(2.39 \pm 1.89) \cdot 10^{-10}$	- 13.20 %	$(1.74 \pm 1.32) \cdot 10^{-10}$	+ 137 %	$(3.23 \pm 0.36) \cdot 10^{-11}$	+ 506 %	$2.10 \cdot 10^{-07}$	$6.54 \cdot 10^{-12}$
AC	$(5.20 \pm 2.27) \cdot 10^{-05}$	- 8.54 %	$(4.57 \pm 2.08) \cdot 10^{-05}$	+ 85 %	$(1.67 \pm 0.14) \cdot 10^{-05}$	+ 267 %	$1.35 \cdot 10^{-04}$	$1.39 \cdot 10^{-05}$
FE	$(8.41 \pm 4.23) \cdot 10^{-07}$	- 9.22 %	$(1.49 \pm 0.32) \cdot 10^{-06}$	+ 42 %	$(8.33 \pm 0.32) \cdot 10^{-07}$	+ 122 %	$8.94 \cdot 10^{-04}$	$6.47 \cdot 10^{-07}$
TE	$(2.84 \pm 1.58) \cdot 10^{-04}$	- 12.22 %	$(2.08 \pm 1.12) \cdot 10^{-04}$	+ 129 %	$(4.04 \pm 0.39) \cdot 10^{-05}$	+ 344 %	$5.23 \cdot 10^{-06}$	$5.46 \cdot 10^{-07}$
WD	$(4.96 \pm 6.52) \cdot 10^{-02}$	- 18.60 %	$(3.61 \pm 4.26) \cdot 10^{-02}$	+ 179 %	$(5.24 \pm 0.05) \cdot 10^{-05}$	7.61 %	$6.20 \cdot 10^{-04}$	$6.57 \cdot 10^{-05}$
FD	$(4.62 \pm 1.55) \cdot 10^{-02}$	-7.19 %	$(6.66 \pm 1.37) \cdot 10^{-02}$	+ 42 %	$(3.72 \pm 0.10) \cdot 10^{-02}$	170 %	$2.34 \cdot 10^{-02}$	$9.80 \cdot 10^{-06}$

Table 18: Global LCA of 1 ha mulch film (economic and mass allocation) – PLA based mulch film

Impact category	Upstream processes (Maize grain)		Upstream processes (Maize stover)		Upstream processes (Beet pulp)		Production and distribution	Intended EoL (Soil Biodegradation)
	Economic	Mass	Economic	Mass	Economic	Mass		
CC	124 ± 47	- 8.07 %	141 ± 43	+ 60.25 %	71 ± 2.8	+ 228 %	292	35.32
PM	$(6.67 \pm 3.26) \cdot 10^{-06}$	- 8.44 %	$(7.47 \pm 2.91) \cdot 10^{-06}$	+ 63.15 %	$(4.11 \pm 0.92) \cdot 10^{-06}$	+ 330 %	$2.52 \cdot 10^{-05}$	$1.18 \cdot 10^{-07}$
HT	$(7.02 \pm 5.55) \cdot 10^{-06}$	- 13.20 %	$(5.11 \pm 3.89) \cdot 10^{-06}$	+ 137 %	$(9.48 \pm 1.07) \cdot 10^{-07}$	+ 506 %	$7.9 \cdot 10^{-06}$	$3.68 \cdot 10^{-09}$
AC	1.53 ± 0.67	- 8.54 %	1.34 ± 0.61	+ 85 %	0.49 ± 0.04	+ 267 %	3.31	0.134
FE	$(2.47 \pm 1.24) \cdot 10^{-02}$	- 9.22 %	$(4.36 \pm 0.95) \cdot 10^{-02}$	+ 42 %	$(2.44 \pm 0.08) \cdot 10^{-02}$	+ 122 %	0.106	$3.3 \cdot 10^{-05}$
TE	8.32 ± 4.65	- 12.22 %	6.10 ± 3.28	+ 129 %	1.19 ± 0.11	+ 344 %	1.08	1.46
WD	1455 ± 1913	- 18.60 %	1059 ± 1250	+ 179 %	1.54 ± 0.01	7.61 %	3.51	0.0166
FD	1354 ± 454	-7.19 %	1953 ± 402	+ 42 %	1105 ± 30	170 %	1630	128

Conclusions

Understanding the social, environmental and techno-economic aspects of agricultural activities and pre-processing of the production of bioproducts is very important as these upstream activities embody a very distinct and independent stage in the bio-products supply chain. Agriculture, for example, is highly determined by geographic and climatic conditions.

One pathway to enhance the production of bioproducts is through the use of carbohydrate-rich biomass (i.e. fermentable sugars). Examples of fermentable sugars are starch (e.g. maize grain) or sugar (sugar beet) crops and lignocellulosic biomass (e.g. maize residues and beet pulp). This report, which is part of Task 2.5, evaluates the upstream LCA of fermentable sugars from maize grain, stover and beet pulp as they are renewable material inputs to the production of the three case studies of the STAR-ProBio project: BoPLA packaging film, PLA mulch film and PBS resin.

This report evaluated 8 agricultural systems in 6 countries and 6 pre-processing activities, which resulted in the combination of 20 different fermentable sugar production scenarios. The functional units (FU) chosen was the amount of fermentable sugars needed to produce the three case studies: 7.5 g, 220 kg and 2.77 kg of fermentable sugars to produce 1 BoPLA packaging film 350 mm x 250 mm , 1 ha of PLA mulch film and 1 kg of PBS resin, respectively. PLA and PBS are the main polymers used in the downstream environmental assessment (in WP3).

Inventory data on the agricultural activities of the selected feedstocks as well as the pre-processing of maize grains into glucose were collected through peer-reviewed studies and databases. On the other hand, pre-processing of lignocellulosic biomass (maize stover and sugar beet pulp) was provided by our AUA partners which are responsible and leader of WP4 (techno-economic assessment of the case studies). Economic allocation was chosen in this upstream LCA, as there is a high difference in prices between the main product and the by-products. Sensitivity analysis was performed to compare mass and economic allocations.

With regard to agriculture cultivation, the results of this upstream LCA show that field emissions, transport, chemical fertilization and agricultural activities are critical factors for environmental impacts. The A8 scenario for maize, for example, which did not use agrochemicals, but slurry, less agricultural machinery and shorter transport had one of the lowest impacts for 1 kg of raw material. As transportation plays a key role in the environmental impacts of agriculture, it is recommended that the pre-treatment phase of these raw materials into fermentable sugars is located close to the agricultural fields, which would reduce considerably the environmental burdens. Sugar beet also loses its sugar content quickly after it is harvested.

In general, when economic allocation is performed, the average values from the 20 scenarios for the production of 1 kg of fermentable sugars emit about 0.50 kg of CO_2 and 6 MJ of energy. The standard variation is very high due to the different agricultural systems considered. Contribution analysis shows that agricultural activities play a fundamental role in the total impacts for maize and stover. However, it has a small contribution to beet pulp, due to its low market value. This LCA proved that the choice of biomass type and pre-treatment technology will have an impact on the global LCA of bio-based products. Particularly in this upstream LCA, this assessment demonstrated that the use of fermentable sugars from beet pulp will reduce the impacts of the three case studies, if economic allocation is applied.

The sensitivity analysis comparing the economic and mass allocation shows that the results for maize grain are not as sensitive, when compared with maize stover or beet pulp. Both showed an extremely high sensitivity in the results. Therefore, the outcomes of this LCA should be combined with technoeconomic analysis, not only considering internal operations, but evaluating these feedstocks from a macroeconomic perspective to understand how the market system behaves if these raw materials are used on a larger scale for bioproducts in the future.

It is very important to discern upstream from downstream processes, as evidence shows that upstream processes have unique characteristics that will affect the overall sustainability of bio-based products. Biorefinery plants, for example, can obtain their biomass from various suppliers and countries, from different types of agricultural systems and geoclimatic conditions. Not to mention the economic and social aspects, such as transportation, working conditions, salary, etc., which may vary according to each biomass supplier. In addition, first generation raw materials, for example, can be highly subsidized, not showing the true value of these raw materials.

This report is an attempt to present the environmental impacts of upstream processes for the Star-ProBio case studies. A variety of gaps will be explored in the future, such as the use of other types and innovative raw materials, for instance, micro and macro algae and cellulose from forestry operations. Additionally, new pre-treatment technologies, especially for processing lignocellulosic crops and new ways of integrating supply chains between the upstream and downstream processes of bio-based products, are expected to emerge in the future.

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Annexes

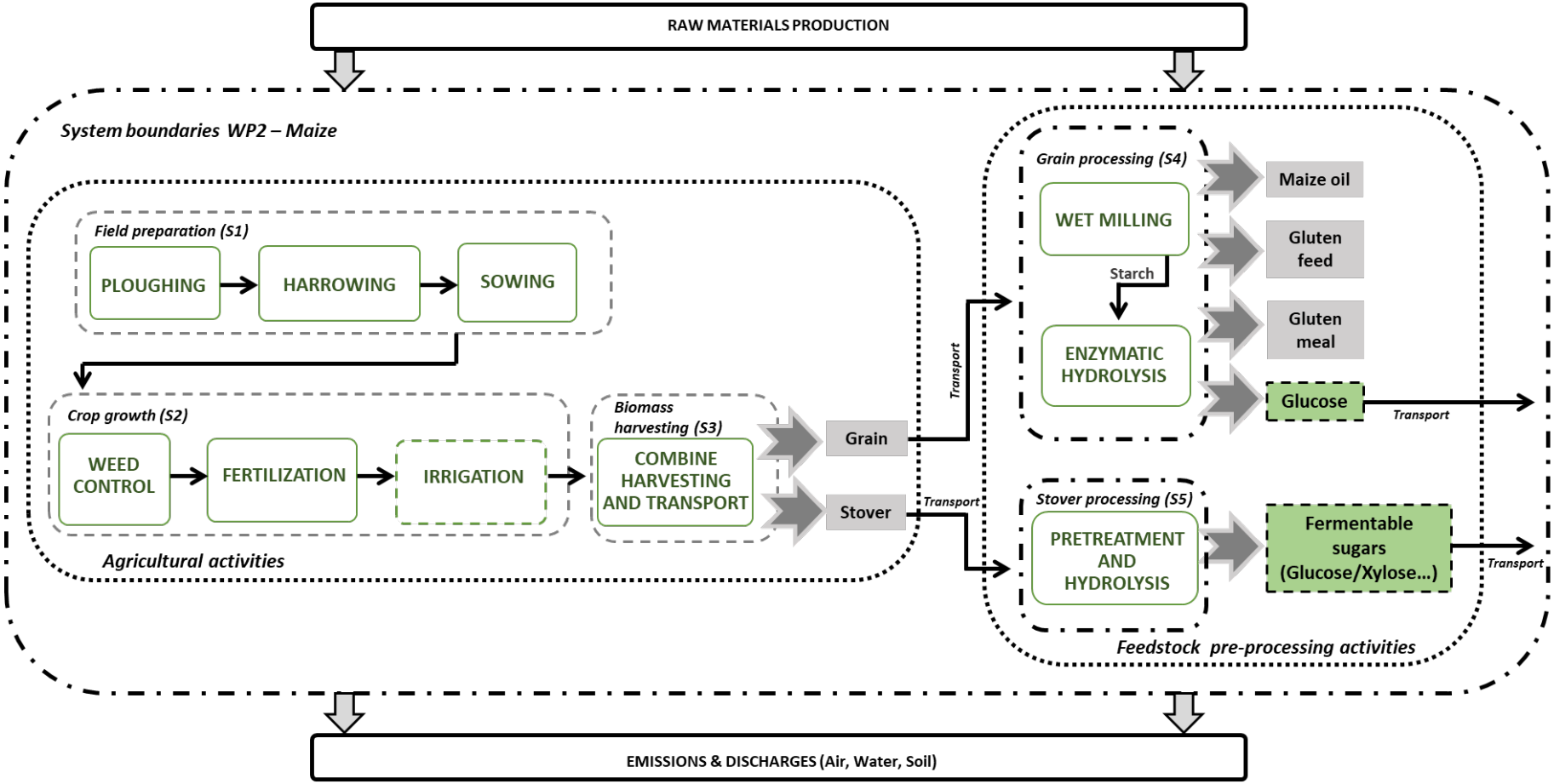
Annex 1. Field emissions calculation

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)
Pesticides emissions	❖ 9% of applied pesticides on the field emitted to air	(European Commission, 2017)
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)
Pesticides emissions	❖ 1% of applied pesticides on the field emitted to air	(European Commission, 2017)

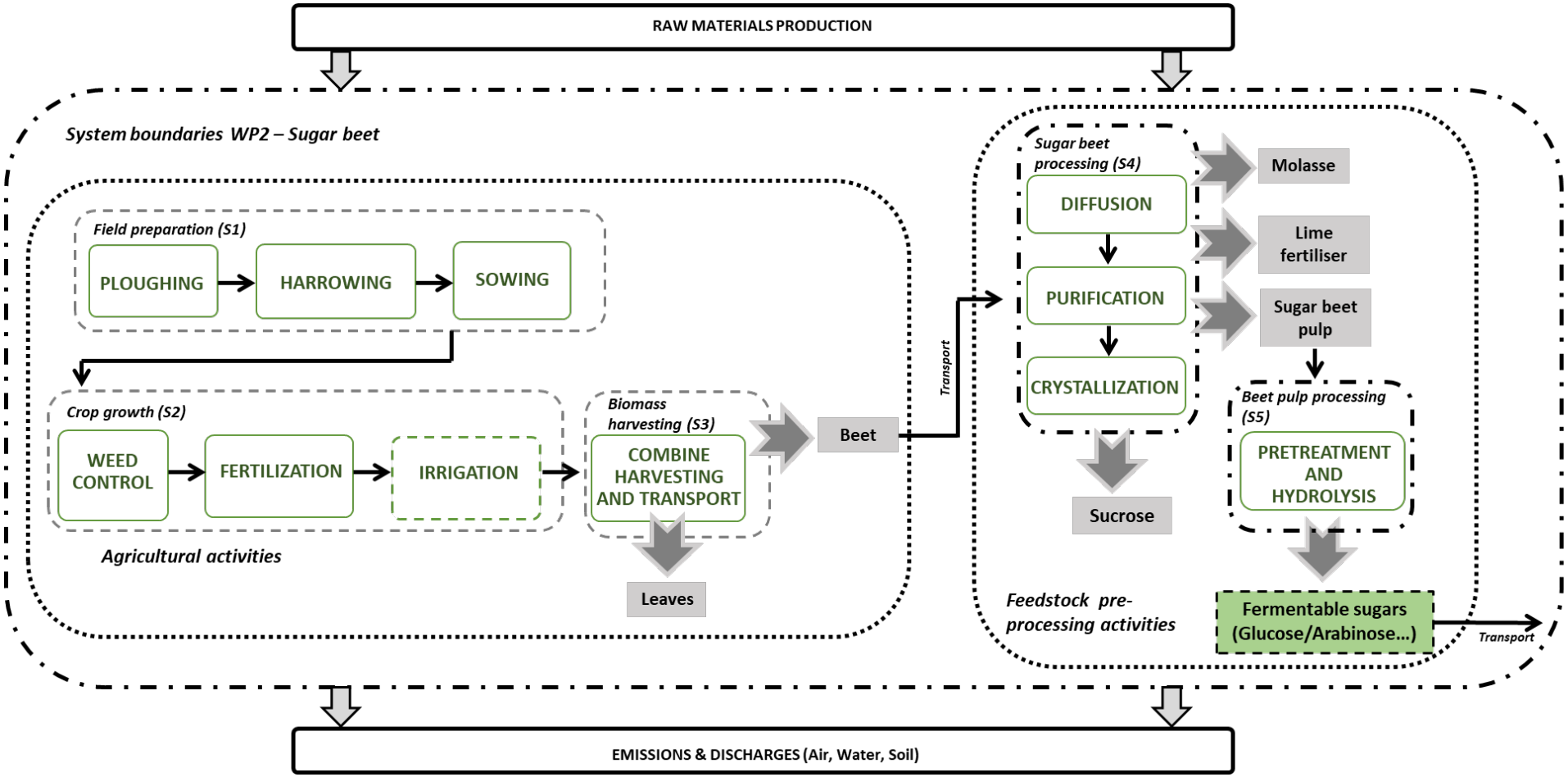
Heavy metals emissions	❖ Heavy metals (Cd, Cu, Zn, Pb, Ni, Cr and Hg) content in mineral fertilisers; ❖ Heavy metals (Cd, Cu, Zn, Pb, Ni, Cr and Hg) content in organic fertilisers (manure); ❖ Heavy metals (Cd, Cu, Zn, Pb, Ni, Cr and Hg) content in the biomass; ❖ Heavy metals leaching	(Durlinger et al., 2017)
Field emissions to soil		
Pesticides emissions	❖ 90% of applied pesticides on the field emitted to soil	(European Commission, 2017)
Heavy metals emissions	❖ Heavy metals (Cd, Cu, Zn, Pb, Ni, Cr and Hg) content in mineral fertilisers; ❖ Heavy metals (Cd, Cu, Zn, Pb, Ni, Cr and Hg) content in organic fertilisers (manure); ❖ Heavy metals (Cd, Cu, Zn, Pb, Ni, Cr and Hg) content in the biomass; ❖ Heavy metals deposition	(Durlinger et al., 2017)

Annex 2: Economic values for maize grain, maize stover and sugar beet

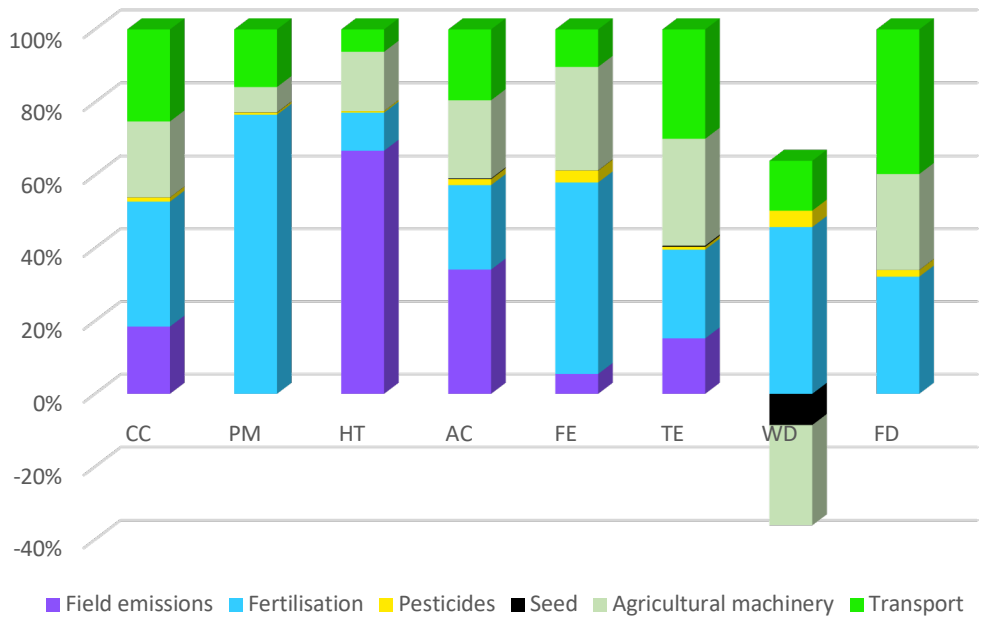
Agriculture	**Price**	**Source**
Maize grain (US)	135 $/t	(USDA, 2019)
Maize grain (IT)	196 $/t	(EUROSTAT, 2019)
Maize grain (BE)	203 $/t	(EUROSTAT, 2019)
Maize stover	58.5 $/t	(Humbird et al., 2011)
Processing (Sugar beet)	**Price**	**Source**
Sucrose	308 €/t	(European Commission, 2019)
Sugar beet pulp	4 €/t	Calculated by AUA partner[a]
Molasses	105 €/t	(Maravíc et al., 2015)
Calcium carbonate	100 €/t	(Durlinger et al., 2017)
Processing (Maize)	**Price**	
Glucose	230 $/t	(USDA, 2019)
Maize gluten feed	89 $/t	(USDA, 2019)
Maize gluten meal	536 $/t	(USDA, 2019)
Maize oil	808 $/t	(USDA, 2019)
Maize germ	300 $/t	(Moncada et al., 2018)



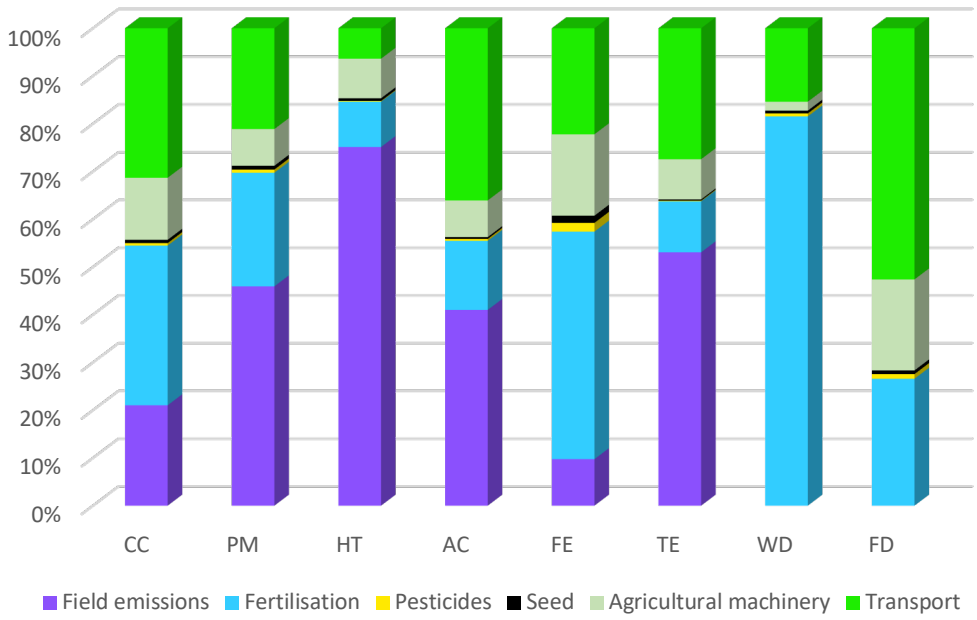
Annex 3: System description of fermentable sugars production from maize grain and stover



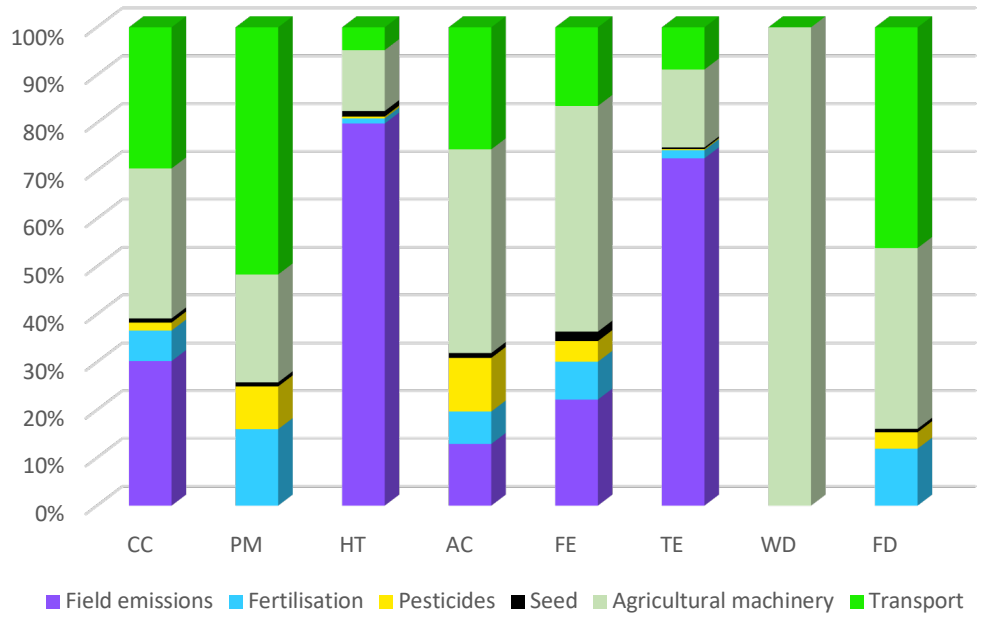
Annex 4: System description of fermentable sugars production from sugar beet and sugar beet pulp



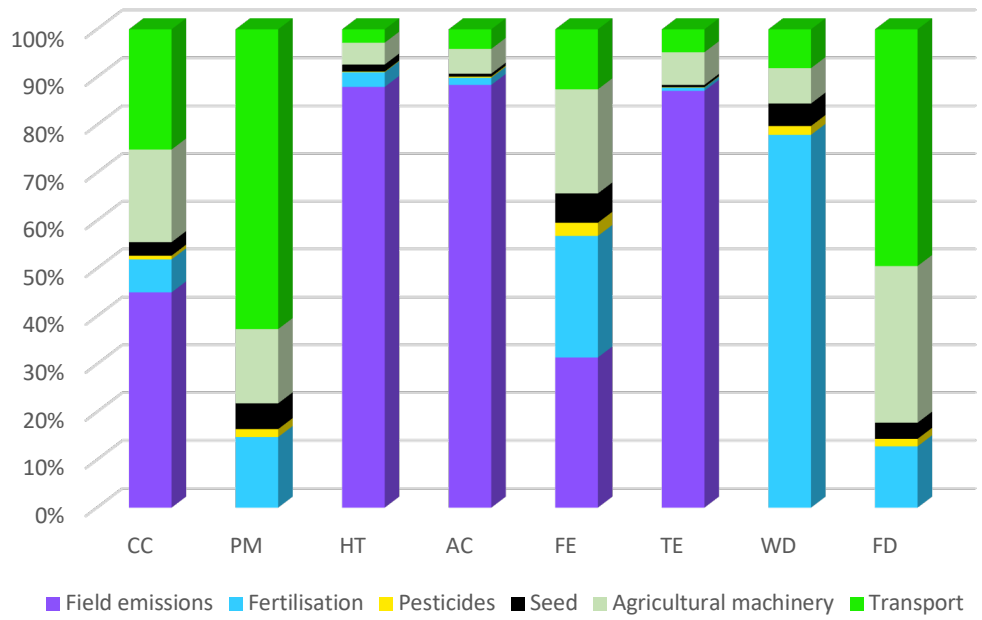
Annex 5: Process contribution for the production of sugar beet in the UK (scenario A1). Acronyms: CC – Climate Change; PM – Particulate Matter; HT – Human Toxicity; AC – Acidification; FE – Freshwater Eutrophication; TE – Terrestrial Eutrophication; WD – Water Depletion and FE – Fossil Depletion; Eutrophication; WD – Water Depletion and FE – Fossil Depletion



Annex 6: Process contribution for the production of maize grain in the US (scenario A5). Economic allocation. 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; Eutrophication; WD – Water Depletion and FE – Fossil Depletion



Annex 7: Process contribution for the production of maize grain in Italy (scenario A7). Economic allocation. 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; Eutrophication; WD – Water Depletion and FE – Fossil Depletion



Annex 8: Process contribution for the production of maize grain in Belgium (scenario A8). Economic allocation. 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; Eutrophication; WD – Water Depletion and FE – Fossil Depletion

Annex 9: Environmental impacts of 7.5 g of fermentable sugar to produce 1 PLA packaging film from the different scenarios (economic allocation)

Impact category	Sc1	Sc2	Sc3	Sc4	Sc5	Sc6	Sc7	Sc8	Sc9	Sc10
CC	$5.69 \cdot 10^{-03}$	$5.33 \cdot 10^{-03}$	$5.92 \cdot 10^{-03}$	$5.54 \cdot 10^{-03}$	$5.42 \cdot 10^{-03}$	$5.07 \cdot 10^{-03}$	$2.52 \cdot 10^{-03}$	$2.26 \cdot 10^{-03}$	$2.52 \cdot 10^{-03}$	$2.27 \cdot 10^{-03}$
PM	$3.41 \cdot 10^{-10}$	$3.07 \cdot 10^{-10}$	$3.43 \cdot 10^{-10}$	$3.09 \cdot 10^{-10}$	$3.01 \cdot 10^{-10}$	$2.68 \cdot 10^{-10}$	$1.26 \cdot 10^{-10}$	$9.95 \cdot 10^{-11}$	$1.03 \cdot 10^{-10}$	$7.73 \cdot 10^{-11}$
HT	$2.22 \cdot 10^{-10}$	$2.12 \cdot 10^{-10}$	$2.23 \cdot 10^{-10}$	$2.13 \cdot 10^{-10}$	$5.91 \cdot 10^{-10}$	$5.69 \cdot 10^{-10}$	$7.77 \cdot 10^{-11}$	$7.30 \cdot 10^{-11}$	$1.10 \cdot 10^{-10}$	$1.04 \cdot 10^{-10}$
AC	$7.44 \cdot 10^{-05}$	$6.78 \cdot 10^{-05}$	$7.68 \cdot 10^{-05}$	$7.02 \cdot 10^{-05}$	$4.35 \cdot 10^{-05}$	$3.80 \cdot 10^{-05}$	$1.86 \cdot 10^{-05}$	$1.39 \cdot 10^{-05}$	$6.15 \cdot 10^{-05}$	$5.53 \cdot 10^{-05}$
FE	$1.01 \cdot 10^{-06}$	$8.90 \cdot 10^{-07}$	$1.04 \cdot 10^{-06}$	$9.18 \cdot 10^{-07}$	$1.53 \cdot 10^{-06}$	$1.39 \cdot 10^{-06}$	$4.46 \cdot 10^{-07}$	$3.46 \cdot 10^{-07}$	$4.73 \cdot 10^{-07}$	$3.72 \cdot 10^{-07}$
TE	$2.74 \cdot 10^{-04}$	$2.54 \cdot 10^{-04}$	$2.80 \cdot 10^{-04}$	$2.61 \cdot 10^{-04}$	$5.80 \cdot 10^{-04}$	$5.50 \cdot 10^{-04}$	$1.35 \cdot 10^{-04}$	$1.21 \cdot 10^{-04}$	$2.00 \cdot 10^{-04}$	$1.83 \cdot 10^{-04}$
LU	0.507	0.496	0.393	0.385	0.828	0.806	$4.83 \cdot 10^{-02}$	$5.27 \cdot 10^{-02}$	0.450	0.440
WD	$8.89 \cdot 10^{-04}$	$2.28 \cdot 10^{-04}$	$8.89 \cdot 10^{-04}$	$2.28 \cdot 10^{-04}$	0.149	0.144	0.102	$9.78 \cdot 10^{-02}$	$8.67 \cdot 10^{-04}$	$2.06 \cdot 10^{-04}$
FD	$5.89 \cdot 10^{-02}$	$5.41 \cdot 10^{-02}$	$5.99 \cdot 10^{-02}$	$5.51 \cdot 10^{-02}$	$6.24 \cdot 10^{-02}$	$5.76 \cdot 10^{-02}$	$3.20 \cdot 10^{-02}$	$2.81 \cdot 10^{-02}$	$2.87 \cdot 10^{-02}$	$2.50 \cdot 10^{-02}$
BIO	20.4	19.6	15.6	15.0	39.6	38.2	1.78	1.62	26.6	25.5
SE	$1.42 \cdot 10^{-02}$	$1.37 \cdot 10^{-02}$	$1.09 \cdot 10^{-02}$	$1.05 \cdot 10^{-02}$	$1.48 \cdot 10^{-03}$	$1.42 \cdot 10^{-03}$	$6.61 \cdot 10^{-05}$	$6.04 \cdot 10^{-05}$	$7.00 \cdot 10^{-04}$	$6.74 \cdot 10^{-04}$

Annex 10: (Cont.) Environmental impacts of 7.5 g of fermentable sugar to produce 1 PLA packaging film from the different scenarios (economic allocation)

Impact category	Sc11	Sc12	Sc13	Sc14	Sc15	Sc16	Sc17	Sc18	Sc19	Sc20
CC	$6.70 \cdot 10^{-03}$	$5.25 \cdot 10^{-03}$	$3.68 \cdot 10^{-03}$	$3.62 \cdot 10^{-03}$	$2.46 \cdot 10^{-03}$	$2.57 \cdot 10^{-03}$	$2.48 \cdot 10^{-03}$	$2.32 \cdot 10^{-03}$	$2.32 \cdot 10^{-03}$	$2.41 \cdot 10^{-03}$
PM	$3.84 \cdot 10^{-10}$	$2.80 \cdot 10^{-10}$	$1.85 \cdot 10^{-10}$	$1.69 \cdot 10^{-10}$	$1.72 \cdot 10^{-10}$	$1.88 \cdot 10^{-10}$	$1.27 \cdot 10^{-10}$	$1.17 \cdot 10^{-10}$	$1.16 \cdot 10^{-10}$	$1.21 \cdot 10^{-10}$
HT	$2.02 \cdot 10^{-10}$	$3.50 \cdot 10^{-10}$	$6.43 \cdot 10^{-11}$	$7.99 \cdot 10^{-11}$	$3.25 \cdot 10^{-11}$	$3.57 \cdot 10^{-11}$	$3.20 \cdot 10^{-11}$	$2.57 \cdot 10^{-11}$	$3.24 \cdot 10^{-11}$	$3.56 \cdot 10^{-11}$
AC	$7.33 \cdot 10^{-05}$	$3.77 \cdot 10^{-05}$	$2.41 \cdot 10^{-05}$	$4.78 \cdot 10^{-05}$	$1.65 \cdot 10^{-05}$	$1.72 \cdot 10^{-05}$	$1.58 \cdot 10^{-05}$	$1.46 \cdot 10^{-05}$	$1.76 \cdot 10^{-05}$	$1.85 \cdot 10^{-05}$
FE	$1.73 \cdot 10^{-06}$	$1.80 \cdot 10^{-06}$	$1.20 \cdot 10^{-06}$	$1.21 \cdot 10^{-06}$	$8.62 \cdot 10^{-07}$	$8.78 \cdot 10^{-07}$	$8.18 \cdot 10^{-07}$	$8.00 \cdot 10^{-07}$	$8.15 \cdot 10^{-07}$	$8.22 \cdot 10^{-07}$
TE	$2.46 \cdot 10^{-04}$	$3.49 \cdot 10^{-04}$	$1.03 \cdot 10^{-04}$	$1.35 \cdot 10^{-04}$	$3.66 \cdot 10^{-05}$	$3.85 \cdot 10^{-05}$	$4.20 \cdot 10^{-05}$	$3.63 \cdot 10^{-05}$	$4.29 \cdot 10^{-05}$	$4.62 \cdot 10^{-05}$
LU	0.389	0.431	$-6.04 \cdot 10^{-03}$	0.218	$2.14 \cdot 10^{-02}$	$3.04 \cdot 10^{-02}$	$2.93 \cdot 10^{-02}$	$7.48 \cdot 10^{-03}$	$4.30 \cdot 10^{-02}$	$5.66 \cdot 10^{-02}$
WD	$9.75 \cdot 10^{-05}$	$8.36 \cdot 10^{-02}$	$6.07 \cdot 10^{-02}$	$7.78 \cdot 10^{-05}$	$5.18 \cdot 10^{-05}$	$5.18 \cdot 10^{-05}$	$5.33 \cdot 10^{-05}$	$5.23 \cdot 10^{-05}$	$5.26 \cdot 10^{-05}$	$5.27 \cdot 10^{-05}$
FD	$8.29 \cdot 10^{-02}$	$7.30 \cdot 10^{-02}$	$5.65 \cdot 10^{-02}$	$5.41 \cdot 10^{-02}$	$3.82 \cdot 10^{-02}$	$3.94 \cdot 10^{-02}$	$3.78 \cdot 10^{-02}$	$3.67 \cdot 10^{-02}$	$3.65 \cdot 10^{-02}$	$3.75 \cdot 10^{-02}$
BIO	18.3	23.9	2.68	16.7	3.65	4.11	4.61	3.38	2.97	3.29
SE	$1.27 \cdot 10^{-02}$	$8.90 \cdot 10^{-04}$	$9.99 \cdot 10^{-05}$	$1.16 \cdot 10^{-03}$	$3.54 \cdot 10^{-04}$	$3.99 \cdot 10^{-04}$	$9.06 \cdot 10^{-05}$	$6.64 \cdot 10^{-05}$	$3.44 \cdot 10^{-05}$	$3.80 \cdot 10^{-05}$

Annex 11: Environmental impacts of 7.5 g of fermentable sugar to produce 1 PLA packaging film from the different scenarios (mass allocation)

Impact category	Sc1	Sc2	Sc3	Sc4	Sc5	Sc6	Sc7	Sc8	Sc9	Sc10
CC	$5.17 \cdot 10^{-03}$	$4.80 \cdot 10^{-03}$	$6.01 \cdot 10^{-03}$	$5.61 \cdot 10^{-03}$	$4.62 \cdot 10^{-03}$	$4.27 \cdot 10^{-03}$	$2.25 \cdot 10^{-03}$	$2.00 \cdot 10^{-03}$	$2.31 \cdot 10^{-03}$	$2.05 \cdot 10^{-03}$
PM	$3.08 \cdot 10^{-10}$	$2.74 \cdot 10^{-10}$	$3.48 \cdot 10^{-10}$	$3.12 \cdot 10^{-10}$	$2.55 \cdot 10^{-10}$	$2.22 \cdot 10^{-10}$	$1.12 \cdot 10^{-10}$	$8.55 \cdot 10^{-11}$	$9.58 \cdot 10^{-11}$	$6.95 \cdot 10^{-11}$
HT	$1.97 \cdot 10^{-10}$	$1.87 \cdot 10^{-10}$	$2.26 \cdot 10^{-10}$	$2.16 \cdot 10^{-10}$	$4.82 \cdot 10^{-10}$	$4.61 \cdot 10^{-10}$	$6.45 \cdot 10^{-11}$	$6.00 \cdot 10^{-11}$	$9.49 \cdot 10^{-11}$	$8.92 \cdot 10^{-11}$
AC	$6.69 \cdot 10^{-05}$	$6.03 \cdot 10^{-05}$	$7.81 \cdot 10^{-05}$	$7.10 \cdot 10^{-05}$	$3.72 \cdot 10^{-05}$	$3.17 \cdot 10^{-05}$	$1.69 \cdot 10^{-05}$	$1.21 \cdot 10^{-05}$	$5.37 \cdot 10^{-05}$	$4.76 \cdot 10^{-05}$
FE	$9.21 \cdot 10^{-07}$	$8.01 \cdot 10^{-07}$	$1.05 \cdot 10^{-06}$	$9.29 \cdot 10^{-07}$	$1.29 \cdot 10^{-06}$	$1.16 \cdot 10^{-06}$	$4.07 \cdot 10^{-07}$	$3.06 \cdot 10^{-07}$	$4.38 \cdot 10^{-07}$	$3.36 \cdot 10^{-07}$
TE	$2.45 \cdot 10^{-04}$	$2.26 \cdot 10^{-04}$	$2.85 \cdot 10^{-04}$	$2.64 \cdot 10^{-04}$	$4.76 \cdot 10^{-04}$	$4.48 \cdot 10^{-04}$	$1.15 \cdot 10^{-04}$	$1.00 \cdot 10^{-04}$	$1.74 \cdot 10^{-04}$	$1.57 \cdot 10^{-04}$
LU	0.449	0.438	0.399	0.390	0.674	0.655	$4.04 \cdot 10^{-02}$	$4.50 \cdot 10^{-02}$	0.384	0.375
WD	$9.00 \cdot 10^{-04}$	$2.27 \cdot 10^{-04}$	$9.04 \cdot 10^{-04}$	$2.31 \cdot 10^{-04}$	0.122	0.116	$8.30 \cdot 10^{-02}$	$7.93 \cdot 10^{-02}$	$8.81 \cdot 10^{-04}$	$2.08 \cdot 10^{-04}$
FD	$5.42 \cdot 10^{-02}$	$4.93 \cdot 10^{-02}$	$6.08 \cdot 10^{-02}$	$5.58 \cdot 10^{-02}$	$5.41 \cdot 10^{-02}$	$4.92 \cdot 10^{-02}$	$2.93 \cdot 10^{-02}$	$2.54 \cdot 10^{-02}$	$2.71 \cdot 10^{-02}$	$2.33 \cdot 10^{-02}$
BIO	18.1	17.3	15.9	15.2E	32.3	31.0	1.48	1.34	22.6	21.7
SE	$1.26 \cdot 10^{-02}$	$1.21 \cdot 10^{-02}$	$1.11 \cdot 10^{-02}$	$1.06 \cdot 10^{-02}$	$1.20 \cdot 10^{-03}$	$1.15 \cdot 10^{-03}$	$5.53 \cdot 10^{-05}$	$4.97 \cdot 10^{-05}$	$5.97 \cdot 10^{-04}$	$5.72 \cdot 10^{-04}$

Annex 12: (Cont.) Environmental impacts of 7.5 g of fermentable sugar to produce 1 PLA packaging film from the different scenarios (mass allocation)

Impact category	Sc11	Sc12	Sc13	Sc14	Sc15	Sc16	Sc17	Sc18	Sc19	Sc20
CC	$1.06 \cdot 10^{-02}$	$9.71 \cdot 10^{-03}$	$5.30 \cdot 10^{-03}$	$5.21 \cdot 10^{-03}$	$9.29 \cdot 10^{-03}$	$9.74 \cdot 10^{-03}$	$6.57 \cdot 10^{-03}$	$6.85 \cdot 10^{-03}$	$7.54 \cdot 10^{-03}$	$7.89 \cdot 10^{-03}$
PM	$6.30 \cdot 10^{-10}$	$5.36 \cdot 10^{-10}$	$2.69 \cdot 10^{-10}$	$2.27 \cdot 10^{-10}$	$1.06 \cdot 10^{-09}$	$1.13 \cdot 10^{-09}$	$3.23 \cdot 10^{-10}$	$3.41 \cdot 10^{-10}$	$3.68 \cdot 10^{-10}$	$3.88 \cdot 10^{-10}$
HT	$3.83 \cdot 10^{-10}$	$9.41 \cdot 10^{-10}$	$1.41 \cdot 10^{-10}$	$1.89 \cdot 10^{-10}$	$2.27 \cdot 10^{-10}$	$2.38 \cdot 10^{-10}$	$1.23 \cdot 10^{-10}$	$1.27 \cdot 10^{-10}$	$2.26 \cdot 10^{-10}$	$2.36 \cdot 10^{-10}$
AC	$1.28 \cdot 10^{-04}$	$7.30 \cdot 10^{-05}$	$3.48 \cdot 10^{-05}$	$1.03 \cdot 10^{-04}$	$6.53 \cdot 10^{-05}$	$6.63 \cdot 10^{-05}$	$3.83 \cdot 10^{-05}$	$3.78 \cdot 10^{-05}$	$7.93 \cdot 10^{-05}$	$8.12 \cdot 10^{-05}$
FE	$2.39 \cdot 10^{-06}$	$3.13 \cdot 10^{-06}$	$1.45 \cdot 10^{-06}$	$1.48 \cdot 10^{-06}$	$2.34 \cdot 10^{-06}$	$2.34 \cdot 10^{-06}$	$1.52 \cdot 10^{-06}$	$1.47 \cdot 10^{-06}$	$1.75 \cdot 10^{-06}$	$1.71 \cdot 10^{-06}$
TE	$4.56 \cdot 10^{-04}$	$9.11 \cdot 10^{-04}$	$2.24 \cdot 10^{-04}$	$3.20 \cdot 10^{-04}$	$1.57 \cdot 10^{-04}$	$1.63 \cdot 10^{-04}$	$1.34 \cdot 10^{-04}$	$1.39 \cdot 10^{-04}$	$2.36 \cdot 10^{-04}$	$2.47 \cdot 10^{-04}$
LU	0.810	1.26	$4.01 \cdot 10^{-2}$	0.686	0.569	0.598	0.331	0.345	0.840	0.885
WD	$1.20 \cdot 10^{-04}$	0.234	0.170	$8.21 \cdot 10^{-05}$	$5.13 \cdot 10^{-05}$	$5.06 \cdot 10^{-05}$	$5.77 \cdot 10^{-05}$	$5.73 \cdot 10^{-05}$	$6.08 \cdot 10^{-05}$	$6.07 \cdot 10^{-05}$
FD	0.119	0.120	$7.36 \cdot 10^{-02}$	$6.74 \cdot 10^{-02}$	0.117	0.121	$8.80 \cdot 10^{-02}$	$9.04 \cdot 10^{-02}$	$9.59 \cdot 10^{-02}$	$9.88 \cdot 10^{-02}$
BIO	35.3	63.8	4.38	44.4	30.7	32.2	21.4	22.2	22.3	23.3
SE	$2.46 \cdot 10^{-02}$	$2.38 \cdot 10^{-03}$	$1.63 \cdot 10^{-04}$	$3.08 \cdot 10^{-03}$	$2.98 \cdot 10^{-03}$	$3.12 \cdot 10^{-03}$	$4.20 \cdot 10^{-04}$	$4.37 \cdot 10^{-04}$	$2.58 \cdot 10^{-04}$	$2.70 \cdot 10^{-04}$

Annex 13: Environmental impacts of 220 kg of fermentable sugar to produce 1 ha of mulch film from the different scenarios (economic allocation)

Impact category	Sc1	Sc2	Sc3	Sc4	Sc5	Sc6	Sc7	Sc8	Sc9	Sc10
CC	166	156	173	162	159	148	73.85	66.33	73.97	66.44
PM	$1 \cdot 10^{-05}$	$9.01 \cdot 10^{-06}$	$1 \cdot 10^{-05}$	$9.05 \cdot 10^{-06}$	$8.83 \cdot 10^{-06}$	$7.87 \cdot 10^{-06}$	$3.7 \cdot 10^{-06}$	$2.92 \cdot 10^{-06}$	$3.03 \cdot 10^{-06}$	$2.27 \cdot 10^{-06}$
HT	$6.5 \cdot 10^{-06}$	$6.22 \cdot 10^{-06}$	$6.53 \cdot 10^{-06}$	$6.25 \cdot 10^{-06}$	$1.73 \cdot 10^{-05}$	$1.67 \cdot 10^{-05}$	$2.28 \cdot 10^{-06}$	$2.14 \cdot 10^{-06}$	$3.23 \cdot 10^{-06}$	$3.06 \cdot 10^{-06}$
AC	2.18	1.98	2.25	2.05	1.27	1.11	0.54	0.40	1.80	1.62
FE	$2.96 \cdot 10^{-02}$	$2.61 \cdot 10^{-02}$	$3.04 \cdot 10^{-02}$	$2.69 \cdot 10^{-02}$	$4.49 \cdot 10^{-02}$	$4.09 \cdot 10^{-02}$	$1.31 \cdot 10^{-02}$	$1.01 \cdot 10^{-02}$	$1.39 \cdot 10^{-02}$	$1.09 \cdot 10^{-02}$
TE	8.03	7.46	8.22	7.64	17.00	16.12	3.97	3.53	5.85	5.35
LU	14,872	14,541	11,514	11,298	24,288	23,636	1,416	1,544	13,193	12,920
WD	26.08	6.68	26.07	6.67	4,382	4,214	2,989	2,868	25.43	6.05
FD	1,726	1,586	1,755	1,615	1,831	1,688	937	824	843	733
BIO	598,756	576,299	458,899	441,212	1,162,582	1,120,216	52,084	47,599	778,840	749,367
SE	416	401	319	307	43.28	41.71	1.93	1.77	20.54	19.76

Annex 14: (Cont.) Environmental impacts of 220 kg of fermentable sugar to produce 1 ha of mulch film from the different scenarios (economic allocation)

Impact category	Sc11	Sc12	Sc13	Sc14	Sc15	Sc16	Sc17	Sc18	Sc19	Sc20
CC	66.44	196	154	107	106	72.17	75.47	72.76	68.04	68.08
PM	$2.27 \cdot 10^{-06}$	$1.13 \cdot 10^{-05}$	$8.22 \cdot 10^{-06}$	$5.43 \cdot 10^{-06}$	$4.96 \cdot 10^{-06}$	$5.04 \cdot 10^{-06}$	$5.51 \cdot 10^{-06}$	$3.74 \cdot 10^{-06}$	$3.42 \cdot 10^{-06}$	$3.4 \cdot 10^{-06}$
HT	$3.06 \cdot 10^{-06}$	$5.93 \cdot 10^{-06}$	$1.03 \cdot 10^{-05}$	$1.89 \cdot 10^{-06}$	$2.34 \cdot 10^{-06}$	$9.54 \cdot 10^{-07}$	$1.05 \cdot 10^{-06}$	$9.38 \cdot 10^{-07}$	$7.54 \cdot 10^{-07}$	$9.5 \cdot 10^{-07}$
AC	1.62	2.15	1.10	0.706	1.40	0.484	0.503	0.462	0.428	0.517
FE	$5.07 \cdot 10^{-02}$	$5.29 \cdot 10^{-02}$	$3.53 \cdot 10^{-02}$	$3.55 \cdot 10^{-02}$	$2.53 \cdot 10^{-02}$	$2.58 \cdot 10^{-02}$	$2.40 \cdot 10^{-02}$	$2.35 \cdot 10^{-02}$	$2.39 \cdot 10^{-02}$	$2.41 \cdot 10^{-02}$
TE	5.35	7.22	10.22	3.02	3.95	1.07	1.12	1.23	1.06	1.25
LU	12,920	11,419	12,630	-177	6,391	626	892	859	219	1,262
WD	6.05	2.86	2,451	1,779	2.28	1.51	1.51	1.56	1.53	1.54
FD	733	2,430	2,141	1,656	1,586	1,121	1,154	1,107	1,077	1,072
BIO	749,367	537,220	701,106	78,716	488,716	107,190	120,525	135,146	99,094	87,176
SE	19.76	373	26.10	2.93	33.91	10.39	11.69	2.65	1.94	1.00

Annex 15: Environmental impacts of 220 kg of fermentable sugar to produce 1 ha of mulch film from the different scenarios (mass allocation)

Impact category	Sc1	Sc2	Sc3	Sc4	Sc5	Sc6	Sc7	Sc8	Sc9	Sc10
CC	151.61	140.83	176.37	164.66	135.37	125.20	66.10	58.54	67.86	60.24
PM	$9.04 \cdot 10^{-06}$	$8.03 \cdot 10^{-06}$	$1.02 \cdot 10^{-05}$	$9.17 \cdot 10^{-06}$	$7.47 \cdot 10^{-06}$	$6.52 \cdot 10^{-06}$	$3.3 \cdot 10^{-06}$	$2.51 \cdot 10^{-06}$	$2.81 \cdot 10^{-06}$	$2.04 \cdot 10^{-06}$
HT	$5.77 \cdot 10^{-06}$	$5.49 \cdot 10^{-06}$	$6.64 \cdot 10^{-06}$	$6.33 \cdot 10^{-06}$	$1.41 \cdot 10^{-05}$	$1.35 \cdot 10^{-05}$	$1.89 \cdot 10^{-06}$	$1.76 \cdot 10^{-06}$	$2.78 \cdot 10^{-06}$	$2.62 \cdot 10^{-06}$
AC	1.96	1.76	2.29	2.08	1.09	0.928	0.494	0.355	1.57	1.39
FE	$2.70 \cdot 10^{-02}$	$2.35 \cdot 10^{-02}$	$3.09 \cdot 10^{-02}$	$2.73 \cdot 10^{-02}$	$3.78 \cdot 10^{-02}$	$3.39 \cdot 10^{-02}$	$1.19 \cdot 10^{-02}$	$8.98 \cdot 10^{-03}$	$1.29 \cdot 10^{-02}$	$9.86 \cdot 10^{-03}$
TE	7.19	6.62	8.35	7.74	13.96	13.13	3.37	2.94	5.09	4.59
LU	13,175	12,857	11,704	11,442	19,784	19,217	1,185	1,319	11,252	11,006
WD	26.41	6.66	26.50	6.76	3,569	3,415	2,436	2,325	25.83	6.10
FD	1,589	1,447	1,784	1,635	1,585	1,443	858	744	795	683
BIO	530,129	508,092	466,470	446,832	946,604	908,188	43,549	39,164	663,655	635,701
SE	368	353	324	310	35.24	33.81	1.62	1.45	17.50	16.76

Annex 16: (Cont.) Environmental impacts of 220 kg of fermentable sugar to produce 1 ha of mulch film from the different scenarios (mass allocation)

Impact category	Sc11	Sc12	Sc13	Sc14	Sc15	Sc16	Sc17	Sc18	Sc19	Sc20
CC	311	284	155	152	272	285	192	200	221	231
PM	$1.85 \cdot 10^{-05}$	$1.57 \cdot 10^{-05}$	$7.89 \cdot 10^{-06}$	$6.65 \cdot 10^{-06}$	$3.12 \cdot 10^{-05}$	$3.31 \cdot 10^{-05}$	$9.49 \cdot 10^{-06}$	$1 \cdot 10^{-05}$	$1.08 \cdot 10^{-05}$	$1.14 \cdot 10^{-05}$
HT	$1.12 \cdot 10^{-05}$	$2.76 \cdot 10^{-05}$	$4.15 \cdot 10^{-06}$	$5.56 \cdot 10^{-06}$	$6.67 \cdot 10^{-06}$	$6.97 \cdot 10^{-06}$	$3.61 \cdot 10^{-06}$	$3.72 \cdot 10^{-06}$	$6.62 \cdot 10^{-06}$	$6.92 \cdot 10^{-06}$
AC	3.76	2.14	1.02	3.03	1.91	1.94	1.12	1.10	2.32	2.38
FE	$7.02 \cdot 10^{-02}$	$9.18 \cdot 10^{-02}$	$4.24 \cdot 10^{-02}$	$4.33 \cdot 10^{-02}$	$6.87 \cdot 10^{-02}$	$6.87 \cdot 10^{-02}$	$4.45 \cdot 10^{-02}$	$4.30 \cdot 10^{-02}$	$5.12 \cdot 10^{-02}$	$5.01 \cdot 10^{-02}$
TE	13.38	26.72	6.56	9.39	4.61	4.79	3.93	4.08	6.92	7.24
LU	2,3767	37,035	1,175	20,116	16,697	17,527	9,715	10,117	24,639	25,957
WD	3.50	6,859	4,979	2.40	1.50	1.48	1.69	1.68	1.78	1.78
FD	3,483	3,516	2,159	1,976	3,430	3,552	2,580	2,650	2,814	2,898
BIO	1,036,172	1,871,298	128,605	1,302,456	900,891	944,202	627,316	652,054	655,599	683,979
SE	721	69.67	4.78	90.39	87.38	91.59	12.33	12.81	7.57	7.90

Annex 17: Environmental impacts of 2.7 kg of fermentable sugar to produce 1 kg of PBS from the different scenarios (economic allocation)

Impact category	Sc1	Sc2	Sc3	Sc4	Sc5	Sc6	Sc7	Sc8	Sc9	Sc10
CC	2.04	1.91	2.12	1.99	1.95	1.82	0.906	0.814	0.907	0.815
PM	$1.23 \cdot 10^{-07}$	$1.11 \cdot 10^{-07}$	$1.23 \cdot 10^{-07}$	$1.11 \cdot 10^{-07}$	$1.08 \cdot 10^{-07}$	$9.66 \cdot 10^{-08}$	$4.54 \cdot 10^{-08}$	$3.58 \cdot 10^{-08}$	$3.71 \cdot 10^{-08}$	$2.78 \cdot 10^{-08}$
HT	$7.97 \cdot 10^{-08}$	$7.63 \cdot 10^{-08}$	$8.02 \cdot 10^{-07}$	$7.67 \cdot 10^{-07}$	$2.13 \cdot 10^{-07}$	$2.05 \cdot 10^{-07}$	$2.8 \cdot 10^{-08}$	$2.63 \cdot 10^{-08}$	$3.97 \cdot 10^{-08}$	$3.76 \cdot 10^{-08}$
AC	$2.68 \cdot 10^{-02}$	$2.44 \cdot 10^{-02}$	$2.77 \cdot 10^{-02}$	$2.53 \cdot 10^{-02}$	$1.57 \cdot 10^{-02}$	$1.37 \cdot 10^{-02}$	$6.69 \cdot 10^{-03}$	$5.00 \cdot 10^{-03}$	$2.21 \cdot 10^{-02}$	$1.99 \cdot 10^{-02}$
FE	$3.63 \cdot 10^{-04}$	$3.20 \cdot 10^{-04}$	$3.74 \cdot 10^{-04}$	$3.30 \cdot 10^{-04}$	$5.51 \cdot 10^{-04}$	$5.02 \cdot 10^{-04}$	$1.60 \cdot 10^{-04}$	$1.25 \cdot 10^{-04}$	$1.70 \cdot 10^{-04}$	$1.34 \cdot 10^{-04}$
TE	$9.86 \cdot 10^{-02}$	$9.16 \cdot 10^{-02}$	0.10	$9.38 \cdot 10^{-02}$	0.209	0.198	$4.87 \cdot 10^{-02}$	$4.34 \cdot 10^{-02}$	$7.18 \cdot 10^{-02}$	$6.57 \cdot 10^{-02}$
LU	182	178	141	138	298	290	17.38	18.95	161	158
WD	0.320	$8.20 \cdot 10^{-02}$	0.320	$8.19 \cdot 10^{-02}$	53.78	51.72	36.68	35.20	0.312	$7.43 \cdot 10^{-02}$
FD	21.19	19.47	21.55	19.82	22.48	20.71	11.51	10.12	10.34	9.00
BIO	7,348	7,072	5,631	5,414	14,268	13,748	639.22	584	9,558	9,196
SE	5.11	4.92	3.91	3.76	0.531	0.511	$2.38 \cdot 10^{-02}$	$2.18 \cdot 10^{-02}$	0.252	0.242

Annex 18: (Cont.) Environmental impacts of 2.7 kg of fermentable sugar to produce 1 kg of PBS from the different scenarios (economic allocation)

Impact category	Sc11	Sc12	Sc13	Sc14	Sc15	Sc16	Sc17	Sc18	Sc19	Sc20
CC	2.41	1.89	1.32	1.30	0.885	0.926	0.892	0.835	0.835	0.869
PM	$1.38 \cdot 10^{-07}$	$1.01 \cdot 10^{-07}$	$6.66 \cdot 10^{-08}$	$6.09 \cdot 10^{-08}$	$6.18 \cdot 10^{-08}$	$6.76 \cdot 10^{-08}$	$4.59 \cdot 10^{-08}$	$4.2 \cdot 10^{-08}$	$4.17 \cdot 10^{-08}$	$4.35 \cdot 10^{-08}$
HT	$7.28 \cdot 10^{-08}$	$1.26 \cdot 10^{-07}$	$2.31 \cdot 10^{-08}$	$2.88 \cdot 10^{-08}$	$1.17 \cdot 10^{-08}$	$1.29 \cdot 10^{-08}$	$1.15 \cdot 10^{-08}$	$9.25 \cdot 10^{-08}$	$1.17 \cdot 10^{-08}$	$1.28 \cdot 10^{-08}$
AC	$2.64 \cdot 10^{-02}$	$1.36 \cdot 10^{-02}$	$8.67 \cdot 10^{-03}$	$1.72 \cdot 10^{-02}$	$5.95 \cdot 10^{-03}$	$6.18 \cdot 10^{-03}$	$5.67 \cdot 10^{-03}$	$5.25 \cdot 10^{-03}$	$6.35 \cdot 10^{-03}$	$6.68 \cdot 10^{-03}$
FE	$6.23 \cdot 10^{-04}$	$6.49 \cdot 10^{-04}$	$4.33 \cdot 10^{-04}$	$4.35 \cdot 10^{-04}$	$3.10 \cdot 10^{-04}$	$3.16 \cdot 10^{-04}$	$2.94 \cdot 10^{-04}$	$2.88 \cdot 10^{-04}$	$2.93 \cdot 10^{-04}$	$2.96 \cdot 10^{-04}$
TE	$8.86 \cdot 10^{-02}$	0.125	$3.71 \cdot 10^{-02}$	$4.86 \cdot 10^{-02}$	$1.32 \cdot 10^{-02}$	$1.39 \cdot 10^{-02}$	$1.51 \cdot 10^{-02}$	$1.31 \cdot 10^{-02}$	$1.54 \cdot 10^{-02}$	$1.66 \cdot 10^{-02}$
LU	140	155	-2.17	78.44	7.69	10.95	10.54	2.69	15.49	20.36
WD	$3.51 \cdot 10^{-02}$	30.08	21.84	$2.80 \cdot 10^{-02}$	$1.87 \cdot 10^{-02}$	$1.86 \cdot 10^{-02}$	$1.92 \cdot 10^{-02}$	$1.88 \cdot 10^{-02}$	$1.89 \cdot 10^{-02}$	$1.90 \cdot 10^{-02}$
FD	29.82	26.28	20.33	19.46	13.76	14.17	13.59	13.22	13.15	13.50
BIO	6,593	8,604	966	5,997	1,315	1,479	1,658	1,216	1,069	1,184
SE	4.58	0.320	$3.60 \cdot 10^{-02}$	0.416	0.127	0.143	$3.26 \cdot 10^{-02}$	$2.39 \cdot 10^{-02}$	$1.24 \cdot 10^{-02}$	$1.37 \cdot 10^{-02}$

Annex 19: Environmental impacts of 2.7 kg of fermentable sugar to produce 1 kg of PBS from the different scenarios (mass allocation)

Impact category	Sc1	Sc2	Sc3	Sc4	Sc5	Sc6	Sc7	Sc8	Sc9	Sc10
CC	1.86	1.72	2.16	2.02	1.66	1.53	0.811	0.718	0.832	0.739
PM	$1.11 \cdot 10^{-07}$	$9.86 \cdot 10^{-08}$	$1.25 \cdot 10^{-07}$	$1.12 \cdot 10^{-07}$	$9.16 \cdot 10^{-08}$	$8 \cdot 10^{-08}$	$4.05 \cdot 10^{-08}$	$3.08 \cdot 10^{-08}$	$3.45 \cdot 10^{-08}$	$2.5 \cdot 10^{-08}$
HT	$7.08 \cdot 10^{-08}$	$6.74 \cdot 10^{-08}$	$8.15 \cdot 10^{-08}$	$7.77 \cdot 10^{-08}$	$1.73 \cdot 10^{-07}$	$1.66 \cdot 10^{-07}$	$2.32 \cdot 10^{-08}$	$2.16 \cdot 10^{-08}$	$3.41 \cdot 10^{-08}$	$3.21 \cdot 10^{-08}$
AC	$2.41 \cdot 10^{-02}$	$2.17 \cdot 10^{-02}$	$2.81 \cdot 10^{-02}$	$2.56 \cdot 10^{-02}$	$1.34 \cdot 10^{-02}$	$1.14 \cdot 10^{-02}$	$6.07 \cdot 10^{-03}$	$4.36 \cdot 10^{-03}$	$1.93 \cdot 10^{-02}$	$1.71 \cdot 10^{-02}$
FE	$3.32 \cdot 10^{-04}$	$2.88 \cdot 10^{-04}$	$3.80 \cdot 10^{-04}$	$3.35 \cdot 10^{-04}$	$4.64 \cdot 10^{-04}$	$4.16 \cdot 10^{-04}$	$1.46 \cdot 10^{-04}$	$1.10 \cdot 10^{-04}$	$1.58 \cdot 10^{-04}$	$1.21 \cdot 10^{-04}$
TE	$8.83 \cdot 10^{-02}$	$8.13 \cdot 10^{-02}$	0.103	$9.50 \cdot 10^{-02}$	0.171	0.161	$4.14 \cdot 10^{-02}$	$3.61 \cdot 10^{-02}$	$6.25 \cdot 10^{-02}$	$5.64 \cdot 10^{-02}$
LU	161	157	143	140	242	235	14.54	16.19	138	135
WD	0.324	$8.18 \cdot 10^{-02}$	0.325	$8.30 \cdot 10^{-02}$	43.80	41.92	29.89	28.54	0.317	$7.50 \cdot 10^{-02}$
FD	19.50	17.76	21.90	20.07	19.46	17.71	10.54	9.13	9.76	8.39
BIO	6,506	6,235	5,724	5,483	11,617	11,145	534	480	8,144	7,801
SE	4.52	4.34	3.98	3.81	0.432	0.415	$1.99 \cdot 10^{-02}$	$1.79 \cdot 10^{-02}$	0.214	0.205

Annex 20: (Cont.) Environmental impacts of 2.7 kg of fermentable sugar to produce 1 kg of PBS from the different scenarios (mass allocation)

Impact category	Sc11	Sc12	Sc13	Sc14	Sc15	Sc16	Sc17	Sc18	Sc19	Sc20
CC	3.82	3.49	1.90	1.87	3.34	3.50	2.36	2.46	2.71	2.83
PM	$2.27 \cdot 10^{-07}$	$1.93 \cdot 10^{-07}$	$9.69 \cdot 10^{-08}$	$8.17 \cdot 10^{-08}$	$3.83 \cdot 10^{-07}$	$4.06 \cdot 10^{-07}$	$1.16 \cdot 10^{-07}$	$1.23 \cdot 10^{-07}$	$1.32 \cdot 10^{-07}$	$1.4 \cdot 10^{-07}$
HT	$1.38 \cdot 10^{-07}$	$3.39 \cdot 10^{-07}$	$5.09 \cdot 10^{-08}$	$6.82 \cdot 10^{-08}$	$8.19 \cdot 10^{-08}$	$8.55 \cdot 10^{-08}$	$4.43 \cdot 10^{-08}$	$4.57 \cdot 10^{-08}$	$8.13 \cdot 10^{-08}$	$8.49 \cdot 10^{-08}$
AC	$4.63 \cdot 10^{-02}$	$2.63 \cdot 10^{-02}$	$1.25 \cdot 10^{-02}$	$3.72 \cdot 10^{-02}$	$2.35 \cdot 10^{-02}$	$2.39 \cdot 10^{-02}$	$1.38 \cdot 10^{-02}$	$1.36 \cdot 10^{-02}$	$2.85 \cdot 10^{-02}$	$2.92 \cdot 10^{-02}$
FE	$8.61 \cdot 10^{-04}$	$1.13 \cdot 10^{-03}$	$5.21 \cdot 10^{-04}$	$5.31 \cdot 10^{-04}$	$8.43 \cdot 10^{-04}$	$8.43 \cdot 10^{-04}$	$5.47 \cdot 10^{-04}$	$5.28 \cdot 10^{-04}$	$6.28 \cdot 10^{-04}$	$6.15 \cdot 10^{-04}$
TE	0.164	0.328	$8.06 \cdot 10^{-02}$	0.115	$5.66 \cdot 10^{-02}$	$5.88 \cdot 10^{-02}$	$4.83 \cdot 10^{-02}$	$5.01 \cdot 10^{-02}$	$8.50 \cdot 10^{-02}$	$8.90 \cdot 10^{-02}$
LU	291	454	14.42	246	204	215	119	124	302	318
WD	$4.31 \cdot 10^{-02}$	84.18	61.11	$2.96 \cdot 10^{-02}$	$1.85 \cdot 10^{-02}$	$1.82 \cdot 10^{-02}$	$2.08 \cdot 10^{-02}$	$2.06 \cdot 10^{-02}$	$2.19 \cdot 10^{-02}$	$2.18 \cdot 10^{-02}$
FD	42.74	43.15	26.50	24.25	42.10	43.60	31.67	32.53	34.53	35.57
BIO	12,716	22,965	1,578	15,984	11,056	11,587	7,698	8,002	8,045	8,394
SE	8.85	0.855	$5.88 \cdot 10^{-02}$	1.10	1.07	1.12	0.151	0.157	$9.30 \cdot 10^{-02}$	$9.70 \cdot 10^{-02}$

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

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