LCA of starch products for the European starch industry association: Summary report

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ACRONYMS

DQR	Data quality rating/ Data quality requirements
DS	dry substance
EC	European Commission
EF	Environmental Footprint
EI	environmental impact
EoL	End of life
EPD	Environmental Product Declaration
FU	functional unit
GHG	greenhouse gas
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
LCA	Life Cycle Assessment
LCDN	Life Cycle Data Network
LCI	life cycle inventory
LCIA	life cycle impact assessment
LCT	life cycle thinking
LULUC	Land use and land use change
NMVOC	non-methane volatile compounds
PCR	Product Category Rules
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules

CHAPTER 1 INTRODUCTION

In view of their mission to assure a reliable and sustainable supply of safe starch-based ingredients, Starch Europe (the European starch industry association) has published various studies on the environmental impact of the starch industry's products over the past decade. In 2012, a study with environmental profiles of a wide range of products was published, based on data collected from a significant number of starch plants across the EU in 2010. In 2015, Starch Europe published its Product Category Rules (PCRs) for the products of the starch industry. PCRs provide guidance and rules for the collection of data, for the calculations and how this information should be presented. The PCRs were based upon the developments in LCA methodology that were ongoing at that time, such as the guidelines recommended by the Commission's Product Environmental Footprint pilots. The environmental profiles of the starch industry's products were updated in accordance with these PCRs.

Recently, an update of the PCRs is performed as well as an update of the associated life cycle assessment of the starch industry's products. Both the PCRs and LCA are updated following as much as possible the most recent PEF methodology report (Zampori and Pant, 2019). This report summarizes the results of the LCA-study for a selection of the sector's products.

Starch Europe can use the results of this LCA study for the following purposes:

- to focus improvement activities on the most important impact-generating process phases;
- for communication with various stakeholders and to exchange, with national and sector initiatives, the knowledge gained;
- to anticipate future legislation regarding environment and certification (product development);
- to participate in the stakeholder consultation process of the European Commission's "Products Environmental Footprint (PEF)" initiative;
- to compose an EPD (Environmental Product Declaration), as described in ISO TR 14025 (ISO, 2006);
- to compare, where applicable, results of this LCA study with results of the previous LCA studies.

The methodology used to determine the environmental impacts of the starch products conforms to the PEF and LCA methodology as prescribed in ISO standards 14040 and 14044 (ISO, 2006). According to these ISO standards, an LCA is carried out in 4 phases:

1. Goal and scope definition of the study;
2. Life cycle data inventory (LCI);
3. Life cycle impact assessment (LCIA);
4. Interpretation.

The design of this report complies with these 4 phases of the LCA, whereby the various chapters describe each phase of the LCA.

CHAPTER 2 DEFINITION OF GOAL AND SCOPE

This LCA has been commissioned by the European Starch Industry Association, Starch Europe, and is based on the Product Category Rules for Starch Industry Products v2.1 (Starch Europe, 2021).

Data has been collected by the members of Starch Europe, which constitute more than 95% of EU starch production. This summary report presents sector-representative environmental profiles of starch industry products in the EU 27 for the year 2019.

2.1. GOAL DEFINITION

The LCA is intended to compose sector-representative environmental profiles of starch industry products to communicate to customers and other interested parties. It is also used to base the PCR document of starch industry products on.

This complete sector study aims to:

- Generate sector-representative ‘environmental profiles’ for relevant starch products;
- Communicate these environmental profiles about starch products as a sector;
- Contribute proactively, through the knowledge gained in the development of the starch sector LCA, to stakeholders and other national/sectors initiatives (e.g. the European Commission’s Single Market for Green Products Initiative).

The intended audience are Starch Europe member companies, customers and other stakeholders. Specifically for communication to stakeholders and customers, this summary report is published that summarizes the methodology and results of the study.

2.2. SCOPE DEFINITION

The scope of this LCA are products of the starch industry. All products listed in Table 1 are included in the LCA, however only a selection is reported in this document (in bold).

Table 1: Overview of products included in the scope of this LCA and their application

From wheat	Application	From maize	Application	From potatoes	Application
(Loose) Bran (as such, after grinding)	*FE*	Steep liquor	*FE, I*	**Potato proteins**	*FE*
Dry wheat feed (bran and solubles mixed, then dried) – pelletilised or not	*FE*	**Dry corn feed (steep liquor mixed with fibres, then dried)**	*FE*	Fruit juice	*FE, I*
Dry (solubilised or not) gluten	*FO, FE*	Wet corn fibres	*FE*	Concentrated fruit juice	*FE*
Wet solubilised gluten	*FO, FE*	Dry germs	*FO, FE*	**Wet pulp**	*FE*
Liquid solubles (as such, after evaporation)	*FE*	Oil	*FO*	Dry pulp (fibres)	*FE*
Wheat germs	*FO, FE, I*	Dry proteins	*FE*		
Liquid glucose (including hydrolysates, fructose and glucose syrups)					*FO, I*
Dry crystallized dextrose					*FO, FE*
Maltodextrin					*FO*
Liquid sorbitol					*FO, I*
Dry sorbitol					*FO, I*
Special polyols					*FO, I*
Native and lightly modified starches					*FO, FE, I*
Modified starch excluding dextrins (e.g. esters and ethers)					*FO, FE, I*
Dextrins					*FO, I*
Potable alcohol					*FO*
Broth (by-product from potable alcohol)					*FE*

(FO = Food, FE = Feed, I = Industrial)

The starch industry products are used in a wide range of applications, including food (e.g. drinks, sweets, soups, bread), feed (e.g. pet food, cattle feed, aquafeed) and other industries (e.g. paper, textiles, plastics, pharmaceuticals). The performance depends on the specific product and application.

The products of the starch industry fulfil multiple functions (Table 1). The functional unit should be considered as a declared unit and does not aim to quantify the performance of a product. The functional unit (FU) is defined as *"1 tonne DS (dry substance) of starch industry product delivered at the customers' entry gate".*

The life cycle stages and processes included in the system boundaries are listed in Table 2. The table also indicates which of the three situations described in the PEF method generally applies:

1. Situation 1: the process is run by the company performing the PEF study.
2. Situation 2: the process is not run by the company performing the PEF study, but the company has access to (company-)specific information.
3. Situation 3: the process is not run by the company performing the PEF study and this company does not have access to (company-)specific information.

Table 2: Life cycle stages

Life cycle stage	Short description of the processes included	Situation
Raw material acquisition and pre-processing: agriculture	The agricultural processes include soil cultivation, sowing, weed control, fertilisation, pest and pathogen control, harvest and drying (if relevant). Growing wheat, maize and potatoes requires energy, water and materials such as fertilisers, pesticides and seeds. It may also result in land transformation. Inputs of auxiliary materials lead to emissions to air, water and soil.	3

Raw material acquisition and pre-processing: transportation	Transport of raw materials from the field to the starch production plants.	2
Manufacturing	All relevant processes, starting with the reception of raw materials need to be included. Depending on the specific starch industry product, these processes may be: reception, dry cleaning, wet cleaning, rasping, steeping, degerminating, grinding/flour milling, dough, separation, sieving, dewatering, washing, refining, mixing & drying, evaporation, drying, solubilising, pressing, protein separation, conversion, hydrogenation, special polyol process, maltodextrin process, crystallisation, fermentation and distillation. These processes require energy, and often also water and auxiliary materials (caustic soda, hydrochloric acid etc.) and may produce waste and emissions to air and water. The manufacturing stage is subdivided into the processes shown in the system boundary diagrams above. This allows to allocate environmental impacts of a process only to the products coming out of this process and to better identify environmental hotspots.	1
Distribution	Transportation from the starch production facility to starch industry customers.	1 or 2

In accordance with the PCR, the following processes are excluded based on the cut-off rule: capital goods for the manufacturing processes of the starch industry, packaging of starch industry products, packaging of incoming auxiliary materials, storage at warehouses, resources and tools for logistic operations at the starch plants and process waste.

The environmental profiles are calculated according to the Environmental Footprint method (EF) and include all EF impact categories listed in Table 3.

Table 3: List of the impact categories included in the environmental profiles

EF impact category	Impact Category indicator	Unit	Characterization model
Climate change **- Climate change -biogenic** **- Climate change - land use and land use change**	Radiative forcing as Global Warming Potential (GWP100)	*kg CO_2 eq*	Baseline model of 100 years of the IPCC (based on IPCC 2013)
Ozone depletion	Ozone Depletion Potential (ODP)	*kg CFC-11 eq*	Steady-state ODPs as in (WMO 2014 + integrations)
Human toxicity, cancer	Comparative Toxic Unit for humans (CTUh)	*CTUh*	USEtox model 2.1 (Fankte et al, 2017)
Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTUh)	*CTUh*	USEtox model 2.1 (Fankte et al, 2017)
Particulate matter	Impact on human health	*disease incidence*	PM method recommended by UNEP (UNEP 2016)
Ionising radiation, human health	Human exposure efficiency relative to U^{235}	*kBq U^{235} eq*	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al, 2000)
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	*kg NMVOC eq*	LOTOS-EUROS model (Van Zelm et al, 2008) as implemented in ReCiPe 2008
Acidification	Accumulated Exceedance (AE)	*mol H+ eq*	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)

EF impact category	Impact Category indicator	Unit	Characterization model
Eutrophication, terrestrial	Accumulated Exceedance (AE)	*mol N eq*	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	*kg P eq*	EUTREND model (Struijs et al, 2009) as implemented in ReCiPe
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	*kg N eq*	EUTREND model (Struijs et al, 2009) as implemented in ReCiPe
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	*CTUe*	USEtox model 2.1 (Fankte et al, 2017)
Land use	• Soil quality index • Biotic production • Erosion resistance • Mechanical filtration • Groundwater replenishment	• *Dimensionless (pt)* • *Kg biotic production* • *kg soil* • *m3 water* • *m3 groundwater*	Soil quality index based on LANCA (Beck et al. 2010 and Bos et al. 2016)
Water use	User deprivation potential (deprivation-weighted water consumption)	*m^3 world eq*	Available WAter REmaining (AWARE) as recommended by UNEP, 2016
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	*kg Sb eq*	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002.
Resource use, fossils	Abiotic resource depletion – fossil fuels (ADP-fossil)	*MJ*	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002

CHAPTER 3 LIFE CYCLE INVENTORY ANALYSIS

3.1. HANDLING MULTI-FUNCTIONAL PROCESSES

Multi-functional processes are handled according to the prescriptions of the PCR. For the agricultural processes economic allocation has been applied, for the starch industry processes physical allocation based on dry substance mass has been applied. Mass allocation was chosen because:

- Mass allocation offers the clearest picture throughout the process tree, it relates directly to the functional unit, and is based on the best available data.
- The impact of the starch slurry process is caused mainly by energy use. As the impact of energy use for cleaning, milling, grinding, rasping,… is directly related to the mass of the process inputs, it is logical to distribute these impacts to the outputs by mass allocation.
- In theory, allocation should be done based on a physical property that is relevant to the function of the provided co-products. The physical characteristics that are relevant for the function of the different co-products differ per starch industry product and as such it is not possible to set one single characteristic which is relevant for all the different output products other than mass.

Table 4 provides the different by-products which are included in the economic allocation of wheat, maize and potatoes.

Table 4: By-products considered for the allocation of crops

Crop	By-products
Wheat	Grain Straw
Maize	Maize Stover
Potatoes	Potatoes

3.2. DATA COLLECTION

In the inventory phase all data needed to analyse the environmental impacts associated with the reference and co-products are gathered. In summary this means that all input flows (materials, energy, water, …) and all output flows (emissions, waste, ….) are described and quantified. This is done for all life cycle phases within the system boundaries.

The inventory phase is performed according to the ISO 14040 and ISO 14044 (data inventory) standards (ISO, 2006). The data inventory process is focused on the following life cycle phases:

1. Growing of maize, wheat or potatoes (agriculture);
2. Production process of starch slurry and its co-products, which is roughly subdivided in:
    a. Production of auxiliary materials and water;
    b. Production of electricity and heat;
    c. Transport steps;
    d. Emissions to water and air
3. Additional processes to produce the final reference products;
4. Distribution of finished products to starch industry customers.

The background data on **agriculture**, i.e. growing of wheat, maize and potato crops, that was used in this study was obtained from the Agri-footprint database (Agri-footprint 5 – economic allocation). Company-specific data on purchased amounts of wheat, maize and potatoes and their countries of origin were provided by Starch Europe members. This data was combined into an averaged and weighted dataset.

For **transport of raw materials** (wheat, maize and potatoes) **to the starch factories**, company-specific information on transport loads, distances and transport modes was provided by all sites. This data was combined into an averaged and weighted dataset.

For the phases that refer directly to the activities of the European Starch Association's Member companies, i.e. **production process of starch slurry and additional processes**, specific data are gathered by a selection of companies, representing 40 production sites. Per reference product, VITO converted the company-specific datasets into one aggregated dataset which is used for the analysis. Aggregation is based on a weighted average, according to the annual production volumes.

For the **distribution** of products to customer's entry gate, no company-specific information was available. Distribution is included in the LCA-study (according to the PCR) by using default values from the PEF-method in combination with Eurostat trade data. However, since the extent to which these default values reflect reality is questionable, distribution is not included in this summary report.

A Data Quality Rating (DQR) according to the PEF requirements was performed. Since this concerns a sector study including different products, the overall DQR entails different values for every product. In general the overall data quality level is shown to be "excellent" (DQR ≤ 1.5) or "very good" (1.5 < DQR ≤ 2.0).

CHAPTER 4 LIFE CYCLE IMPACT ASSESSMENT RESULTS

4.1. LCA RESULTS

Usually, the inventory process generates a long list of data, which may be difficult to interpret. The life cycle impact assessment (LCIA) relates the large number of inventory values to a smaller number of environmental themes (environmental impact categories) so that the outcome of the assessment is more convenient.

LCAs do not represent a complete picture of the environmental impacts of a system. They represent a picture of those aspects that can be quantified. Any judgments that are based on the interpretation of LCI data must bear in mind this limitation and, if necessary, obtain additional environmental information from other sources (hygienic aspects, risk assessment, etc.). The LCIA results are relative expressions and do not predict any exceeding of thresholds, safety margins or risks.

As defined in the goal and scope, the Environmental Footprint method is used to calculate the impacts for each category. This report includes both

- Individual environmental profiles for a selection of products, covering all impact categories defined in the EF method;
- Comparative environmental profiles for climate change, showing the climate change impact of all products included in the LCA.

VITO used the LCA software package “SimaPro” for performing the Life Cycle Impact Assessment (LCIA) and generating the environmental profiles of the different starch products.

4.2. INDIVIDUAL ENVIRONMENTAL PROFILES OF STARCH PRODUCTS

This paragraph discusses the individual environmental profiles of a selection of starch products. Individual environmental profiles allow to get a clear insight in those life cycle stages that contribute the most to the environmental burden of each product.

The result of the impact assessment is a table and/or figure in which the environmental themes (impact categories) are presented, describing the environmental profile of “1 tonne dry substance of reference product” (functional unit). For the environmental profile of the starch products, the cradle-to-gate cycle is subdivided into different life cycle phases (Raw material acquisition and pre-processing: agriculture and transportation, manufacturing). For the life cycle phases which occur at the Starch Europe member companies, contribution to the environmental impact is attributed to different process elements, i.e. the use of auxiliary materials, energy or water, water treatment and transportation.

4.2.1. STARCH SLURRY AND CO-PRODUCTS FROM WHEAT

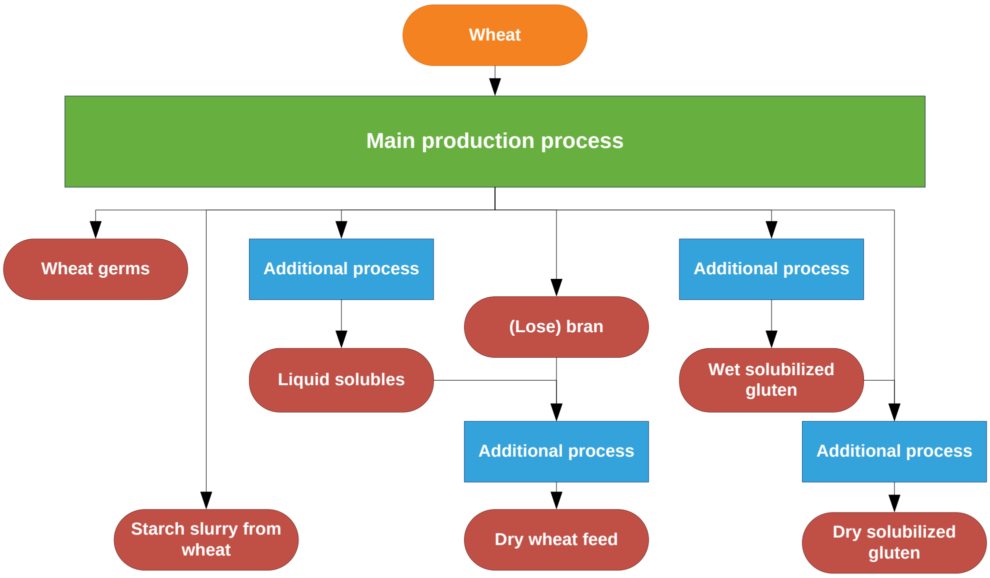


Figure 1: Simplified process chart of the production of starch slurry and co-products from wheat

During the production of starch slurry from wheat, a number of co-products is produced as well. Starch slurry is produced as a primary step in the manufacturing process of the starch products and serves as an intermediary to produce other products from. To produce some final products, i.e. liquid solubles, dry wheat feed, wet solubilised gluten and dry wheat gluten, additional process steps are required which generate additional impacts. The environmental profiles of dry wheat feed and dry (solubilized) gluten are presented below.

→ **Dry wheat feed**

To produce **dry wheat feed**, liquid solubles and wheat bran are mixed together and dried. In this process, several inputs such as energy and auxiliary materials are necessary. The environmental profile for 1 tonne DS dry wheat feed is shown in Figure 2.

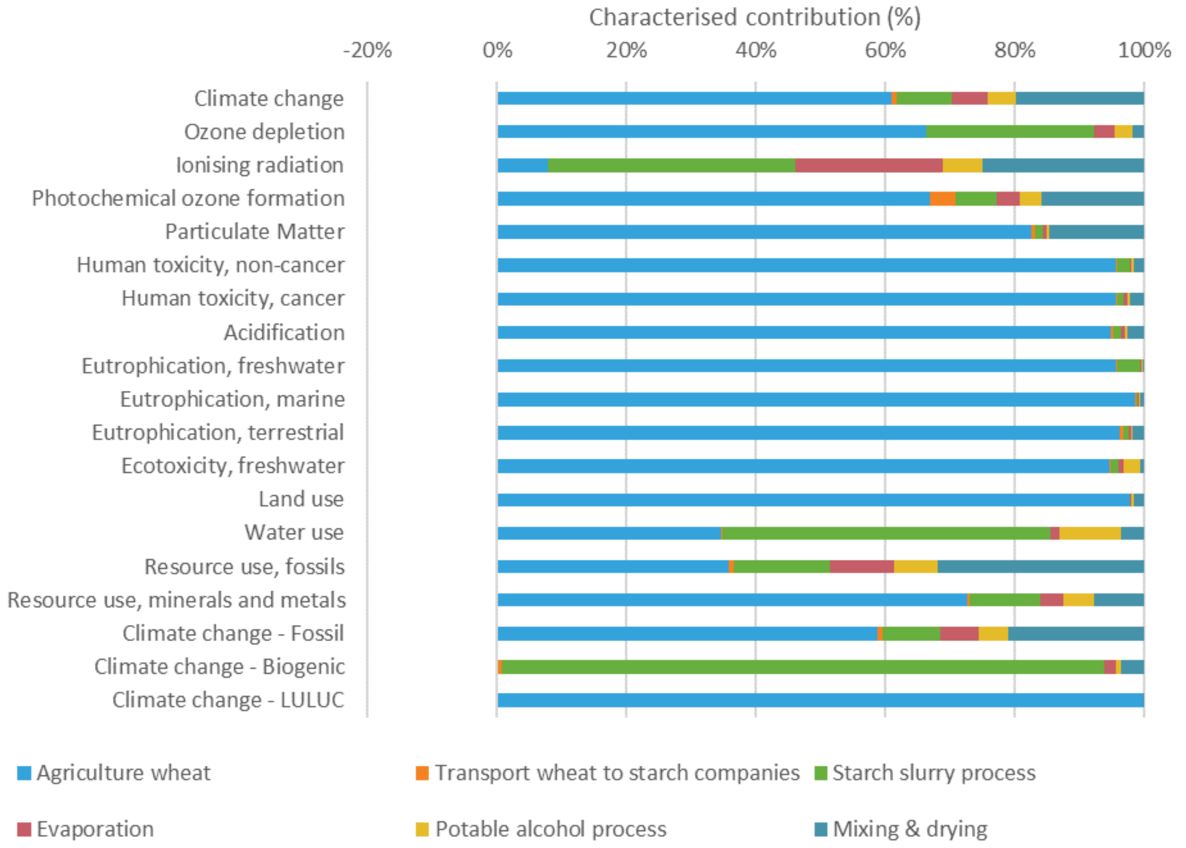


Figure 2: Environmental profile of 1 tonne DS dry wheat feed

Table 5: Characterised results per tonne DS - dry wheat feed

Characterised contribution	Unit	Total excl. distribution	Agriculture wheat	Transport wheat to starch companies	Starch slurry process	Evaporation	Potable alcohol process	Mixing & drying
Climate change	*kg CO_2 eq*	9.15E+02	5.58E+02	7.11E+00	7.90E+01	5.06E+01	3.86E+01	1.82E+02
Ozone depletion	*kg CFC11 eq*	4.04E-06	2.69E-06	2.49E-11	1.04E-06	1.31E-07	1.10E-07	7.26E-08
Ionising radiation	*kBq U-235 eq*	5.66E+01	4.46E+00	2.81E-02	2.16E+01	1.29E+01	3.41E+00	1.41E+01
Photochemical ozone formation	*kg NMVOC eq*	1.35E+00	9.02E-01	5.38E-02	8.46E-02	4.99E-02	4.58E-02	2.12E-01
Particulate Matter	*disease inc.*	7.91E-05	6.54E-05	4.46E-07	9.37E-07	3.72E-07	4.44E-07	1.15E-05
Human toxicity, non-cancer	*CTUh*	3.52E-05	3.37E-05	5.08E-08	7.01E-07	1.06E-07	1.37E-07	5.46E-07
Human toxicity, cancer	*CTUh*	8.81E-07	8.43E-07	1.04E-09	9.85E-09	4.51E-09	4.30E-09	1.84E-08
Acidification	*mol H^+ eq*	9.50E+00	9.01E+00	5.13E-02	1.05E-01	4.79E-02	5.43E-02	2.36E-01
Eutrophication, freshwater	*kg P eq*	1.42E-01	1.36E-01	4.11E-05	5.28E-03	1.27E-04	1.88E-04	3.89E-04
Eutrophication, marine	*kg N eq*	1.17E+01	1.16E+01	2.49E-02	3.05E-02	1.51E-02	1.60E-02	7.19E-02
Eutrophication, terrestrial	*mol N eq*	4.18E+01	4.02E+01	2.71E-01	2.62E-01	1.60E-01	1.58E-01	7.00E-01
Ecotoxicity, freshwater	*CTUe*	3.99E+04	3.78E+04	6.51E+01	4.59E+02	2.87E+02	1.03E+03	2.60E+02
Land use	*Pt*	8.20E+04	8.03E+04	2.69E+01	-4.98E+01	6.53E+01	2.98E+02	1.30E+03
Water use	*m^3 depriv.*	1.23E+02	4.26E+01	2.53E-01	6.23E+01	1.78E+00	1.15E+01	4.44E+00
Resource use, fossils	*MJ*	9.28E+03	3.32E+03	8.94E+01	1.36E+03	9.28E+02	6.20E+02	2.96E+03
Resource use, minerals and metals	*kg Sb eq*	1.47E-04	1.07E-04	4.32E-07	1.61E-05	5.14E-06	7.18E-06	1.13E-05
Climate change - Fossil	*kg CO_2 eq*	8.63E+02	5.07E+02	7.05E+00	7.77E+01	5.05E+01	3.86E+01	1.82E+02
Climate change - Biogenic	*kg CO_2 eq*	1.38E+00	0.00E+00	1.16E-02	1.29E+00	2.54E-02	9.27E-03	4.93E-02
Climate change - LULUC	*kg CO_2 eq*	5.10E+01	5.09E+01	4.69E-02	8.07E-03	6.27E-03	1.46E-02	6.17E-02

Tthe environmental impact of dry wheat feed production can mainly be attributed to the growing of wheat. Mixing and drying (teal bars) has relevant contributions to the impact categories that are linked to energy use; ionising radiation, fossil resources use and climate change (fossil) as well as to particulate matter which is mainly due to the release of dust particles in the mixing and drying process. Since liquid solubles are used as an input to the mixing and drying process, the impact caused by its production step (i.e. evaporation) is also visible in this graph. It should be noted that the potable alcohol process (yellow bars) also contributes to the environmental impact of dry wheat feed, since broth – a by-product from alcohol production – can be used as an input. Its relative contribution to the impact of dry wheat feed is rather small for all categories, however.

→ Dry wheat gluten

Dry wheat gluten, is produced by drying the wet solubilized gluten and dewatered gluten (output of starch slurry process). This drying step mostly requires energy as an input: electricity, heat as well as natural gas for direct dryers.

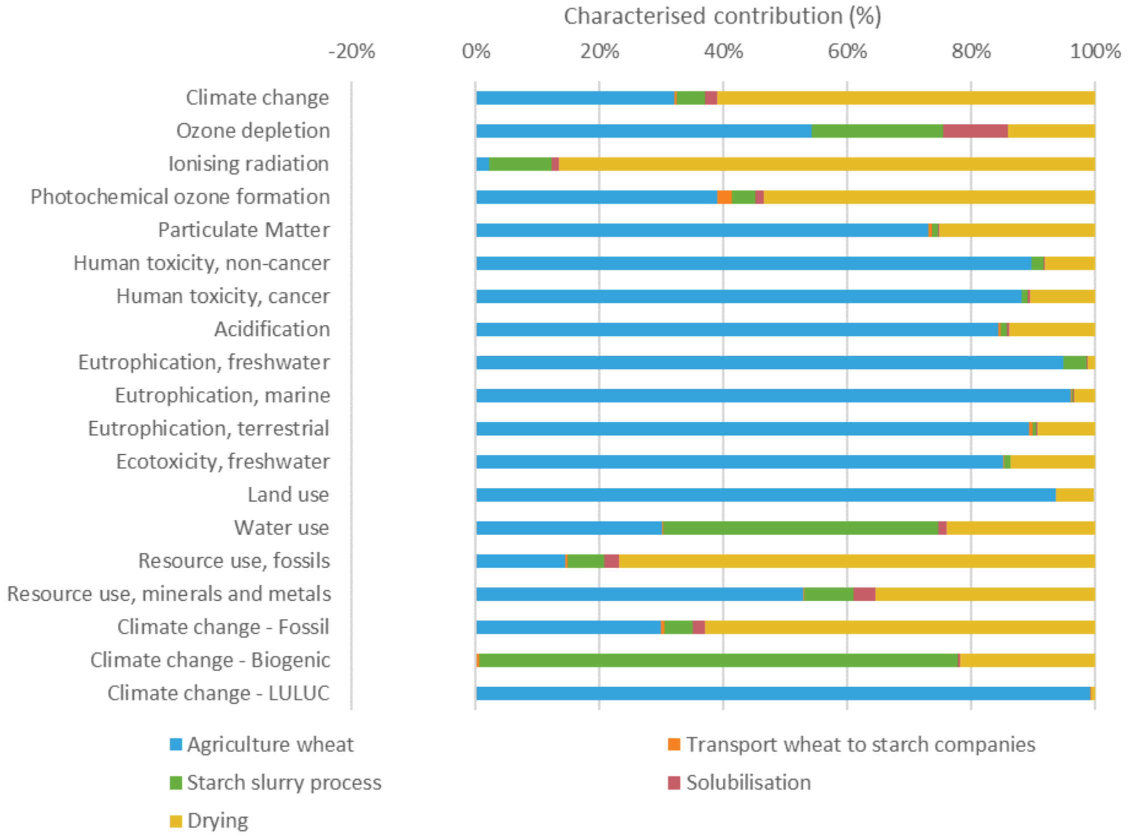


Figure 3: Environmental profile of 1 tonne DS dry wheat gluten

Table 6: Characterised results per tonne DS - dry wheat gluten

Characterised contribution	Unit	Total excl. distribution	Agriculture wheat	Transport wheat to starch companies	Starch slurry process	Solubilisation	Drying
Climate change	*kg CO_2 eq*	1.7E+03	5.4E+02	6.8E+00	7.6E+01	3.4E+01	1.0E+03
Ozone depletion	*kg CFC11 eq*	4.7E-06	2.6E-06	2.4E-11	1.0E-06	5.0E-07	6.7E-07
Ionising radiation	*kBq U-235 eq*	2.0E+02	4.3E+00	2.7E-02	2.1E+01	2.4E+00	1.8E+02
Photochemical ozone formation	*kg NMVOC eq*	2.2E+00	8.7E-01	5.2E-02	8.1E-02	3.1E-02	1.2E+00
Particulate Matter	*disease inc.*	8.6E-05	6.3E-05	4.3E-07	9.0E-07	2.6E-07	2.2E-05

Human toxicity, non-cancer	*CTUh*	3.6E-05	3.2E-05	4.9E-08	6.7E-07	6.9E-08	2.9E-06
Human toxicity, cancer	*CTUh*	9.2E-07	8.1E-07	1.0E-09	9.5E-09	3.2E-09	9.6E-08
Acidification	*mol H^+ eq*	1.0E+01	8.6E+00	4.9E-02	1.0E-01	3.2E-02	1.4E+00
Eutrophication, freshwater	*kg P eq*	1.4E-01	1.3E-01	3.9E-05	5.1E-03	2.4E-04	1.6E-03
Eutrophication, marine	*kg N eq*	1.2E+01	1.1E+01	2.4E-02	2.9E-02	8.7E-03	4.0E-01
Eutrophication, terrestrial	*mol N eq*	4.3E+01	3.9E+01	2.6E-01	2.5E-01	9.5E-02	4.0E+00
Ecotoxicity, freshwater	*CTUe*	4.3E+04	3.6E+04	6.3E+01	4.4E+02	3.4E+01	5.8E+03
Land use	*Pt*	8.2E+04	7.7E+04	2.6E+01	-4.8E+01	-3.8E+01	5.0E+03
Water use	*m^3 depriv.*	1.4E+02	4.1E+01	2.4E-01	6.0E+01	1.9E+00	3.3E+01
Resource use, fossils	*MJ*	2.2E+04	3.2E+03	8.6E+01	1.3E+03	5.5E+02	1.7E+04
Resource use, minerals and metals	*kg Sb eq*	1.9E-04	1.0E-04	4.2E-07	1.5E-05	7.0E-06	6.9E-05
Climate change - Fossil	*kg CO_2 eq*	1.6E+03	4.9E+02	6.8E+00	7.5E+01	3.4E+01	1.0E+03
Climate change - Biogenic	*kg CO_2 eq*	1.6E+00	0.0E+00	1.1E-02	1.2E+00	5.6E-03	3.5E-01
Climate change - LULUC	*kg CO_2 eq*	4.9E+01	4.9E+01	4.5E-02	7.7E-03	2.2E-03	2.9E-01

The environmental profile of dry wheat gluten again shows a significant contribution of the agricultural phase to most of the impact categories. For some impact categories (e.g. climate change, ionizing radiation, water and resource use) however, the starch plant production processes (starch slurry process, drying and solubilization) account for a very important contribution as well. Especially for the energy-related impact categories (climate change, ionizing radiation and fossil resources use), the contribution of the drying process (yellow bars) is very important. It is clear from the profile that this contribution is mainly caused by the large need for electricity and heat (including the use of gas in direct dryers) in starch slurry production, wet solubilized gluten production (solubilization) and the dry wheat feed production (drying).

4.2.2. STARCH SLURRY AND CO-PRODUCTS FROM MAIZE

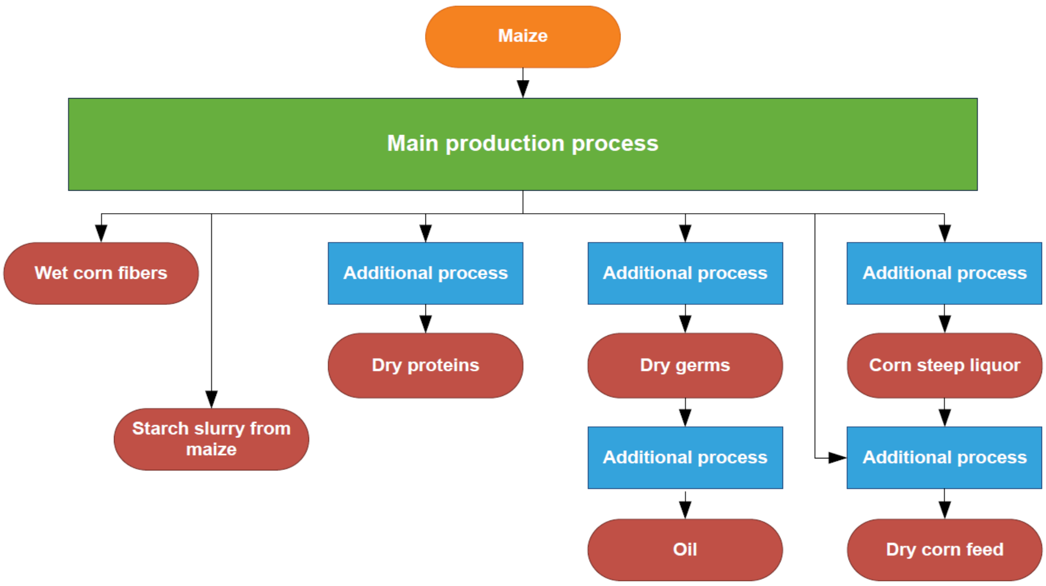


Figure 4: Simplified process chart of the production of starch slurry and co-products from maize

During maize starch slurry production, a number of relevant co-products is produced. Starch slurry and wet corn fibers are outputs of the main process step and therefore have the same impact per tonne dry substance of each product. Maize starch slurry is an intermediary product to produce 'more complex' products such as dry proteins, dry germs, oil, corn steep liquor and dry corn feed. To this end, the starch slurry production is followed by some additional process steps which in turn generate additional environmental impacts. The environmental profile of dry corn feed is reported below.

→ Dry corn feed

Dry corn feed is produced by drying corn steep liquor (output of evaporation) and dewatered fibers (output of starch slurry process). The additional fibre drying step mostly requires input of energy (electricity, heat and natural gas). The environmental profile for dry corn feed is shown in Figure 5.

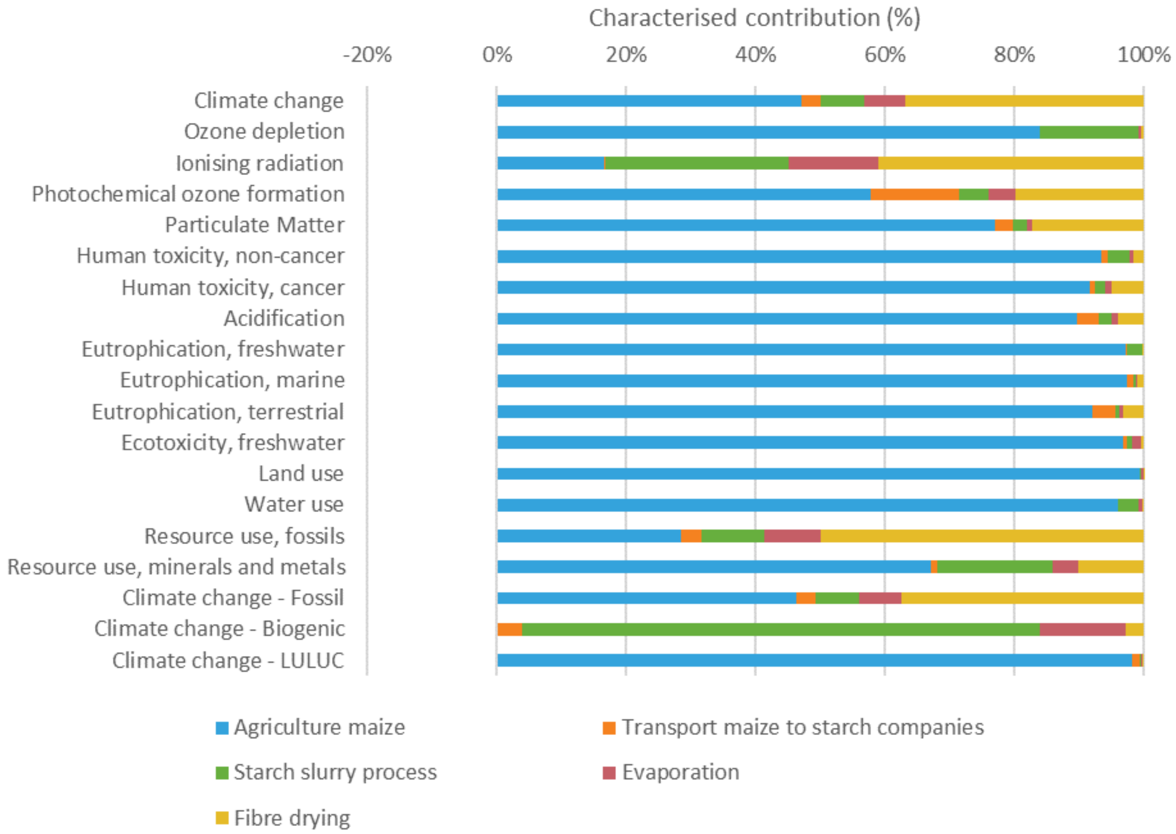


Figure 5: Environmental profile of 1 tonne DS dry corn feed

Table 7: Characterised results per tonne DS - dry corn feed

Characterised contribution	Unit	Total excl. distribution	Agriculture maize	Transport maize to starch companies	Starch slurry process	Evaporation	Fibre drying
Climate change	*kg CO_2 eq*	1.0E+03	4.9E+02	3.1E+01	7.0E+01	6.7E+01	3.8E+02
Ozone depletion	*kg CFC11 eq*	6.7E-06	5.6E-06	1.1E-10	1.0E-06	2.7E-08	2.2E-08
Ionising radiation	*kBq U-235 eq*	5.5E+01	9.1E+00	1.2E-01	1.5E+01	7.5E+00	2.2E+01
Photochemical ozone formation	*kg NMVOC eq*	1.7E+00	1.0E+00	2.4E-01	8.0E-02	7.1E-02	3.5E-01
Particulate Matter	*disease inc.*	7.0E-05	5.4E-05	1.9E-06	1.5E-06	5.6E-07	1.2E-05
Human toxicity, non-cancer	*CTUh*	1.9E-05	1.7E-05	2.2E-07	6.0E-07	1.3E-07	2.8E-07
Human toxicity, cancer	*CTUh*	6.2E-07	5.6E-07	4.8E-09	9.9E-09	6.5E-09	3.0E-08
Acidification	*mol H^+ eq*	8.0E+00	7.2E+00	2.7E-01	1.5E-01	7.0E-02	3.2E-01
Eutrophication, freshwater	*kg P eq*	1.7E-01	1.6E-01	1.7E-04	4.0E-03	1.7E-04	1.5E-04
Eutrophication, marine	*kg N eq*	9.8E+00	9.6E+00	1.1E-01	2.6E-02	2.3E-02	9.5E-02

Eutrophication, terrestrial	*mol N eq*	3.4E+01	3.2E+01	1.2E+00	2.3E-01	2.3E-01	1.1E+00
Ecotoxicity, freshwater	*CTUe*	6.9E+04	6.7E+04	3.0E+02	6.4E+02	8.9E+02	2.8E+02
Land use	*Pt*	7.8E+04	7.7E+04	1.1E+02	5.5E+01	3.1E+02	2.4E+01
Water use	*m^3 depriv.*	2.8E+03	2.7E+03	1.1E+00	8.6E+01	1.5E+01	6.4E+00
Resource use, fossils	*MJ*	1.3E+04	3.6E+03	4.1E+02	1.2E+03	1.1E+03	6.3E+03
Resource use, minerals and metals	*kg Sb eq*	1.9E-04	1.3E-04	2.0E-06	3.4E-05	7.4E-06	1.9E-05
Climate change - Fossil	*kg CO_2 eq*	1.0E+03	4.7E+02	3.0E+01	6.9E+01	6.6E+01	3.8E+02
Climate change - Biogenic	*kg CO_2 eq*	1.2E+00	0.0E+00	4.9E-02	9.8E-01	1.6E-01	3.4E-02
Climate change - LULUC	*kg CO_2 eq*	1.7E+01	1.7E+01	2.0E-01	2.2E-02	6.0E-02	1.5E-02

For most impact categories, maize cultivation is the largest contributor. However, the energy-related impact categories (ionizing radiation, fossil resource use and climate change due to fossil and biogenic emissions) are mainly affected by starch plant processes. The environmental profile also shows that fibre drying generally accounts for a larger impact compared to evaporation and the maize starch slurry process. The impact generated by fibre drying is caused by the use of electricity and heat, covering almost the entire impact. Exceptions exist for freshwater eutrophication (auxiliary materials as main contributor) and particulate matter (caused by dust emissions).

4.2.3. STARCH SLURRY AND CO-PRODUCTS FROM POTATOES

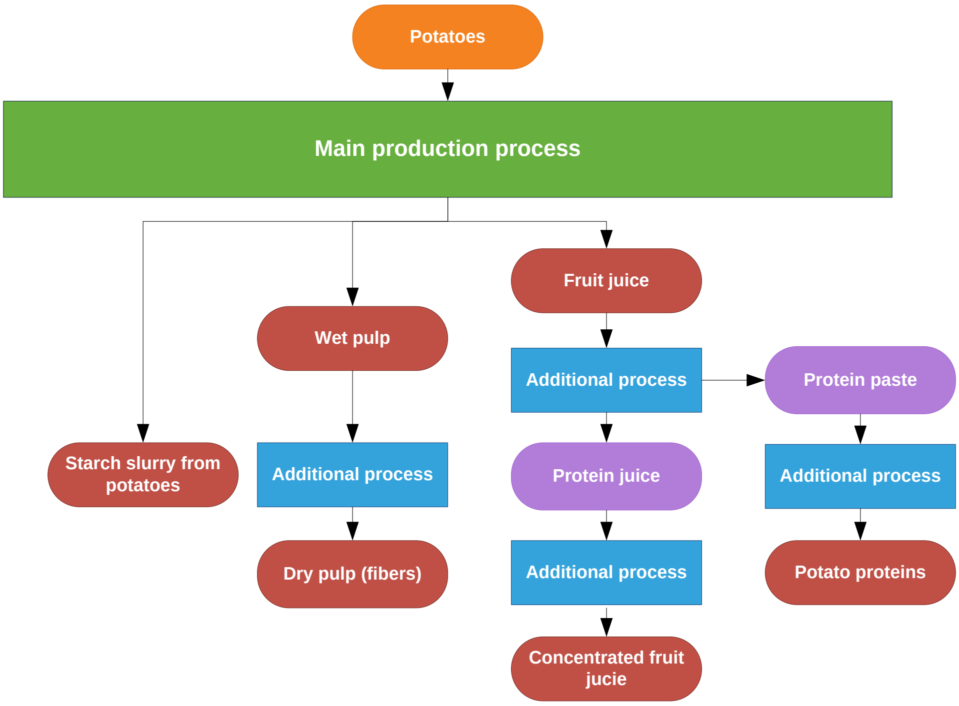


Figure 6: Simplified process chart of the production of starch slurry and co-products from potatoes

Also during the production of potato starch slurry, a number of relevant co-products is produced as well. Starch slurry, wet pulp and fruit juice are outputs of the main process, which are all intermediary products. However, part of the wet pulp and fruit juice is sold as such. To produce concentrated fruit juice, dry pulp and potato proteins, one or more additional process steps are needed after the starch slurry process, which in turn generate additional environmental impacts.

→ Wet pulp

The environmental profile of 1 tonne DS **wet pulp** is shown in Figure 7.

The environmental profile shows that cultivation of the potato crop is the largest contributor for all impact categories except ionising radiation and climate change due to biogenic emissions. For these categories the main production process is the major contributor to the impact (over 90%). There is a small environmental benefit of the main process on water use. This is a result of treatment of generated waste water during the main process; more specifically it may be the result of avoided fertiliser production (sludge contains nutrients and can therefore be applied on the fields replacing other fertiliser and as such avoiding its production). Potato transport to the starch production factories has a rather small impact (max. 10%).

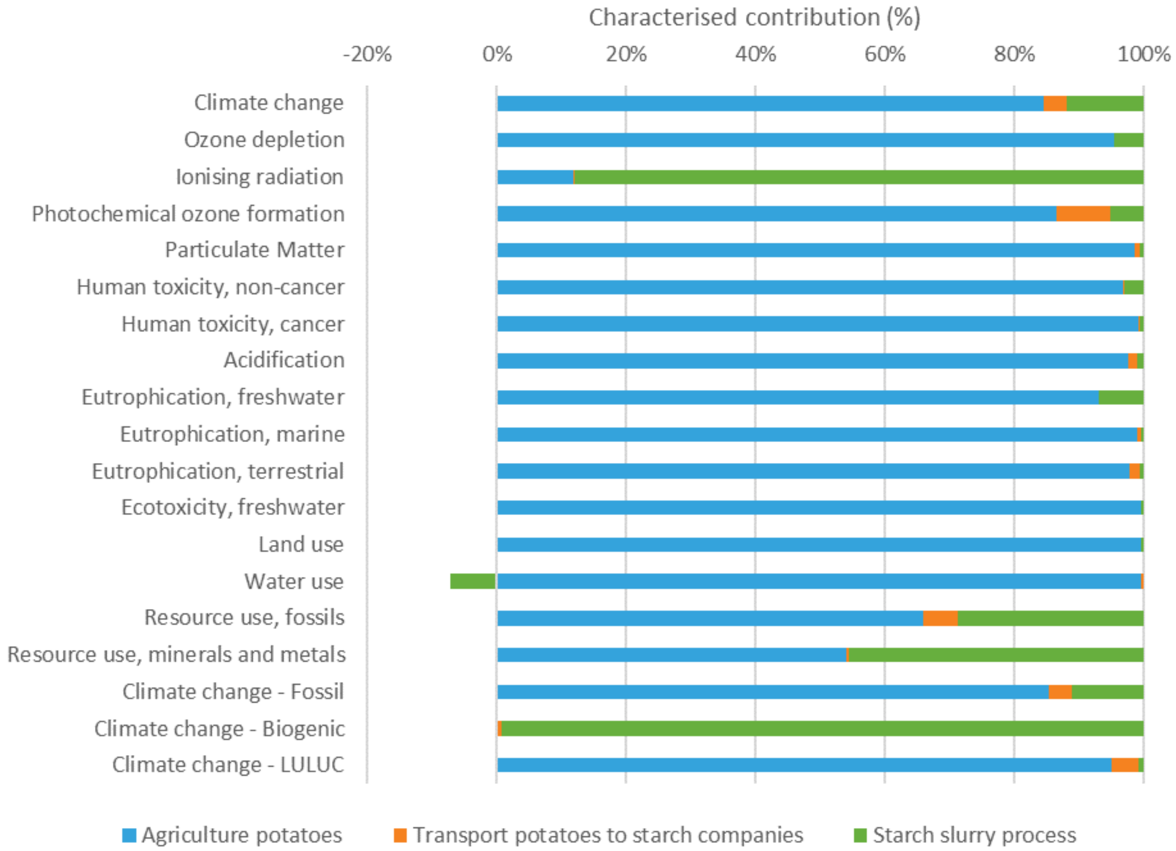


Figure 7: Environmental profile of 1 tonne DS wet pulp

Table 8: Characterised results per tonne DS – wet pulp

Characterised contribution	Unit	Total excl. distribution	Agriculture potatoes	Transport potatoes to starch companies	Starch slurry process
Climate change	*kg CO_2 eq*	4.7E+02	4.0E+02	1.7E+01	5.6E+01
Ozone depletion	*kg CFC11 eq*	4.4E-06	4.2E-06	6.5E-11	2.0E-07
Ionising radiation	*kBq U-235 eq*	5.7E+01	6.8E+00	7.3E-02	5.0E+01
Photochemical ozone formation	*kg NMVOC eq*	1.2E+00	1.1E+00	1.0E-01	6.4E-02
Particulate Matter	*disease inc.*	6.0E-05	6.0E-05	4.2E-07	3.7E-07
Human toxicity, non-cancer	*CTUh*	6.1E-05	5.9E-05	1.2E-07	1.8E-06
Human toxicity, cancer	*CTUh*	1.7E-06	1.7E-06	2.7E-09	1.1E-08
Acidification	*mol H^+ eq*	8.1E+00	7.9E+00	1.1E-01	7.3E-02

Eutrophication, freshwater	*kg P eq*	2.3E-01	2.2E-01	1.1E-04	1.6E-02
Eutrophication, marine	*kg N eq*	8.7E+00	8.6E+00	5.3E-02	3.7E-02
Eutrophication, terrestrial	*mol N eq*	3.6E+01	3.5E+01	5.8E-01	1.8E-01
Ecotoxicity, freshwater	*CTUe*	3.2E+05	3.2E+05	1.7E+02	1.2E+03
Land use	*Pt*	5.3E+04	5.3E+04	7.0E+01	1.8E+02
Water use	*m^3 depriv.*	1.7E+02	1.8E+02	6.6E-01	-1.3E+01
Resource use, fossils	*MJ*	4.4E+03	2.9E+03	2.3E+02	1.2E+03
Resource use, minerals and metals	*kg Sb eq*	2.4E-04	1.3E-04	1.1E-06	1.1E-04
Climate change - Fossil	*kg CO_2 eq*	4.7E+02	4.0E+02	1.7E+01	5.2E+01
Climate change - Biogenic	*kg CO_2 eq*	4.0E+00	0.0E+00	3.0E-02	4.0E+00
Climate change - LULUC	*kg CO_2 eq*	2.9E+00	2.8E+00	1.2E-01	2.5E-02

→ **Potato proteins**

The production of **potato proteins** requires two additional process steps after the main starch slurry process; protein separation and protein paste drying. These two processes result in additional impacts, generated on top of the impact caused by the starch slurry process. The additional processes require input of energy, water and auxiliary materials. The environmental profile of 1 tonne DS potato proteins is shown in Figure 8.

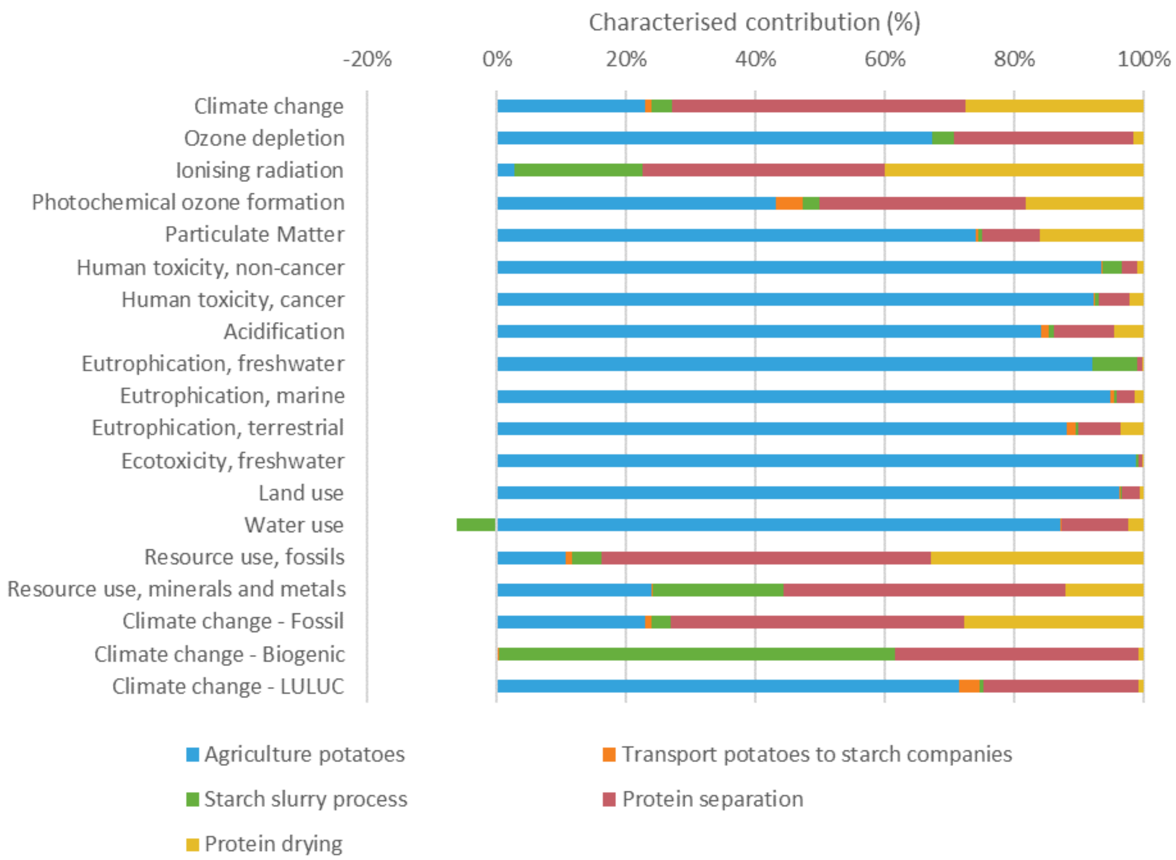


Figure 8: Environmental profile of 1 tonne DS potato proteins

Table 9: Characterised results per tonne DS - potato proteins

Characterised contribution	Unit	Total excl. distribution	Agriculture potatoes	Transport potatoes to starch	Starch slurry process	Protein seperation	Protein drying
Climate change	*kg CO_2 eq*	1.7E+03	4.0E+02	1.7E+01	5.6E+01	7.9E+02	4.8E+02
Ozone depletion	*kg CFC11 eq*	6.2E-06	4.2E-06	6.4E-11	2.0E-07	1.7E-06	9.9E-08
Ionising radiation	*kBq U-235 eq*	2.5E+02	6.8E+00	7.3E-02	5.0E+01	9.4E+01	1.0E+02
Photochemical ozone formation	*kg NMVOC eq*	2.5E+00	1.1E+00	1.0E-01	6.4E-02	7.9E-01	4.5E-01
Particulate Matter	*disease inc.*	8.1E-05	6.0E-05	4.2E-07	3.7E-07	7.2E-06	1.3E-05
Human toxicity, non-cancer	*CTUh*	6.3E-05	5.9E-05	1.2E-07	1.8E-06	1.5E-06	6.3E-07
Human toxicity, cancer	*CTUh*	1.8E-06	1.7E-06	2.7E-09	1.1E-08	8.6E-08	4.0E-08
Acidification	*mol H^+ eq*	9.4E+00	7.9E+00	1.1E-01	7.3E-02	8.8E-01	4.2E-01
Eutrophication, freshwater	*kg P eq*	2.3E-01	2.1E-01	1.1E-04	1.6E-02	2.2E-03	2.4E-04
Eutrophication, marine	*kg N eq*	9.1E+00	8.6E+00	5.3E-02	3.7E-02	2.5E-01	1.3E-01
Eutrophication, terrestrial	*mol N eq*	4.0E+01	3.5E+01	5.8E-01	1.8E-01	2.6E+00	1.4E+00
Ecotoxicity, freshwater	CTUe	3.2E+05	3.2E+05	1.7E+02	1.2E+03	1.8E+03	8.4E+02
Land use	Pt	5.5E+04	5.3E+04	7.0E+01	1.8E+02	1.5E+03	3.3E+02
Water use	m3 depriv.	2.0E+02	1.8E+02	6.6E-01	-1.3E+01	2.1E+01	5.2E+00
Resource use, fossils	MJ	2.7E+04	2.9E+03	2.3E+02	1.2E+03	1.4E+04	8.8E+03
Resource use, minerals and metals	kg Sb eq	5.4E-04	1.3E-04	1.1E-06	1.1E-04	2.3E-04	6.5E-05
Climate change - Fossil	*kg CO_2 eq*	1.7E+03	4.0E+02	1.7E+01	5.2E+01	7.9E+02	4.8E+02
Climate change - Biogenic	*kg CO_2 eq*	6.5E+00	0.0E+00	3.0E-02	4.0E+00	2.4E+00	5.4E-02
Climate change - LULUC	*kg CO_2 eq*	3.9E+00	2.8E+00	1.2E-01	2.5E-02	9.3E-01	3.1E-02

The impact of potato growing is the largest contributor to most of the environmental impact categories, such as e.g. human toxicity, eutrophication, land use and water use. For all categories except ionizing radiation and particulate matter, the impact of protein separation is higher than that of protein drying. Protein separation is also a more important contributor than the potato starch slurry process to all categories except climate change due to biogenic emissions and freshwater eutrophication. The starch slurry process has an environmental benefit on water use (only), which can be attributed to waste water treatment.

The impact of protein separation is related to the use of electricity and heat, and to a lesser extent to the use of auxiliary materials.
The impact of the drying process also results from electricity and heat consumption.

4.2.4. Liquid glucose, sorbitols and polyols, maltodextrins and dextrose

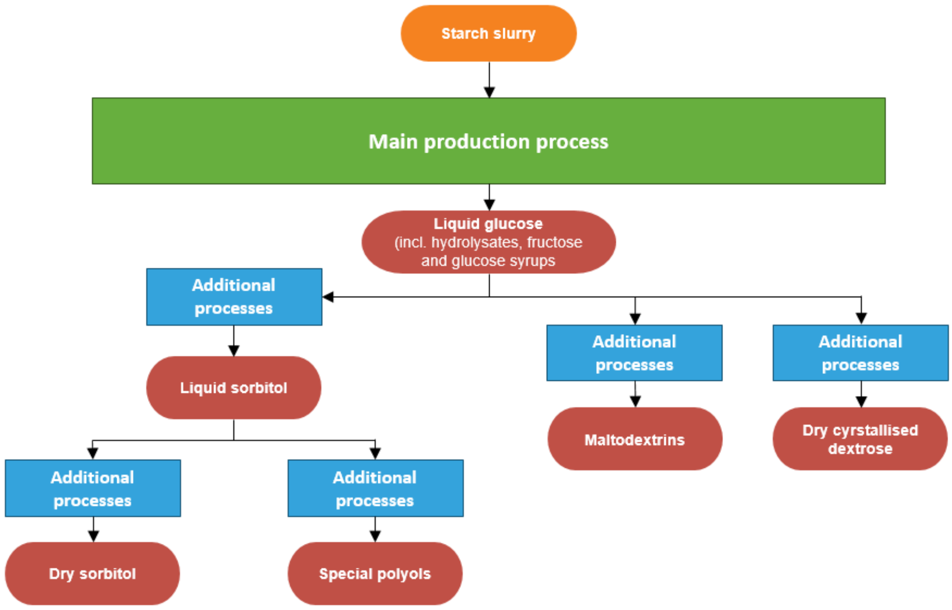


Figure 9: Simplified process chart of liquid glucose, liquid/dry sorbitol, special polyols, maltodextrins and dry crystallised dextrose production

For the production of liquid glucose[1], the input of starch slurry is required. In the EU liquid glucose is derived almost exclusively from wheat and maize starch slurry. In this study, the composition of the input starch slurry is a weighted average calculated from reported amounts by the member companies

A number of final products can be produced from liquid glucose through one or more additional process steps (in turn generating additional environmental impact). Therefore the total environmental impact of final liquid glucose products will consist of:

- the impact related to the agricultural phase;
- the impact related to the starch slurry process;
- the impact related to the liquid glucose production process;
- the impact related to the additional processes, yielding the other final products.

The environmental profiles reported here are all based on a weighted average starch slurry mixture as an input.

→ Liquid glucose

For the production of **liquid glucose**, inputs of water, electricity and heat (including natural gas) and auxiliary materials are required. Outputs are under the form of emissions to water. Even though liquid glucose is an intermediate product, it is also sold as such. The environmental profile for 1 tonne DS liquid glucose is shown in Figure 10.

[1] Note that 'liquid glucose' refers to liquid glucose, hydrolysates, fructose and glycose syrups, which are all outputs of the liquid glucose process. For simplicity, only liquid glucose is mentioned in the report.

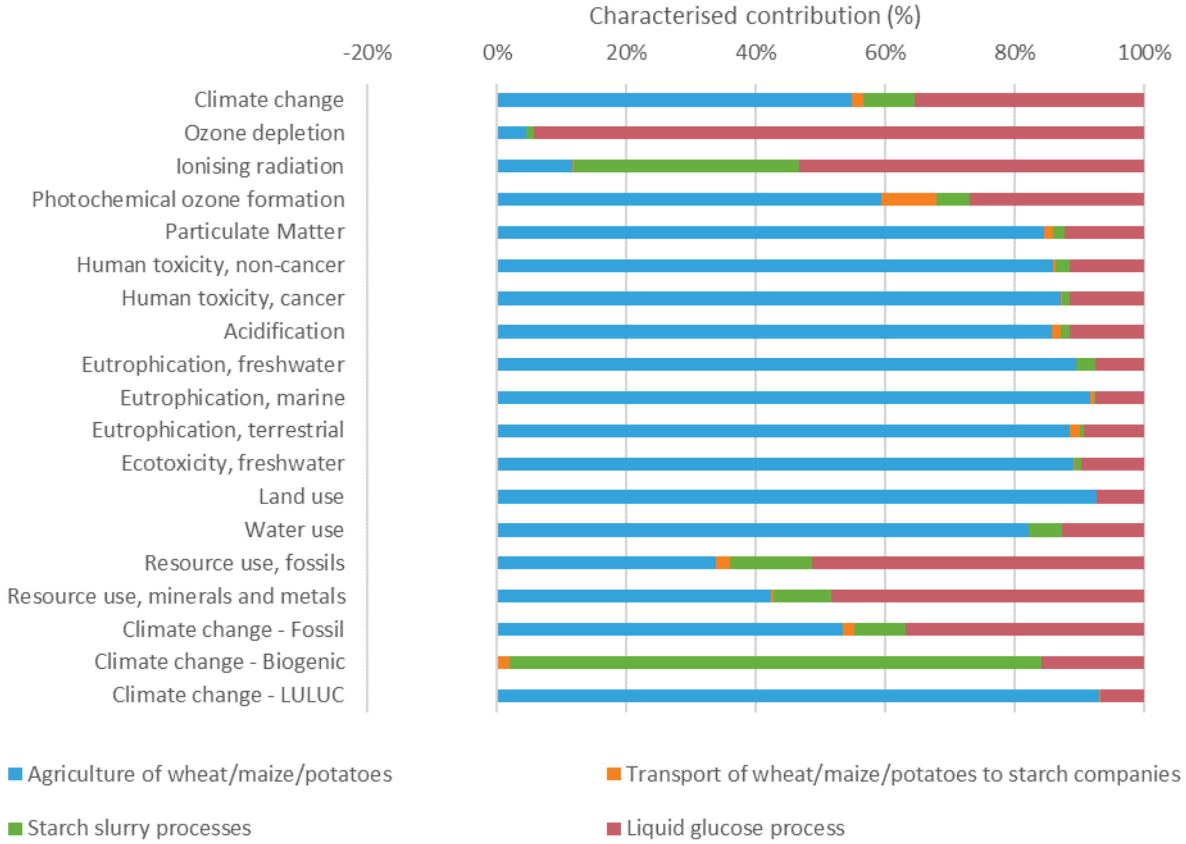


Figure 10: Environmental profile of 1 tonne DS liquid glucose

Table 10: Characterised results per tonne DS – liquid glucose

Characterised contribution	Unit	Total excl. distribution	Agriculture of wheat/maize/potatoes	Transport of wheat/maize/potatoes to starch companies	Starch slurry processes	Glucose process
Climate change	*kg CO_2 eq*	8.5E+02	4.6E+02	1.5E+01	6.6E+01	3.0E+02
Ozone depletion	*kg CFC11 eq*	7.7E-05	3.5E-06	5.4E-11	9.0E-07	7.3E-05
Ionising radiation	*kBq U-235 eq*	4.8E+01	5.7E+00	6.0E-02	1.7E+01	2.6E+01
Photochemical ozone formation	*kg NMVOC eq*	1.4E+00	8.3E-01	1.2E-01	7.2E-02	3.8E-01
Particulate Matter	*disease inc.*	6.3E-05	5.3E-05	9.3E-07	1.0E-06	7.7E-06
Human toxicity, non-cancer	*CTUh*	2.7E-05	2.4E-05	1.1E-07	5.8E-07	3.2E-06
Human toxicity, cancer	*CTUh*	7.4E-07	6.4E-07	2.3E-09	8.7E-09	8.4E-08
Acidification	*mol H^+ eq*	8.4E+00	7.2E+00	1.3E-01	1.1E-01	9.7E-01
Eutrophication, freshwater	*kg P eq*	1.4E-01	1.3E-01	8.7E-05	4.2E-03	1.1E-02
Eutrophication, marine	*kg N eq*	1.0E+01	9.4E+00	5.5E-02	2.5E-02	7.7E-01
Eutrophication, terrestrial	*mol N eq*	3.6E+01	3.2E+01	6.0E-01	2.2E-01	3.4E+00
Ecotoxicity, freshwater	*CTUe*	5.1E+04	4.6E+04	1.5E+02	4.7E+02	5.0E+03
Land use	*Pt*	7.5E+04	6.9E+04	5.7E+01	-3.3E+00	5.4E+03
Water use	*m^3 depriv.*	1.2E+03	1.0E+03	5.4E-01	6.3E+01	1.6E+02
Resource use, fossils	*MJ*	8.9E+03	3.0E+03	2.0E+02	1.1E+03	4.6E+03
Resource use, minerals and metals	*kg Sb eq*	2.4E-04	1.0E-04	9.6E-07	2.1E-05	1.2E-04

Climate change - Fossil	*kg CO_2 eq*	8.1E+02	4.3E+02	1.5E+01	6.5E+01	3.0E+02
Climate change - Biogenic	*kg CO_2 eq*	1.2E+00	0.0E+00	2.4E-02	1.0E+00	2.0E-01
Climate change - LULUC	*kg CO_2 eq*	3.4E+01	3.2E+01	9.9E-02	1.2E-02	2.3E+00

The environmental profile of liquid glucose reveals that the agricultural life cycle phase (i.e. wheat, maize cultivation) still contributes importantly to many impact categories. It is the major contributor to climate change (fossil and land use and land use change), human toxicity, acidification, particulate matter, eutrophication, ecotoxicity, land use, water use. The liquid glucose process account for a relevant contribution to the impact categories climate change (biogenic), ionizing radiation, resource use (fossil and minerals and metals). The environmental profile also shows that the contribution of the liquid glucose process is higher (factor 4 and higher, for many categories) than that of the starch slurry process for every impact category, except climate change (biogenic). In the latter case, waste water treatment of the starch slurry process water is largely responsible for the impact. Transport of wheat and maize to the factories overall has a small contribution to the environmental impact of liquid glucose.

Auxiliary materials used for the liquid glucose process contribute largely to many impact categories. The production of, for instance, hydrochloric acid and sodium hydroxide is responsible for this contribution. Depending on the impact category, also electricity and heat consumption (combined) contribute largely to the impact.

→ **Dry crystallised dextrose**

The production of **dry crystallised dextrose**, requires crystallisation and subsequent drying[2] of liquid glucose. The crystallisation and drying process require inputs from water, energy and, to a lesser extent, auxiliary materials. These processes therefore generate impacts on top of the impacts from agriculture, starch slurry production and liquid glucose production to make up the total environmental impact of 1 tonne DS dry crystallised dextrose (see Figure 11).

[2] Crystallization and drying are treated as one process.

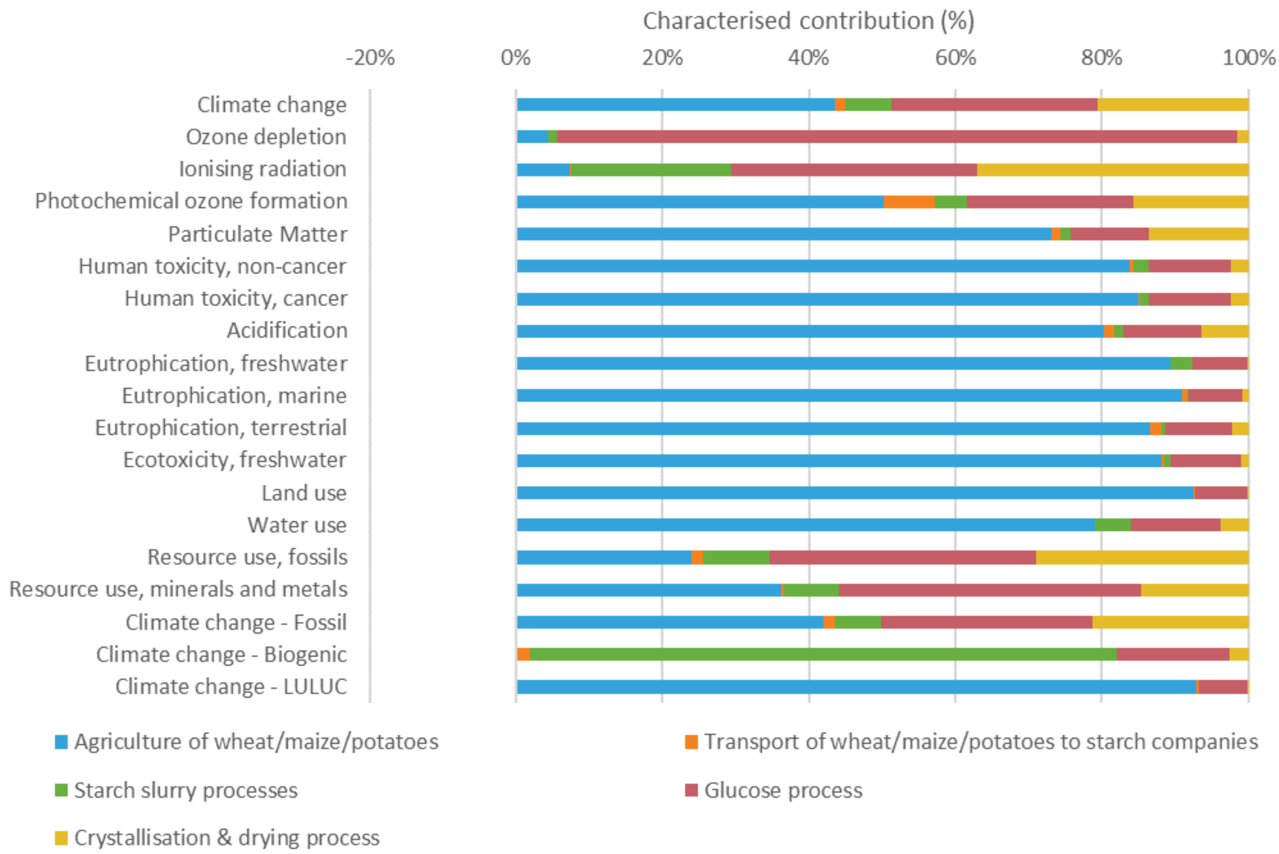


Figure 11: Environmental profile of 1 tonne DS dry crystallised dextrose

Table 11: Characterised results per tonne DS – dry crystallised dextrose

Characterised contribution	Unit	Total excl. distribution	Agriculture of wheat/maize/potatoes	Transport of wheat/maize/potatoes to starch companies	Starch slurry processes	Glucose process	Crystallisation & drying process
Climate change	*kg CO_2 eq*	1.3E+03	5.8E+02	1.9E+01	8.2E+01	3.7E+02	2.7E+02
Ozone depletion	*kg CFC11 eq*	9.7E-05	4.3E-06	6.7E-11	1.1E-06	9.0E-05	1.5E-06
Ionising radiation	*kBq U-235 eq*	9.5E+01	7.1E+00	7.5E-02	2.1E+01	3.2E+01	3.5E+01
Photochemical ozone formation	*kg NMVOC eq*	2.1E+00	1.0E+00	1.5E-01	9.0E-02	4.7E-01	3.2E-01
Particulate Matter	*disease inc.*	9.1E-05	6.6E-05	1.2E-06	1.3E-06	9.6E-06	1.2E-05
Human toxicity, non-cancer	*CTUh*	3.5E-05	2.9E-05	1.3E-07	7.3E-07	4.0E-06	8.3E-07
Human toxicity, cancer	*CTUh*	9.4E-07	8.0E-07	2.9E-09	1.1E-08	1.0E-07	2.2E-08
Acidification	*mol H^+ eq*	1.1E+01	9.0E+00	1.6E-01	1.4E-01	1.2E+00	7.1E-01
Eutrophication, freshwater	*kg P eq*	1.8E-01	1.6E-01	1.1E-04	5.3E-03	1.4E-02	1.9E-04
Eutrophication, marine	*kg N eq*	1.3E+01	1.2E+01	6.8E-02	3.1E-02	9.6E-01	9.3E-02
Eutrophication, terrestrial	*mol N eq*	4.6E+01	4.0E+01	7.4E-01	2.7E-01	4.2E+00	1.0E+00
Ecotoxicity, freshwater	*CTUe*	6.4E+04	5.7E+04	1.8E+02	5.9E+02	6.2E+03	5.9E+02
Land use	*Pt*	9.3E+04	8.6E+04	7.0E+01	-4.1E+00	6.8E+03	5.2E+01
Water use	*m^3 depriv.*	1.6E+03	1.3E+03	6.7E-01	7.9E+01	2.0E+02	6.0E+01
Resource use, fossils	*MJ*	1.6E+04	3.8E+03	2.5E+02	1.4E+03	5.7E+03	4.6E+03
Resource use, minerals and metals	*kg Sb eq*	3.5E-04	1.3E-04	1.2E-06	2.7E-05	1.4E-04	5.1E-05

Climate change - Fossil	*kg CO_2 eq*	1.3E+03	5.4E+02	1.9E+01	8.1E+01	3.7E+02	2.7E+02
Climate change - Biogenic	*kg CO_2 eq*	1.6E+00	0.0E+00	3.0E-02	1.3E+00	2.5E-01	4.0E-02
Climate change - LULUC	*kg CO_2 eq*	4.2E+01	3.9E+01	1.2E-01	1.5E-02	2.8E+00	2.0E-02

The agricultural life cycle phase remains an important contributor to many impact categories; particularly for the contribution to particulate matter, human toxicity, acidification, eutrophication, ecotoxicity, land use, water use and climate change due to land use and land use change. For most impact categories the impact of crystallisation and drying (yellow bars) is smaller than the liquid glucose process (red bars), except for ionising radiation and particulate matter. The contribution of the starch slurry process is the smallest of all the starch industry processes involved in the production of dry crystallised dextrose for all impact categories except for biogenic climate change, freshwater eutrophication and water use.

The energy inputs of electricity and heat (combined) in the crystallisation and drying process are responsible for a large share of the environmental impact Dust emissions only significantly impact particulate matter, while water consumption only has a large impact on water use (depletion). Auxiliary materials have the largest contributions to ozone depletion, freshwater eutrophication and resource use (minerals and metals).

→ Maltodextrins

Maltodextrins are produced during a maltodextrine process and a subsequent drying step[3]. These require mostly energy as an input. The environmental profile for maltodextrin is shown in Figure 12.

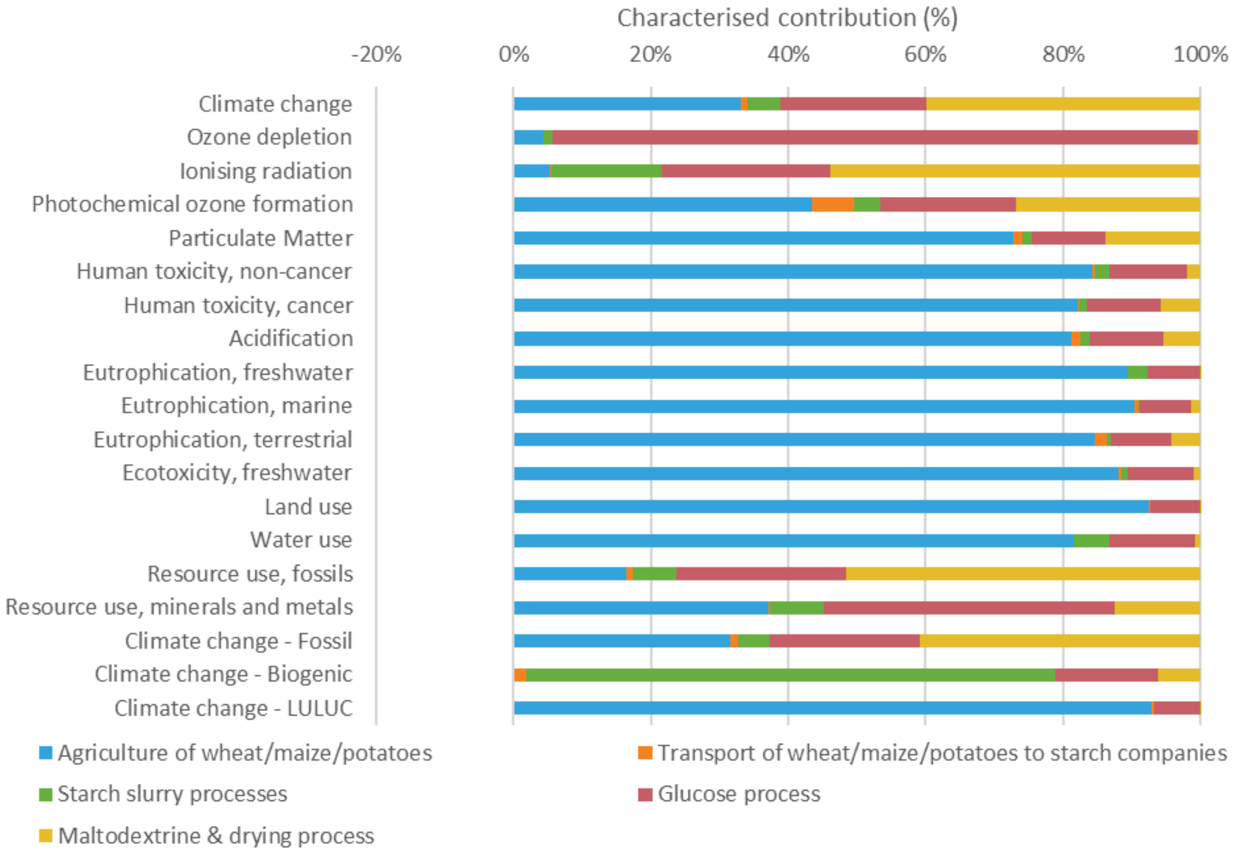


Figure 12: Environmental profile of 1 tonne DS maltodextrin

[3] The maltodextrine process and drying are treated as one process.

Table 12: Characterised results per tonne DS – maltodextrin

Characterised contribution	Unit	Total excl. distribution	Agriculture of wheat/maize/potatoes	Transport of wheat/maize/potatoes to starch companies	Starch slurry processes	Glucose process	Maltodextrine & drying process
Climate change	*kg CO_2 eq*	1.4E+03	4.7E+02	1.5E+01	6.7E+01	3.0E+02	5.7E+02
Ozone depletion	*kg CFC11 eq*	7.8E-05	3.5E-06	5.4E-11	9.1E-07	7.3E-05	3.6E-07
Ionising radiation	*kBq U-235 eq*	1.1E+02	5.7E+00	6.1E-02	1.7E+01	2.6E+01	5.7E+01
Photochemical ozone formation	*kg NMVOC eq*	1.9E+00	8.4E-01	1.2E-01	7.3E-02	3.8E-01	5.2E-01
Particulate Matter	*disease inc.*	7.4E-05	5.4E-05	9.4E-07	1.0E-06	7.8E-06	1.0E-05
Human toxicity, non-cancer	*CTUh*	2.8E-05	2.4E-05	1.1E-07	5.9E-07	3.2E-06	5.4E-07
Human toxicity, cancer	*CTUh*	7.9E-07	6.5E-07	2.4E-09	8.8E-09	8.5E-08	4.5E-08
Acidification	*mol H^+ eq*	9.0E+00	7.3E+00	1.3E-01	1.1E-01	9.8E-01	4.8E-01
Eutrophication, freshwater	*kg P eq*	1.5E-01	1.3E-01	8.8E-05	4.3E-03	1.1E-02	2.1E-04
Eutrophication, marine	*kg N eq*	1.0E+01	9.5E+00	5.5E-02	2.6E-02	7.8E-01	1.5E-01
Eutrophication, terrestrial	*mol N eq*	3.8E+01	3.2E+01	6.0E-01	2.2E-01	3.4E+00	1.6E+00
Ecotoxicity, freshwater	*CTUe*	5.2E+04	4.6E+04	1.5E+02	4.8E+02	5.0E+03	5.5E+02
Land use	*Pt*	7.6E+04	7.0E+04	5.7E+01	-3.3E+00	5.5E+03	7.8E+01
Water use	*m^3 depriv.*	1.3E+03	1.0E+03	5.4E-01	6.4E+01	1.6E+02	9.4E+00
Resource use, fossils	*MJ*	1.9E+04	3.1E+03	2.0E+02	1.2E+03	4.6E+03	9.6E+03
Resource use, minerals and metals	*kg Sb eq*	2.8E-04	1.0E-04	9.7E-07	2.2E-05	1.2E-04	3.5E-05
Climate change - Fossil	*kg CO_2 eq*	1.4E+03	4.4E+02	1.5E+01	6.6E+01	3.0E+02	5.7E+02
Climate change - Biogenic	*kg CO_2 eq*	1.3E+00	0.0E+00	2.5E-02	1.0E+00	2.0E-01	8.3E-02
Climate change - LULUC	*kg CO_2 eq*	3.4E+01	3.2E+01	1.0E-01	1.3E-02	2.3E+00	3.3E-02

The environmental profile of maltodextrin shows many similarities with the dry crystallised dextrose profile. The contribution of the agricultural life cycle phase is very similar and the starch slurry process is again the smallest contributor out of the three manufacturing processes involved in the production of maltodextrin for all impact categories except for biogenic climate change, freshwater eutrophication and water use and also for human toxicity (non-cancer). Also similarly the contribution of the maltodextrine and drying process (yellow bars) is generally smaller than that of the liquid glucose process (red bars).

The combined energy inputs for the maltodextrine and drying process account for the majority of the impact except for ozone depletion, freshwater eutrophication and water use. For these impact categories, either auxiliary materials or water use are the major contributor.

→ **Liquid sorbitol**

The production of **liquid sorbitol** from hydrogenation of liquid glucose requires energy, water and auxiliary materials (among which hydrogen gas, of course). The environmental profile for liquid sorbitol is shown in Figure 13.

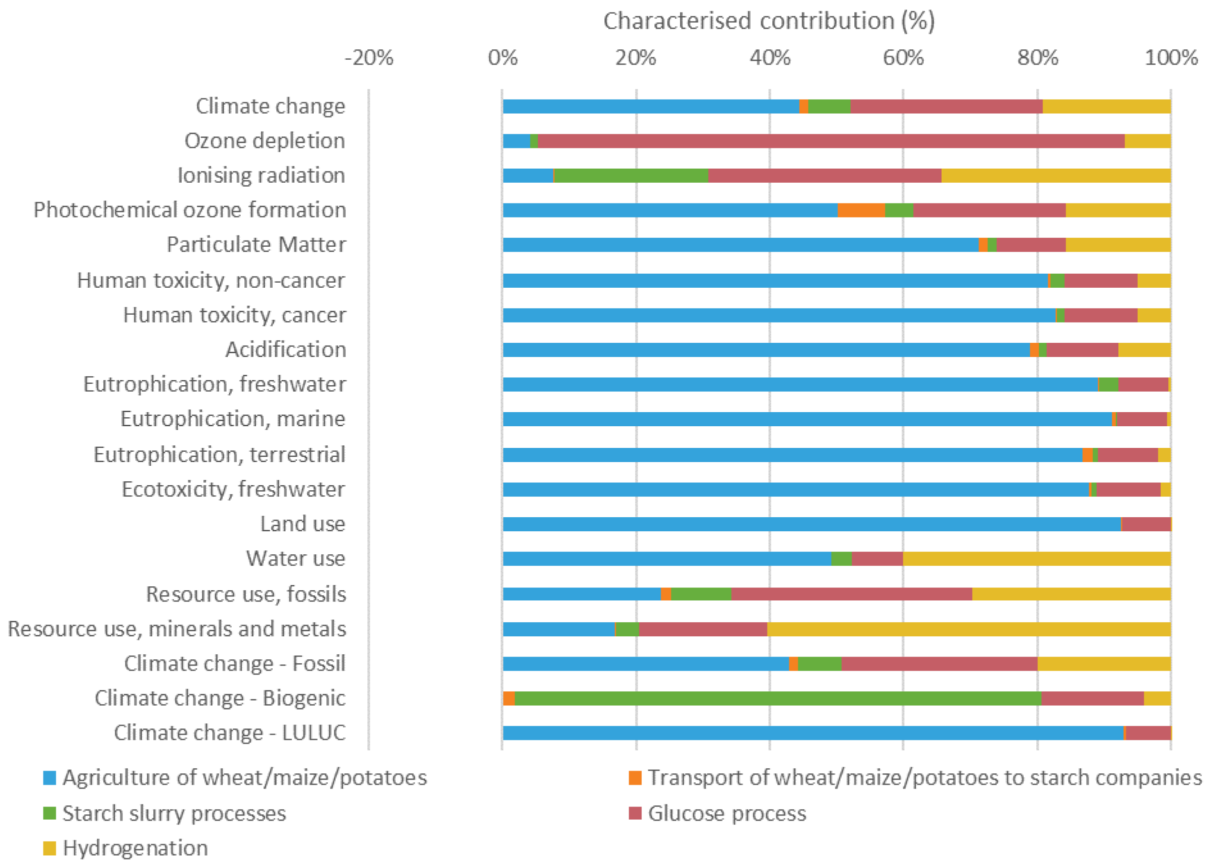


Figure 13: Environmental profile of 1 tonne DS liquid sorbitol

Table 13: Characterised results per tonne DS – liquid sorbitol

Characterised contribution	Unit	Total excl. distribution	Agriculture of wheat/maize/potatoes	Transport of wheat/maize/potatoes to starch companies	Starch slurry processes	Glucose process	Hydrogenation
Climate change	*kg CO_2 eq*	1.0E+03	4.6E+02	1.5E+01	6.6E+01	3.0E+02	2.0E+02
Ozone depletion	*kg CFC11 eq*	8.2E-05	3.5E-06	5.4E-11	9.0E-07	7.2E-05	5.7E-06
Ionising radiation	*kBq U-235 eq*	7.3E+01	5.6E+00	6.0E-02	1.7E+01	2.6E+01	2.5E+01
Photochemical ozone formation	*kg NMVOC eq*	1.7E+00	8.3E-01	1.2E-01	7.2E-02	3.8E-01	2.6E-01
Particulate Matter	*disease inc.*	7.4E-05	5.3E-05	9.2E-07	1.0E-06	7.7E-06	1.2E-05
Human toxicity, non-cancer	*CTUh*	2.9E-05	2.4E-05	1.1E-07	5.8E-07	3.2E-06	1.5E-06
Human toxicity, cancer	*CTUh*	7.7E-07	6.4E-07	2.3E-09	8.6E-09	8.4E-08	3.9E-08
Acidification	*mol H^+ eq*	9.1E+00	7.2E+00	1.3E-01	1.1E-01	9.6E-01	7.3E-01
Eutrophication, freshwater	*kg P eq*	1.4E-01	1.3E-01	8.6E-05	4.2E-03	1.1E-02	5.8E-04
Eutrophication, marine	*kg N eq*	1.0E+01	9.4E+00	5.5E-02	2.5E-02	7.6E-01	6.5E-02
Eutrophication, terrestrial	*mol N eq*	3.7E+01	3.2E+01	5.9E-01	2.2E-01	3.4E+00	7.2E-01
Ecotoxicity, freshwater	*CTUe*	5.2E+04	4.5E+04	1.5E+02	4.7E+02	5.0E+03	7.9E+02
Land use	*Pt*	7.4E+04	6.9E+04	5.6E+01	-3.2E+00	5.4E+03	6.1E+01
Water use	*m^3 depriv.*	2.1E+03	1.0E+03	5.3E-01	6.3E+01	1.6E+02	8.3E+02
Resource use, fossils	*MJ*	1.3E+04	3.0E+03	2.0E+02	1.1E+03	4.6E+03	3.8E+03
Resource use, minerals and metals	*kg Sb eq*	6.0E-04	1.0E-04	9.5E-07	2.1E-05	1.2E-04	3.6E-04

Climate change - Fossil	*kg CO_2 eq*	1.0E+03	4.3E+02	1.5E+01	6.5E+01	3.0E+02	2.0E+02
Climate change - Biogenic	*kg CO_2 eq*	1.3E+00	0.0E+00	2.4E-02	1.0E+00	2.0E-01	5.4E-02
Climate change - LULUC	*kg CO_2 eq*	3.4E+01	3.1E+01	9.8E-02	1.2E-02	2.3E+00	2.2E-02

The environmental profile shows that, again, the agricultural phase is the major contributor to many impact categories. When focusing on the manufacturing processes, the liquid glucose process has a larger contribution than hydrogenation, except for particulate matter, water use and minerals and metals resource use. The contribution of the starch slurry to the environmental impact is the smallest of the three for all categories except for biogenic climate change. Transport of raw materials (wheat, maize and potatoes) has a small relative contribution to all impact categories.

Auxiliary materials, mainly hydrogen, contribute in an important way to the hydrogenation process' environmental impact. Also the combined contribution of heat and electricity remains high for climate change, ionising radiation, photochemical ozone formation, eutrophication, fossil resource use and fossil climate change. As observed before, dust emissions and water consumption only contribute to respectively particulate matter and water depletion.

→ **Dry sorbitol**

Dry sorbitol is produced by drying liquid sorbitol, which requires mostly energy as an input (both electricity and heat). The environmental profile for dry sorbitol is visualised in Figure 14.

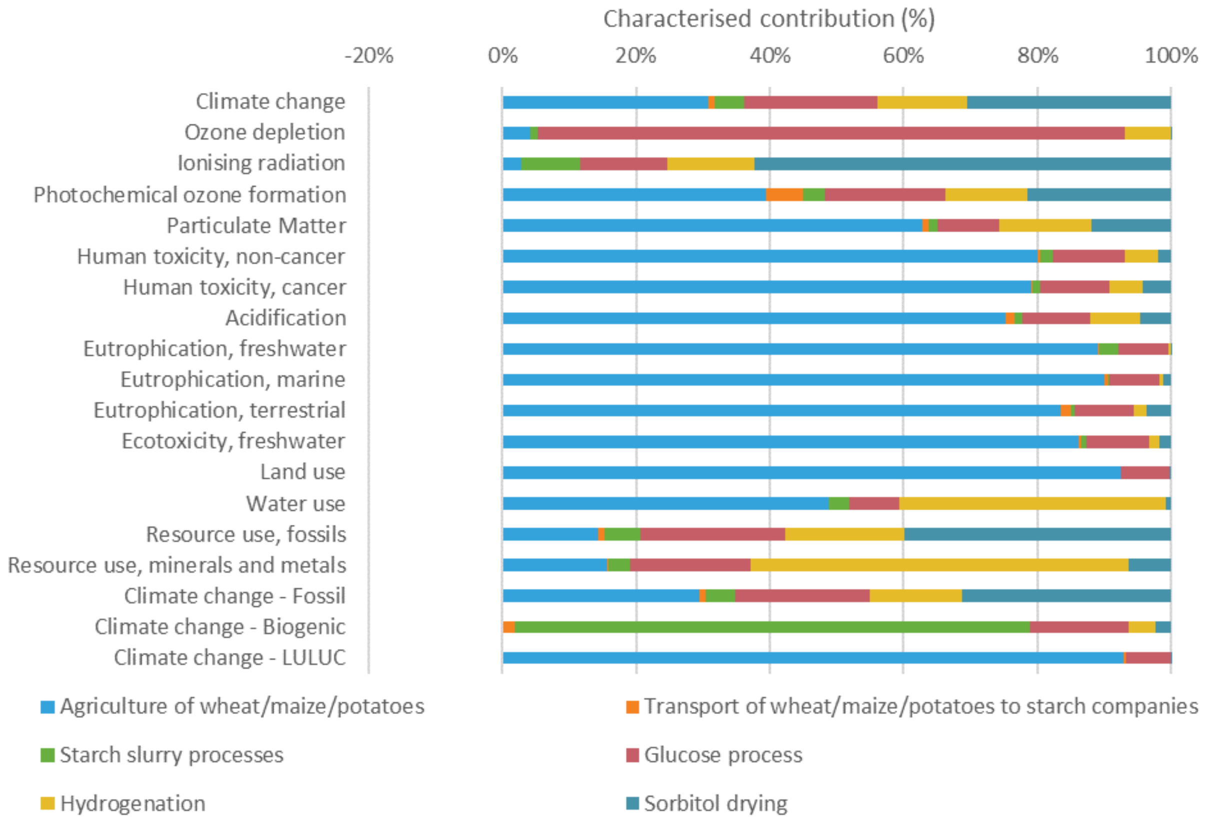


Figure 14: Environmental profile of 1 tonne DS dry sorbitol

Table 14: Characterised results per tonne DS – dry sorbitol

Characterised contribution	Unit	Total excl. distribution	Agriculture of wheat/maize/potatoes	Transport of wheat/maize/potatoes to starch companies	Starch slurry processes	Glucose process	Hydrogenation	Sorbitol drying
Climate change	*kg CO_2 eq*	1.50E+03	4.6E+02	1.5E+01	6.6E+01	3.0E+02	2.0E+02	4.6E+02
Ozone depletion	*kg CFC11 eq*	8.25E-05	3.5E-06	5.4E-11	9.0E-07	7.2E-05	5.7E-06	1.3E-07
Ionising radiation	*kBq U-235 eq*	1.94E+02	5.6E+00	6.0E-02	1.7E+01	2.6E+01	2.5E+01	1.2E+02
Photochemical ozone formation	*kg NMVOC eq*	2.11E+00	8.3E-01	1.2E-01	7.2E-02	3.8E-01	2.6E-01	4.5E-01
Particulate Matter	*disease inc.*	8.44E-05	5.3E-05	9.2E-07	1.0E-06	7.7E-06	1.2E-05	1.0E-05
Human toxicity, non-cancer	*CTUh*	2.94E-05	2.4E-05	1.1E-07	5.8E-07	3.2E-06	1.5E-06	5.7E-07
Human toxicity, cancer	*CTUh*	8.07E-07	6.4E-07	2.3E-09	8.6E-09	8.4E-08	3.9E-08	3.5E-08
Acidification	*mol H^+ eq*	9.55E+00	7.2E+00	1.3E-01	1.1E-01	9.6E-01	7.3E-01	4.4E-01
Eutrophication, freshwater	*kg P eq*	1.44E-01	1.3E-01	8.6E-05	4.2E-03	1.1E-02	5.8E-04	5.6E-05
Eutrophication, marine	*kg N eq*	1.04E+01	9.4E+00	5.5E-02	2.5E-02	7.6E-01	6.5E-02	1.3E-01
Eutrophication, terrestrial	*mol N eq*	3.82E+01	3.2E+01	5.9E-01	2.2E-01	3.4E+00	7.2E-01	1.4E+00
Ecotoxicity, freshwater	*CTUe*	5.28E+04	4.5E+04	1.5E+02	4.7E+02	5.0E+03	7.9E+02	9.2E+02
Land use	*Pt*	7.46E+04	6.9E+04	5.6E+01	-3.2E+00	5.4E+03	6.1E+01	1.2E+02
Water use	*m^3 depriv.*	2.08E+03	1.0E+03	5.3E-01	6.3E+01	1.6E+02	8.3E+02	1.5E+01
Resource use, fossils	*MJ*	2.11E+04	3.0E+03	2.0E+02	1.1E+03	4.6E+03	3.8E+03	8.4E+03
Resource use, minerals and metals	*kg Sb eq*	6.44E-04	1.0E-04	9.5E-07	2.1E-05	1.2E-04	3.6E-04	4.1E-05
Climate change - Fossil	*kg CO_2 eq*	1.47E+03	4.3E+02	1.5E+01	6.5E+01	3.0E+02	2.0E+02	4.6E+02
Climate change - Biogenic	*kg CO_2 eq*	1.33E+00	0.0E+00	2.4E-02	1.0E+00	2.0E-01	5.4E-02	3.1E-02
Climate change - LULUC	*kg CO_2 eq*	3.38E+01	3.1E+01	9.8E-02	1.2E-02	2.3E+00	2.2E-02	1.8E-02

The profile of dry sorbitol shows that the agricultural phase remains a major contributor to many impact categories, even when considering four manufacturing processes at this point. It appears that the liquid glucose process (red bars) remains the process with the highest influence of the four which holds true for all impact categories, except for climate change (fossil and biogenic), ionising radiation, photochemical ozone formation, particulate matter, water use, resource use, climate change. However, the sorbitol drying process (teal bars) appears to be the manufacturing process with the highest influence on ionising radiation, photochemical ozone formation, particulate matter, fossil resources use and fossil climate change. This is due to the consumption of energy. Overall, the contribution of the starch slurry process to the environmental impact is small compared to the other three for all categories except, notably, for biogenic climate change. Transport of raw materials (wheat, maize and potatoes) has a small (< 5%) relative contribution to all impact categories.

4.2.5. NATIVE STARCH

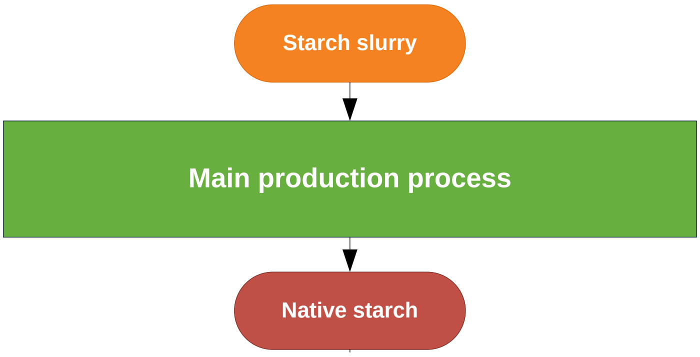


Figure 15: Simplified process chart of the production of native starch

For the production of native starch[4], the input of starch slurry is required. The starch slurry may be either wheat, maize or potato starch slurry or a mixture. The composition of the input starch slurry is a weighted average calculated from reported amounts by the member companies.

All processes considered, the total environmental impact of native starch consists of:

- the impact related to the agricultural phase;
- the impact related to the starch slurry process;
- the impact related to the native starch production process.

Eventually, dextrins can be derived from native starch through an additional process step. Dextrins are discussed separately.

In the **native starch** production process, inputs of water, electricity and heat (including natural gas) and auxiliary materials are required. Outputs are under the form of emissions to air and water. Native starch is a final product (although it also serves as an intermediate to produce dextrins from). The environmental profile is shown in Figure 16.

The environmental profile shows that the agricultural phase (cultivation of wheat, maize and potatoes) is a large contributor to many impact categories; the majority of the impact on ozone depletion, particulate matter, human toxicity, acidification, eutrophication, freshwater ecotoxicity, land use, water use and climate change due to land use and land use change is caused by agriculture. The combined manufacturing processes for native starch contribute importantly to ozone depletion, ionising radiation, resource use (fossils and minerals and metals), climate change (fossil and biogenic). The native starch process most importantly affects the impact categories resource use, ozone depletion, ionising radiation, particulate matter and climate change (fossil and total). Overall climate change is affected mostly by agriculture, but also significantly by the manufacturing processes. Transport of wheat, maize and potatoes to the factories does not account for a significant impact, except for photochemical ozone depletion.

[4] Note that 'native starch' refers to native starch and lightly modified starch. For simplicity, only native starch is mentioned in the report.

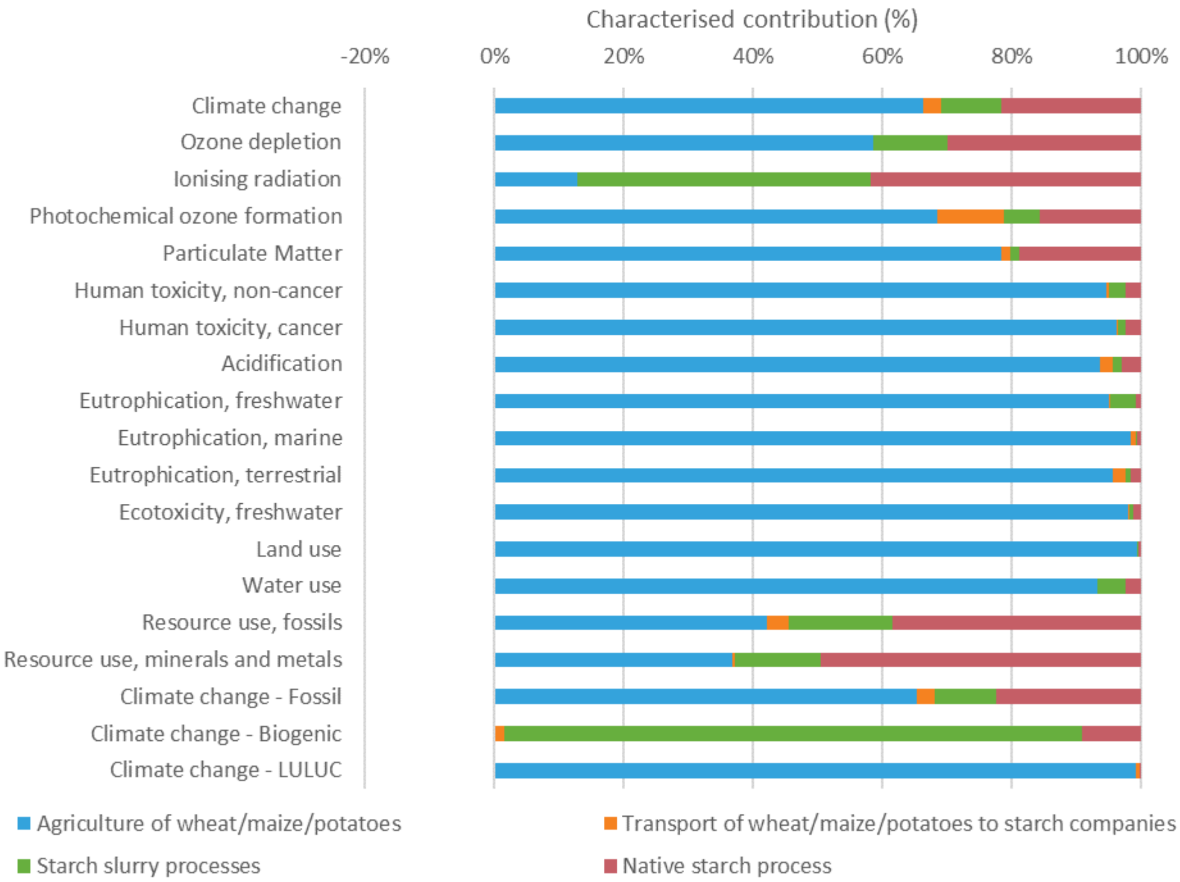


Figure 16: Environmental profile of 1 tonne DS native starch

Table 15: Characterised results per tonne DS – native starch

Characterised contribution	Unit	Total excl. distribution	Agriculture of wheat/maize/potatoes	Transport of wheat/maize/potatoes to starch companies	Starch slurry processes	Native starch process
Climate change	*kg CO_2 eq*	7.34E+02	4.9E+02	1.9E+01	6.9E+01	1.6E+02
Ozone depletion	*kg CFC11 eq*	7.24E-06	4.2E-06	7.0E-11	8.4E-07	2.2E-06
Ionising radiation	*kBq U-235 eq*	5.38E+01	6.9E+00	7.8E-02	2.4E+01	2.2E+01
Photochemical ozone formation	*kg NMVOC eq*	1.41E+00	9.7E-01	1.4E-01	7.7E-02	2.2E-01
Particulate Matter	*disease inc.*	7.43E-05	5.8E-05	1.1E-06	1.1E-06	1.4E-05
Human toxicity, non-cancer	*CTUh*	3.30E-05	3.1E-05	1.4E-07	8.8E-07	8.0E-07
Human toxicity, cancer	*CTUh*	9.12E-07	8.8E-07	3.0E-09	9.9E-09	2.2E-08
Acidification	*mol H^+ eq*	8.36E+00	7.8E+00	1.6E-01	1.2E-01	2.6E-01
Eutrophication, freshwater	*kg P eq*	1.69E-01	1.6E-01	1.1E-04	6.9E-03	1.4E-03
Eutrophication, marine	*kg N eq*	1.00E+01	9.9E+00	6.9E-02	3.0E-02	6.0E-02
Eutrophication, terrestrial	*mol N eq*	3.63E+01	3.5E+01	7.5E-01	2.2E-01	6.3E-01
Ecotoxicity, freshwater	*CTUe*	1.10E+05	1.1E+05	1.9E+02	6.7E+02	1.3E+03
Land use	*Pt*	7.23E+04	7.2E+04	7.3E+01	4.3E+01	3.8E+02
Water use	*m^3 depriv.*	1.30E+03	1.2E+03	7.0E-01	5.6E+01	3.2E+01
Resource use, fossils	*MJ*	7.82E+03	3.3E+03	2.6E+02	1.3E+03	3.0E+03

Resource use, minerals and metals	*kg Sb eq*	3.22E-04	1.2E-04	1.2E-06	4.3E-05	1.6E-04
Climate change - Fossil	*kg CO_2 eq*	7.07E+02	4.6E+02	1.9E+01	6.7E+01	1.6E+02
Climate change - Biogenic	*kg CO_2 eq*	1.88E+00	0.0E+00	3.2E-02	1.7E+00	1.7E-01
Climate change - LULUC	*kg CO_2 eq*	2.53E+01	2.5E+01	1.3E-01	1.8E-02	6.8E-02

Overall, heat and auxiliary materials cause the largest share of the environmental impact of the native starch process. For the latter, mainly the production of auxiliary materials such as sodium hydroxide and hydrochloric acid is important.

4.2.6. Dextrins

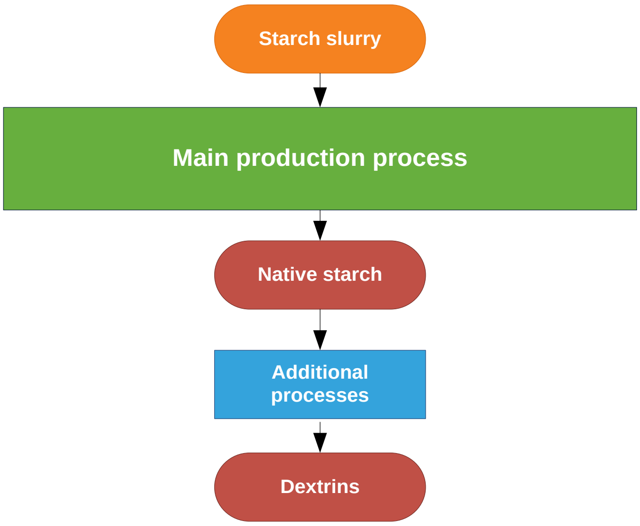


Figure 17: Simplified process chart of the production of dextrins

Dextrins, as mentioned earlier, are derived from native starch, which in turn is produced from starch slurry. Since dextrins are produced in an additional step in line with the native starch process, the input starch slurry composition is the same.

The accumulated impact due to the additional process to produce dextrins entails:

- the impact related to the agricultural phase;
- the impact related to the starch slurry process;
- the impact related to the native starch production process;
- the impact related to the dextrins production process.

Dextrins require inputs of water, electricity and heat (including natural gas) and some auxiliary materials for their production. Outputs are under the form of emissions to air.

The environmental profile for dextrins is shown in Figure 18. This reveals that the impact of dextrins remains dominated by the agricultural phase for many impact categories except for ionising radiation, resource use (fossil and minerals and metals) and biogenic climate change. For these impact categories the manufacturing processes (starch slurry process, native starch process and drying) are the major contributor to the impact. The impact of drying is comparable to that of the native starch process; for many impact categories the lengths of the yellow and red bars are similar. The impact of raw materials (wheat, maize and potatoes) transport is not significant, except for photochemical ozone formation. Regarding climate change, half of the impact is caused by agriculture and the remainder is caused by the manufacturing processes (of which the generated impact decreases in the process series: drying > native starch process > starch slurry process).

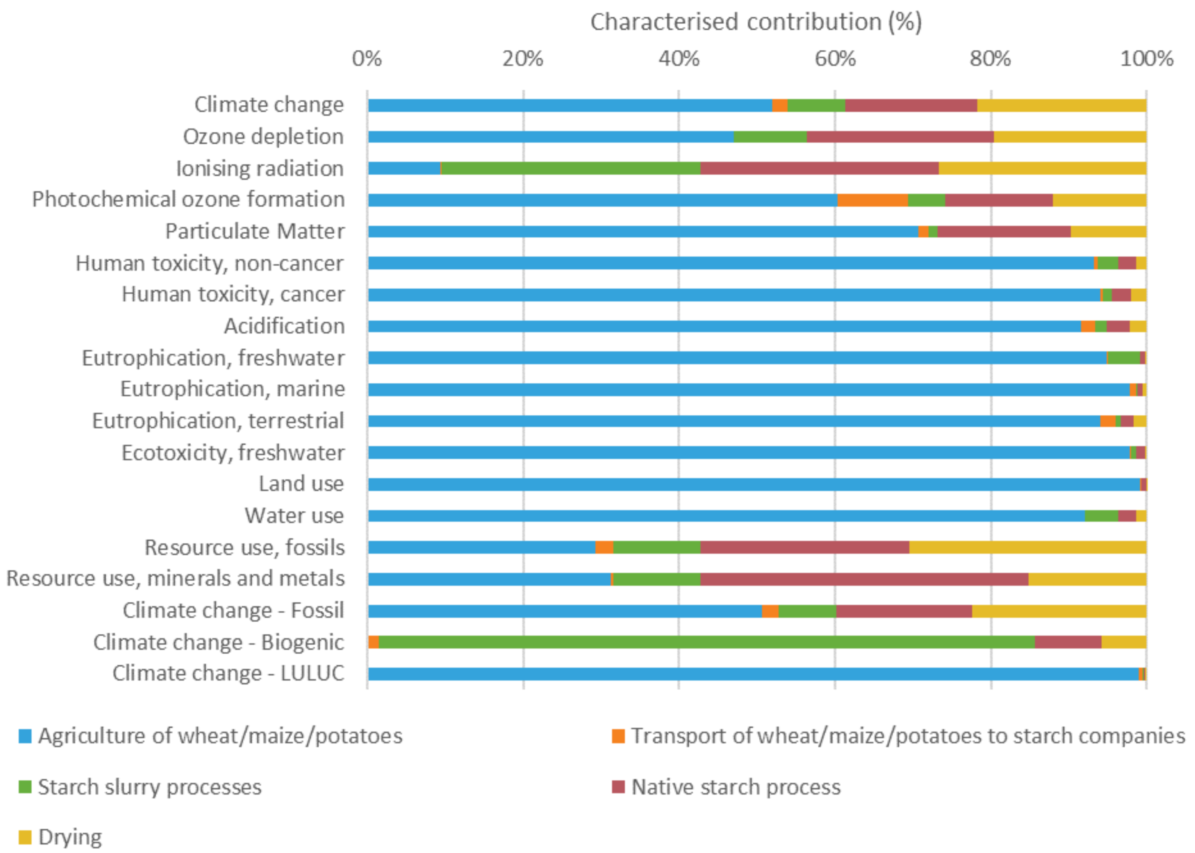


Figure 18: Environmental profile of 1 tonne DS dextrins

Table 16: Characterised results per tonne DS – dextrins

Characterised contribution	Unit	Total excl. distribution	Agriculture of wheat/maize/potatoes	Transport of wheat/maize/potatoes to starch companies	Starch slurry processes	Native starch process	Drying
Climate change	*kg CO_2 eq*	9.4E+02	4.9E+02	1.9E+01	6.9E+01	1.6E+02	2.0E+02
Ozone depletion	*kg CFC11 eq*	9.0E-06	4.2E-06	6.9E-11	8.4E-07	2.2E-06	1.8E-06
Ionising radiation	*kBq U-235 eq*	7.3E+01	6.9E+00	7.8E-02	2.4E+01	2.2E+01	2.0E+01
Photochemical ozone formation	*kg NMVOC eq*	1.6E+00	9.7E-01	1.4E-01	7.7E-02	2.2E-01	1.9E-01
Particulate Matter	*disease inc.*	8.2E-05	5.8E-05	1.1E-06	1.1E-06	1.4E-05	8.0E-06
Human toxicity, non-cancer	*CTUh*	3.3E-05	3.1E-05	1.4E-07	8.8E-07	8.0E-07	4.3E-07
Human toxicity, cancer	*CTUh*	9.3E-07	8.8E-07	3.0E-09	9.9E-09	2.2E-08	1.9E-08
Acidification	*mol H^+ eq*	8.5E+00	7.8E+00	1.6E-01	1.2E-01	2.6E-01	1.9E-01
Eutrophication, freshwater	*kg P eq*	1.7E-01	1.6E-01	1.1E-04	6.8E-03	1.4E-03	2.4E-04
Eutrophication, marine	*kg N eq*	1.0E+01	9.9E+00	6.8E-02	3.0E-02	6.0E-02	5.6E-02
Eutrophication, terrestrial	*mol N eq*	3.7E+01	3.5E+01	7.4E-01	2.2E-01	6.3E-01	6.2E-01
Ecotoxicity, freshwater	*CTUe*	1.1E+05	1.1E+05	1.9E+02	6.7E+02	1.3E+03	2.5E+02
Land use	*Pt*	7.2E+04	7.2E+04	7.3E+01	4.3E+01	3.8E+02	7.4E+01
Water use	*m^3 depriv.*	1.3E+03	1.2E+03	6.9E-01	5.6E+01	3.2E+01	1.7E+01
Resource use, fossils	*MJ*	1.1E+04	3.3E+03	2.6E+02	1.3E+03	3.0E+03	3.4E+03

Resource use, minerals and metals	*kg Sb eq*	3.8E-04	1.2E-04	1.2E-06	4.3E-05	1.6E-04	5.8E-05
Climate change - Fossil	*kg CO_2 eq*	9.1E+02	4.6E+02	1.9E+01	6.7E+01	1.6E+02	2.0E+02
Climate change - Biogenic	*kg CO_2 eq*	2.0E+00	0.0E+00	3.2E-02	1.7E+00	1.7E-01	1.1E-01
Climate change - LULUC	*kg CO_2 eq*	2.5E+01	2.5E+01	1.3E-01	1.7E-02	6.8E-02	4.1E-02

4.2.7. MODIFIED STARCH

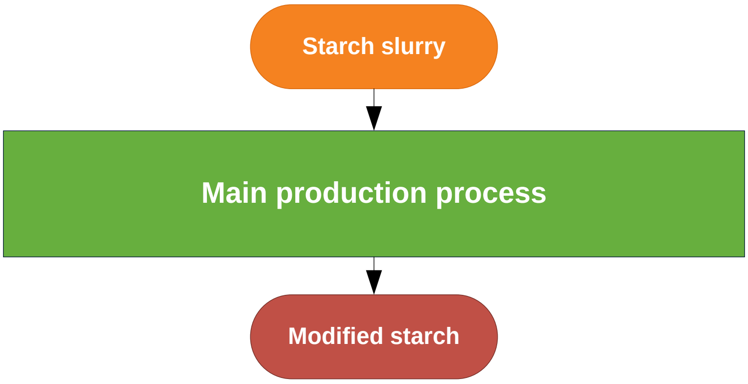


Figure 19: Simplified process chart of the production of modified starch

Starch slurry is modified using auxiliary materials to produce modified starch. The starch slurry may be either wheat, maize or potato starch slurry or a mixture. The composition of the input starch slurry for modified starch production is a weighted average calculated from reported amounts by the member companies.

All processes considered, the total environmental impact of modified starch consists of:

- the impact related to the agricultural phase;
- the impact related to the starch slurry process;
- the impact related to the modified starch production process.

In the **modified starch** production process, various auxiliary materials, water, electricity and heat (including natural gas) are required inputs. The environmental profile is shown in Figure 20.

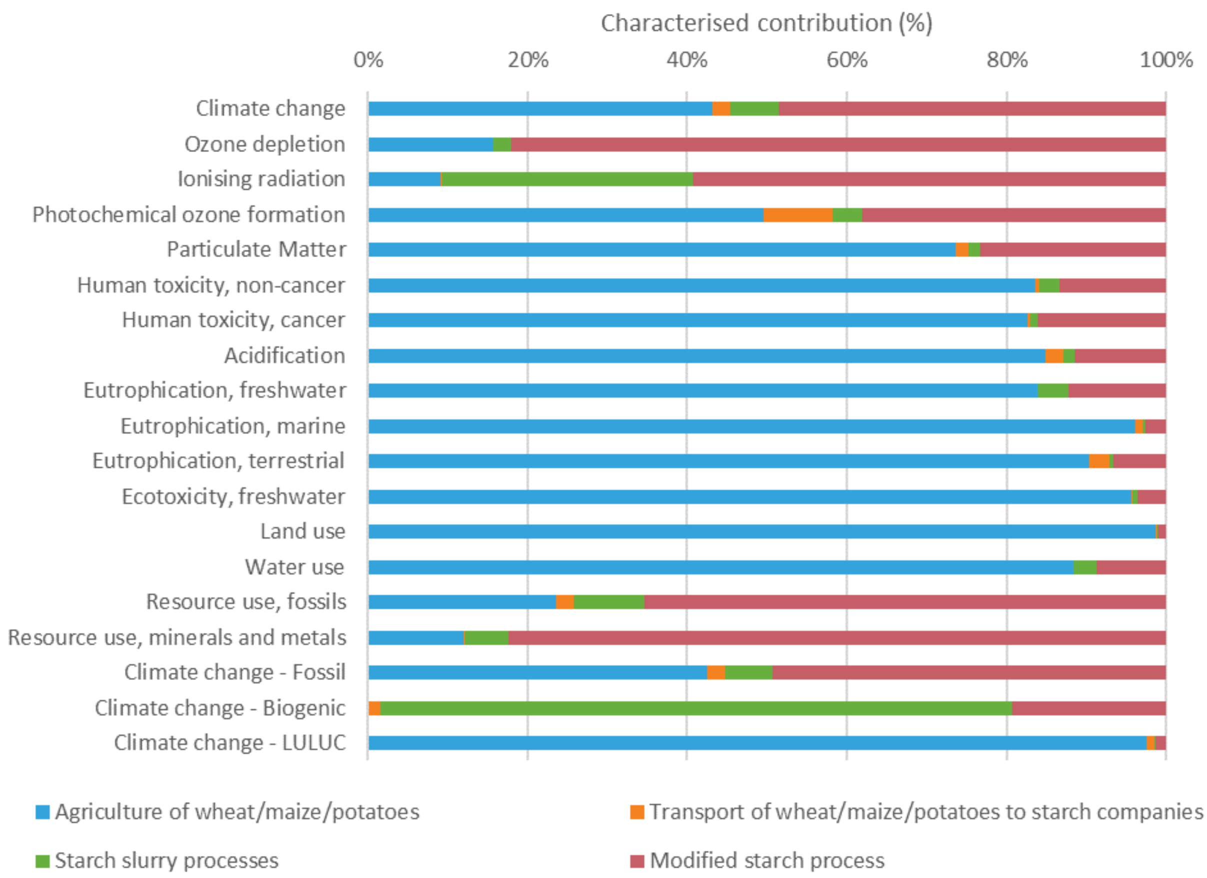


Figure 20: Environmental profile of 1 tonne DS modified starch

Table 17: Characterised results per tonne DS – modified starch

Characterised contribution	Unit	Total excl. Distribution	Agriculture of wheat/maize/potatoes	Transport of wheat/maize/potatoes to starch companies	Starch slurry processes	Modified starch process
Climate change	*kg CO_2 eq*	1.1E+03	4.6E+02	2.4E+01	6.6E+01	5.2E+02
Ozone depletion	*kg CFC11 eq*	3.1E-05	4.9E-06	8.6E-11	7.4E-07	2.6E-05
Ionising radiation	*kBq U-235 eq*	8.6E+01	7.9E+00	9.7E-02	2.7E+01	5.1E+01
Photochemical ozone formation	*kg NMVOC eq*	2.0E+00	1.0E+00	1.8E-01	7.5E-02	7.8E-01
Particulate Matter	*disease inc.*	7.7E-05	5.7E-05	1.3E-06	1.1E-06	1.8E-05
Human toxicity, non-cancer	*CTUh*	3.9E-05	3.2E-05	1.7E-07	1.0E-06	5.2E-06
Human toxicity, cancer	*CTUh*	1.2E-06	9.5E-07	3.8E-09	1.0E-08	1.9E-07
Acidification	*mol H^+ eq*	8.9E+00	7.5E+00	2.0E-01	1.2E-01	1.0E+00
Eutrophication, freshwater	*kg P eq*	2.1E-01	1.8E-01	1.4E-04	8.1E-03	2.6E-02
Eutrophication, marine	*kg N eq*	9.7E+00	9.4E+00	8.4E-02	3.0E-02	2.6E-01
Eutrophication, terrestrial	*mol N eq*	3.7E+01	3.3E+01	9.2E-01	2.1E-01	2.4E+00
Ecotoxicity, freshwater	*CTUe*	1.5E+05	1.5E+05	2.4E+02	7.9E+02	5.6E+03
Land use	*Pt*	7.0E+04	6.9E+04	9.1E+01	8.6E+01	7.1E+02
Water use	*m^3 depriv.*	1.8E+03	1.6E+03	8.6E-01	5.0E+01	1.6E+02
Resource use, fossils	*MJ*	1.4E+04	3.3E+03	3.2E+02	1.2E+03	9.2E+03
Resource use, minerals and metals	*kg Sb eq*	1.0E-03	1.3E-04	1.5E-06	5.7E-05	8.6E-04

Climate change - Fossil	*kg CO_2 eq*	1.1E+03	4.5E+02	2.4E+01	6.4E+01	5.2E+02
Climate change - Biogenic	*kg CO_2 eq*	2.5E+00	0.0E+00	3.9E-02	2.0E+00	4.9E-01
Climate change - LULUC	*kg CO_2 eq*	1.5E+01	1.5E+01	1.6E-01	2.2E-02	2.0E-01

The environmental profile of 1 tonne DS modified starch shows that the agricultural phase remains an important contributor to the environmental impact. On the categories where agriculture has a less important effect, the modified starch process appears to be a large (or even the largest) contributor, which is the case for, for instance, ozone depletion, ionising radiation, resource use (fossil and minerals and metals) and fossil climate change. These categories are typically impacted a lot by energy consumption. The impact of the modified starch process is a lot higher than the starch slurry process for any given impact category except biogenic climate change. Transport of wheat, maize and potatoes to the factories does not accounts for a significant impact, except for photochemical ozone depletion.

In general, an important part of the environmental impact of the modified starch process is caused by consumption of auxiliary materials. The contributions of heat and electricity remain large as well. Dust emissions and water use only contribute relatively largely on respectively particulate matter and water use (depletion) but remain unimportant for the other categories. Waste water emission appears to make an insignificant contribution to any impact category.

4.2.8. POTABLE ALCOHOL

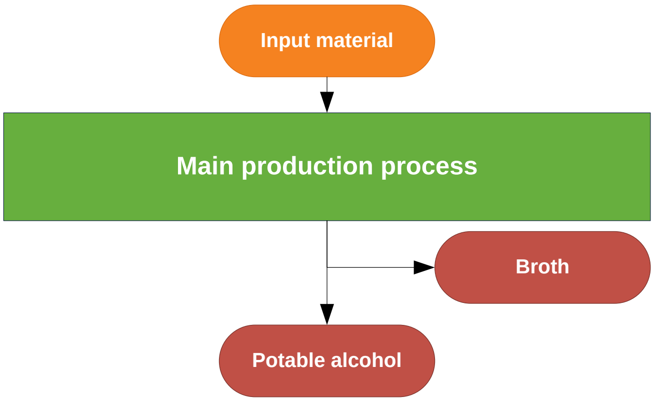


Figure 21: Simplified process chart of production of potable alcohol and co-product broth

In order to produce potable alcohol, a variety of input materials can be used, such as starch slurry, fine fibers or fermentable sugars. Depending on the input material, the environmental profile of potable alcohol differs. In the reported datasets received for this study, the raw input material consisted entirely of wheat starch slurry.

Potable alcohol and **broth** are output products of the same process and therefore have the same impact per tonne dry substance of each product. The impact generated by potable alcohol consists of:

- The impact related to the agricultural phase;
- The impact related to the starch slurry process;
- The impact related to the potable alcohol process.

The potable alcohol production process requires energy (electricity, heat and natural gas), water and auxiliary materials (including enzymes) as inputs. This process generates carbon dioxide emissions to air. As this carbon dioxide is biogenic and carbon uptake during plant growth was not included, biogenic carbon emissions are not taken into account either.

The environmental profile for potable alcohol is shown in Figure 22.

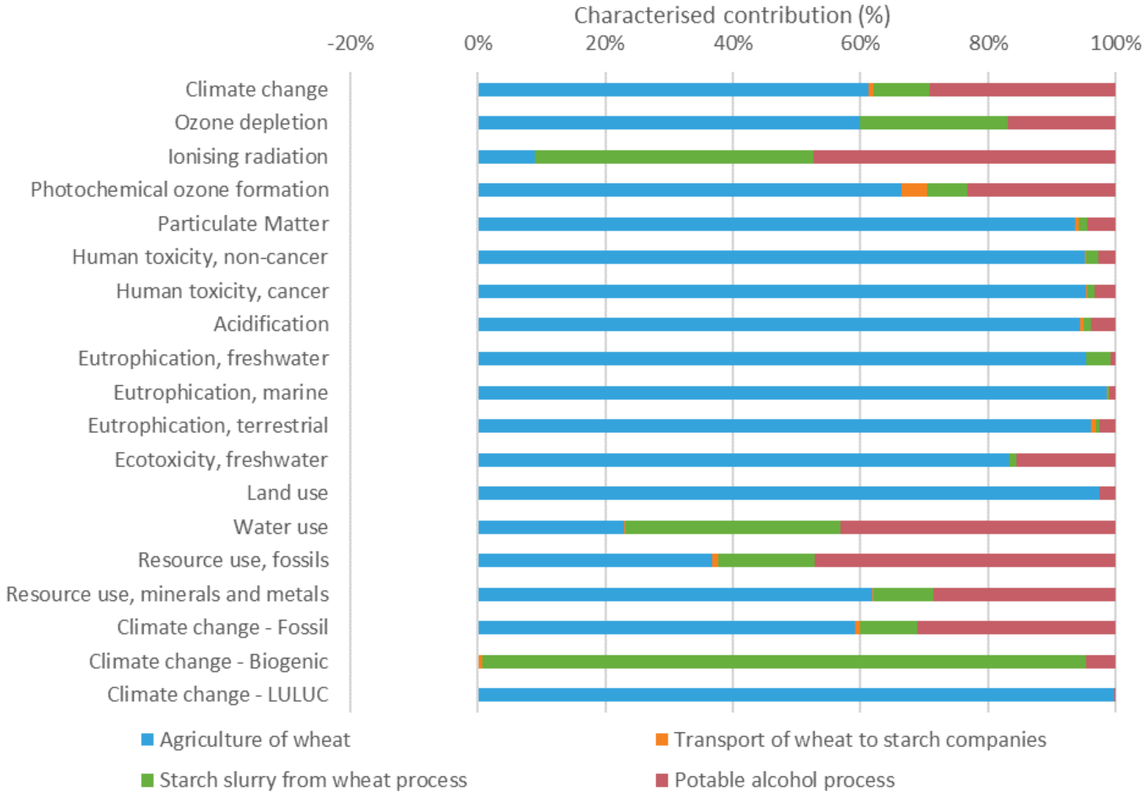


Figure 22: Environmental profile of 1 tonne potable alcohol

Table 18: Characterised results per tonne – potable alcohol

Characterised contribution	Unit	Total excl. distribution	Agriculture of wheat	Transport of wheat to starch companies	Starch slurry from wheat process	Potable alcohol process
Climate change	*kg CO_2 eq*	1.2E+03	7.4E+02	9.4E+00	1.0E+02	3.5E+02
Ozone depletion	*kg CFC11 eq*	5.9E-06	3.5E-06	3.3E-11	1.4E-06	1.0E-06
Ionising radiation	*kBq U-235 eq*	6.6E+01	5.9E+00	3.7E-02	2.9E+01	3.1E+01
Photochemical ozone formation	*kg NMVOC eq*	4.3E+00	1.2E+00	7.1E-02	1.1E-01	4.2E-01
Particulate Matter	*disease inc.*	1.1E-04	8.6E-05	5.9E-07	1.2E-06	4.0E-06
Human toxicity, non-cancer	*CTUh*	4.8E-05	4.4E-05	6.7E-08	9.2E-07	1.2E-06
Human toxicity, cancer	*CTUh*	1.2E-06	1.1E-06	1.4E-09	1.3E-08	3.9E-08
Acidification	*mol H^+ eq*	1.6E+01	1.2E+01	6.8E-02	1.4E-01	4.9E-01
Eutrophication, freshwater	*kg P eq*	1.9E-01	1.8E-01	5.4E-05	7.0E-03	1.7E-03
Eutrophication, marine	*kg N eq*	1.7E+01	1.5E+01	3.3E-02	4.0E-02	1.5E-01
Eutrophication, terrestrial	*mol N eq*	6.7E+01	5.3E+01	3.6E-01	3.5E-01	1.4E+00
Ecotoxicity, freshwater	*CTUe*	6.3E+04	5.0E+04	8.6E+01	6.0E+02	9.3E+03
Land use	*Pt*	1.1E+05	1.1E+05	3.5E+01	-6.6E+01	2.7E+03
Water use	*m^3 depriv.*	2.5E+02	5.6E+01	3.3E-01	8.2E+01	1.0E+02
Resource use, fossils	*MJ*	1.5E+04	4.4E+03	1.2E+02	1.8E+03	5.6E+03
Resource use, minerals and metals	*kg Sb eq*	2.4E-04	1.4E-04	5.7E-07	2.1E-05	6.5E-05
Climate change - Fossil	*kg CO_2 eq*	1.4E+03	6.7E+02	9.3E+00	1.0E+02	3.5E+02
Climate change - Biogenic	*kg CO_2 eq*	2.2E+00	0.0E+00	1.5E-02	1.7E+00	8.4E-02
Climate change - LULUC	*kg CO_2 eq*	6.9E+01	6.7E+01	6.2E-02	1.1E-02	1.3E-01

The impact of the agricultural phase remains high on many impact categories. The contribution of the manufacturing processes (starch slurry process and potable alcohol process) however is important on many impact categories as well. When comparing the manufacturing processes, it is clear that the potable alcohol process is the larger contributor to almost all categories except ozone depletion, freshwater eutrophication and biogenic carbon change. This large relative contribution is caused by the energy (heat) consumption in the potable alcohol process. Transport of wheat to the starch companies has no significant impact on any category. The impact on climate change is mainly determined by cultivation of wheat, followed by the manufacturing processes of which the potable alcohol process is the major contributor.

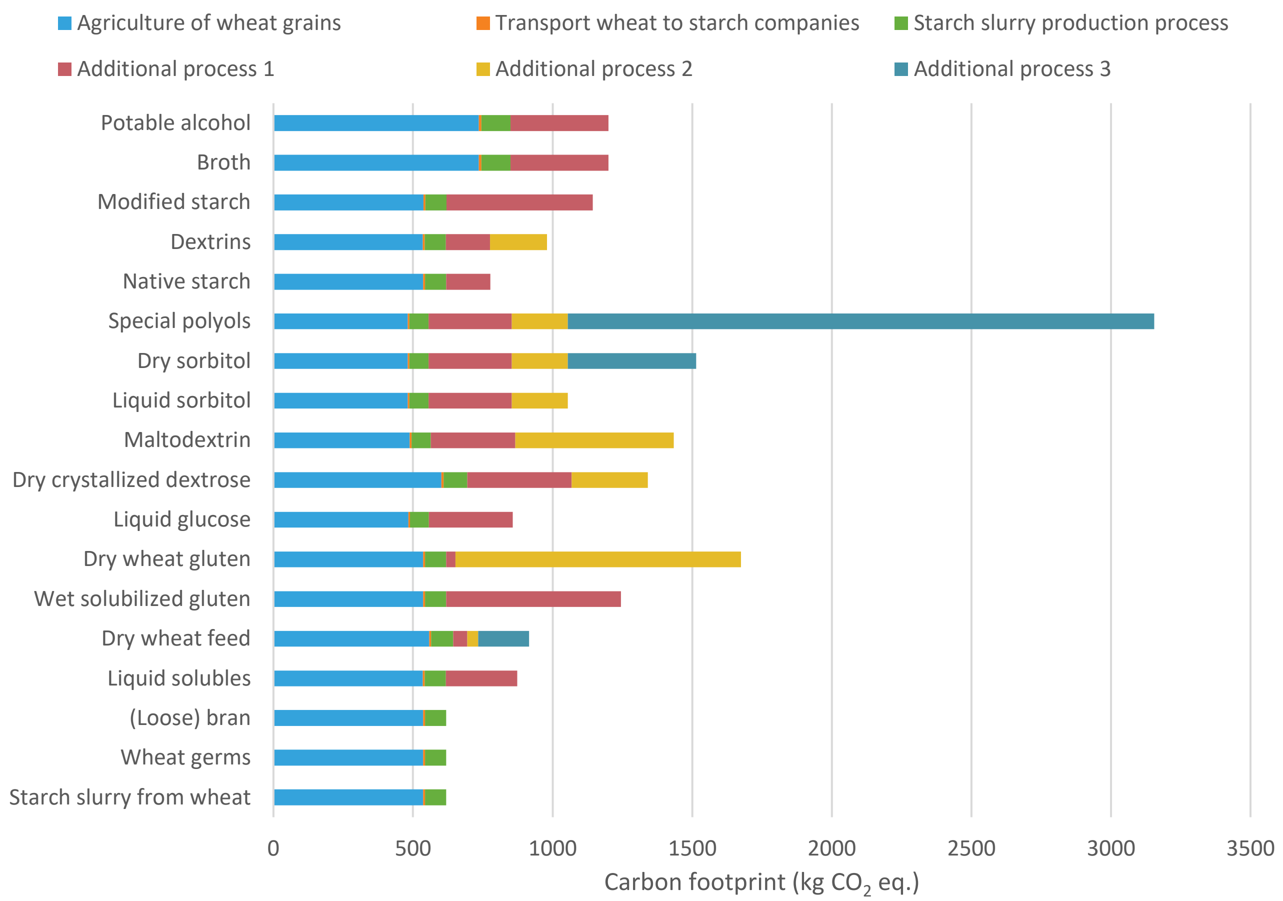
The impact of the potable alcohol process is mainly caused by energy consumption. Water consumption only has a large contribution to the impact category water use (depletion). The auxiliaries also have a significant impact on some categories (ozone depletion, freshwater eutrophication, resource use (minerals and metals)). The treatment of waste water does not have a significant influence on any impact category.

4.3. COMPARATIVE ENVIRONMENTAL PROFILES

The impact of all products starting from one raw material is presented in one graph for climate change (carbon footprint). The comparison has been made as well for the products starting from the weighted average mixture of raw materials.
The profile for starch slurry is shown as well, although this is an intermediate product and not sold as such. Since it is an important intermediate product and building block in the environmental profile of the other reference products, the impact is shown separately.

4.3.1. CLIMATE CHANGE IMPACT OF PRODUCTS FROM WHEAT

When producing starch slurry from wheat, six co-products are produced as well, two of which (wheat germs and loose bran) need no additional processes and therefore have the same profile as the starch slurry. Starting from starch slurry from wheat, 11 final products can be produced.



Reference product	Total excl. distribution (kg CO_2 eq.)	Agriculture of wheat grains	Transport wheat to starch companies	Starch slurry process	Additional process 1	Additional process 2	Additional process 3
Starch slurry from wheat	618,6	535,9	6,83	75,9			
Wheat germs	618,6	535,9	6,83	75,9			
(Loose) bran	618,6	535,9	6,83	75,9			
Liquid solubles	873	534,7	6,81	75,7	Evaporation: 255,9		
Dry wheat feed	915,4	558,2	7,11	79,0	Evaporation: 50,6	Potable alcohol process: 38,6	Mixing and drying: 181,9
Wet solubilised gluten	1245,1	535,9	6,83	75,9	Solubilisation: 626,4		
Dry wheat gluten	1674.5	536,0	6,83	75,9	Solubilisation: 33,6	Drying: 1022,1	
Liquid glucose*	857,5	482,8	6,15	68,4	Liquid glucose production: 300,1		
Dry crystallised dextrose	1341,1	601,3	7,66	85,1	Liquid glucose production: 373,8	Crystallisation + drying: 273,2	
Maltodextrins	1433,4	488,1	6,22	69,1	Liquid glucose production: 303,4	Maltodextrins process + drying: 566,6	
Liquid sorbitol	1054,6	481,0	6,13	68,1	Liquid glucose production: 299,0	hydrogenation: 200,4	

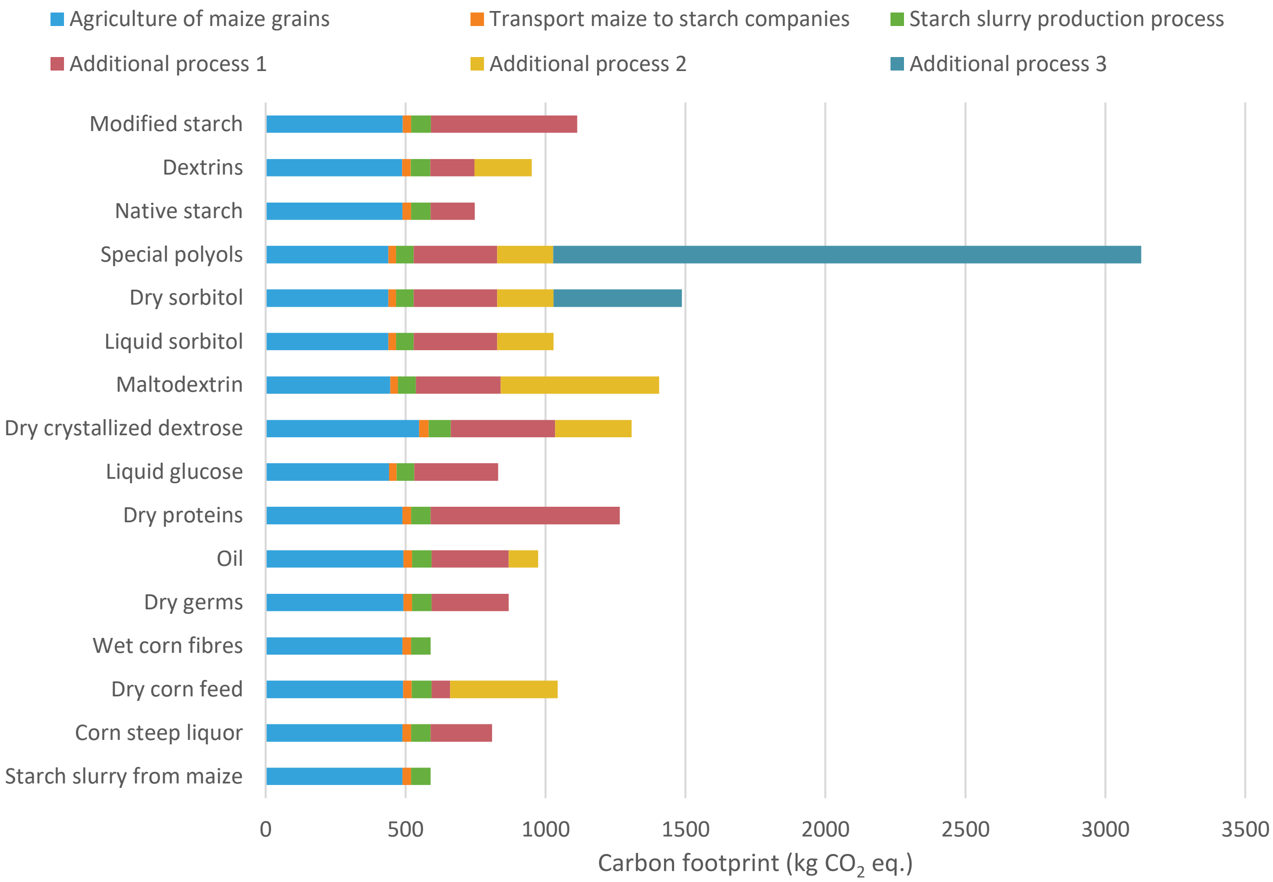
Dry sorbitol	1514,1	481,0	6,13	68,1	Liquid glucose production: 299,0	hydrogenation: 200,4	Drying: 459,6
Special polyols	3155	481,0	6,13	68,1	Liquid glucose production: 299,0	hydrogenation: 200,4	Special polyol process + drying: 2100,5
Native starch	776,7	535,7	6,83	75,8	Native starch production: 158,3		
Dextrins	980,1	535,0	6,82	75,7	Native starch production: 158,1	Drying: 204,5	
Modified starch	1143,3	536,8	6,84	76,0	Modified starch production: 523,7		
Broth	1199,9	735,5	9,37	104,1	Potable alcohol production: 350,8		
Potable alcohol	1199,8	735,5	9,37	104,1	Potable alcohol production: 350,8		

Figure 23: Comparative carbon footprint profile per tonne DS reference/co-product from wheat

The cultivation of wheat grains has for the considered products a contribution of between 480 and 740 kg CO_2 eq. per tonne DS reference or co-product. This contribution comes mainly from lime, dolomite and fertiliser emissions at the field and to a smaller extent from the production of fertilizers, energy use from agricultural machinery and drying of the grains. This contribution of the agricultural life cycle stage is directly linked to the amount of starch slurry necessary to produce a certain output product. Broth and alcohol require more starch slurry input compared to for example maltodextrins. The more additional process steps are required after the starch slurry process, the more significant the contribution of the starch plants' processes become. The use of energy (both electricity as heat) in the processing steps is very important for climate change. This is logical since combustion emissions such as carbon dioxide, methane and dinitrogen monoxide contribute greatly to the greenhouse effect. The starch products having the largest carbon footprint are dry wheat gluten, maltodextrins, dry sorbitol and special polyols. For dry wheat gluten, dry sorbitol and maltodextrins, especially the drying process has a large contribution. For special polyols the special polyol and drying process is the most important contributor.

4.3.2. CLIMATE CHANGE IMPACT OF PRODUCTS FROM MAIZE

When producing starch slurry from maize, six co-products are produced as well, which all need additional processing. Starting from starch slurry from maize, nine reference products can be produced. Since for potable alcohol and broth, no starch slurry from maize was reported as an input, their profile is not shown in the comparison.



Reference product	Total excl. distribution (kg CO_2 eq.)	Agriculture of maize grains	Transport wheat to maize companies	Starch slurry production process	Additional process 1	Additional process 2	Additional process 3
Starch slurry from maize	589,0	488,8	30,47	69,7			
Corn steep liquor	809,2	489,0	30,49	69,7	Evaporation: 220,9		
Dry corn feed	1042,9	491,5	30,64	70,1	Evaporation: 66,5	Fibre drying: 384,1	
Wet corn fibres	589,0	488,8	30,47	69,7			
Dry germs	868,5	491,9	30,67	70,2	Germ drying: 275,8		
Oil	973,1	492,0	30,68	70,2	Germ drying: 275,9	Pressing: 104,3	
Dry proteins	1265,5	488,8	30,48	69,7	Protein drying: 676,5		
Liquid glucose	830,8	440,4	27,46	62,8	Liquid glucose production: 300,1		
Dry crystallized dextrose	1307,9	548,5	34,20	78,2	Liquid glucose production: 373,8	Crystallisation + drying: 273,2	
Maltodextrin	1406,5	445,2	27,76	63,5	Liquid glucose production: 303,4	Maltodextrins process + drying: 566,6	
Liquid sorbitol	1028,0	438,7	27,35	62,6	Liquid glucose production: 299,0	hydrogenation: 200,4	

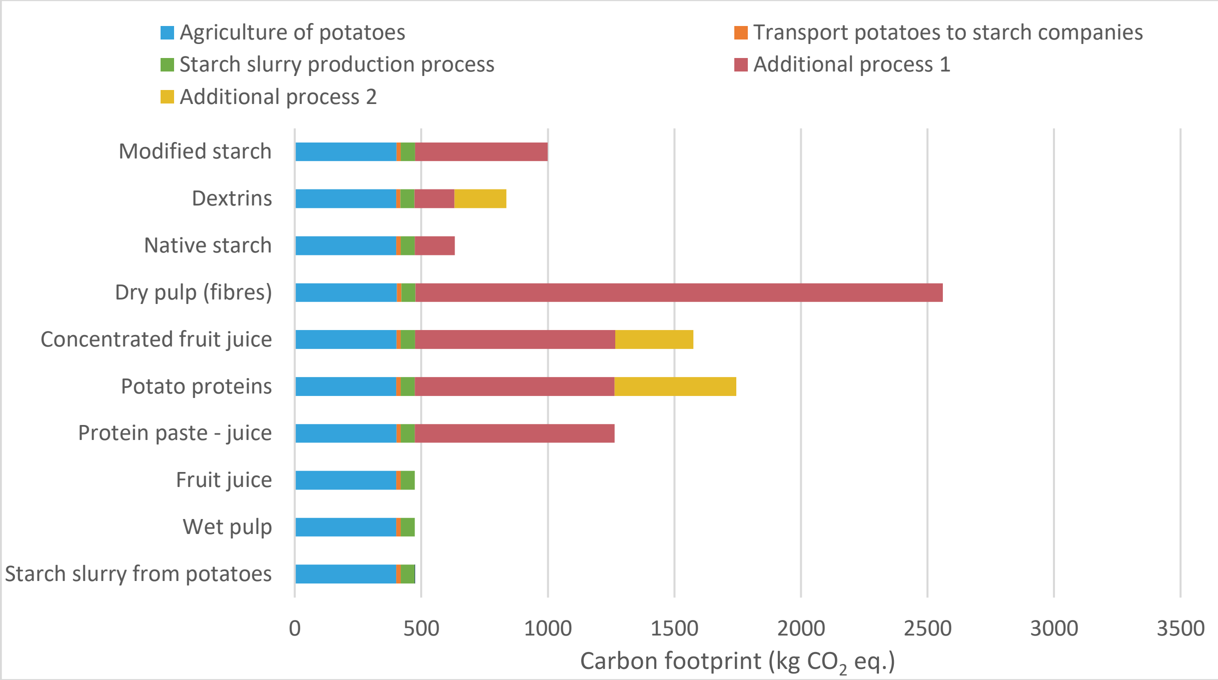
Dry sorbitol	1487,5	438,7	27,35	62,6	Liquid glucose production: 299,0	hydrogenation: 200,4	Drying: 459,6
Special polyols	3128,5	438,7	27,35	62,6	Liquid glucose production: 299,0	hydrogenation: 200,4	Special polyol process + drying: 2100,5
Native starch	747,1	488,6	30,46	69,7	Native starch production: 158,3		
Dextrins	950,5	487,9	30,42	69,6	Native starch production: 158,1	Drying: 204,5	
Modified starch	1113,7	489,6	30,53	69,8	Modified starch production: 523,7		

Figure 24: Comparative carbon footprint profile per tonne DS reference/co-product from maize

For most products the agricultural life cycle phase contributes quite significantly to the carbon footprint. Similarly to the impact of wheat grains, this contribution comes mainly from lime, dolomite and fertiliser emissions on the field and to a smaller extent from the production of fertilisers, energy use from agricultural machinery and drying of the maize grains. The more additional process steps are needed after starch slurry production, the more significant the contribution of the starch plants' processes becomes. For dry proteins, the step after the starch slurry production is a drying step, which requires a lot of energy. Due to combustion of fuels, emissions that contribute to the greenhouse effect are created. The additional processing steps for the products liquid glucose, dry crystallised dextrose, maltodextrin, liquid sorbitol, dry sorbitol, special polyols, native starch, dextrins and modified starch are identical to the additional processing steps to produce these products from wheat.

4.3.3. CLIMATE CHANGE IMPACT OF PRODUCTS FROM POTATOES

When producing starch slurry from potatoes, six final co-products are produced, two of which need no additional processes (fruit juice and wet pulp) and therefore have the same profile as the starch slurry. Starting from starch slurry from potatoes, three final reference products can be produced. For the other final products no starch slurry from potatoes is used as an input.



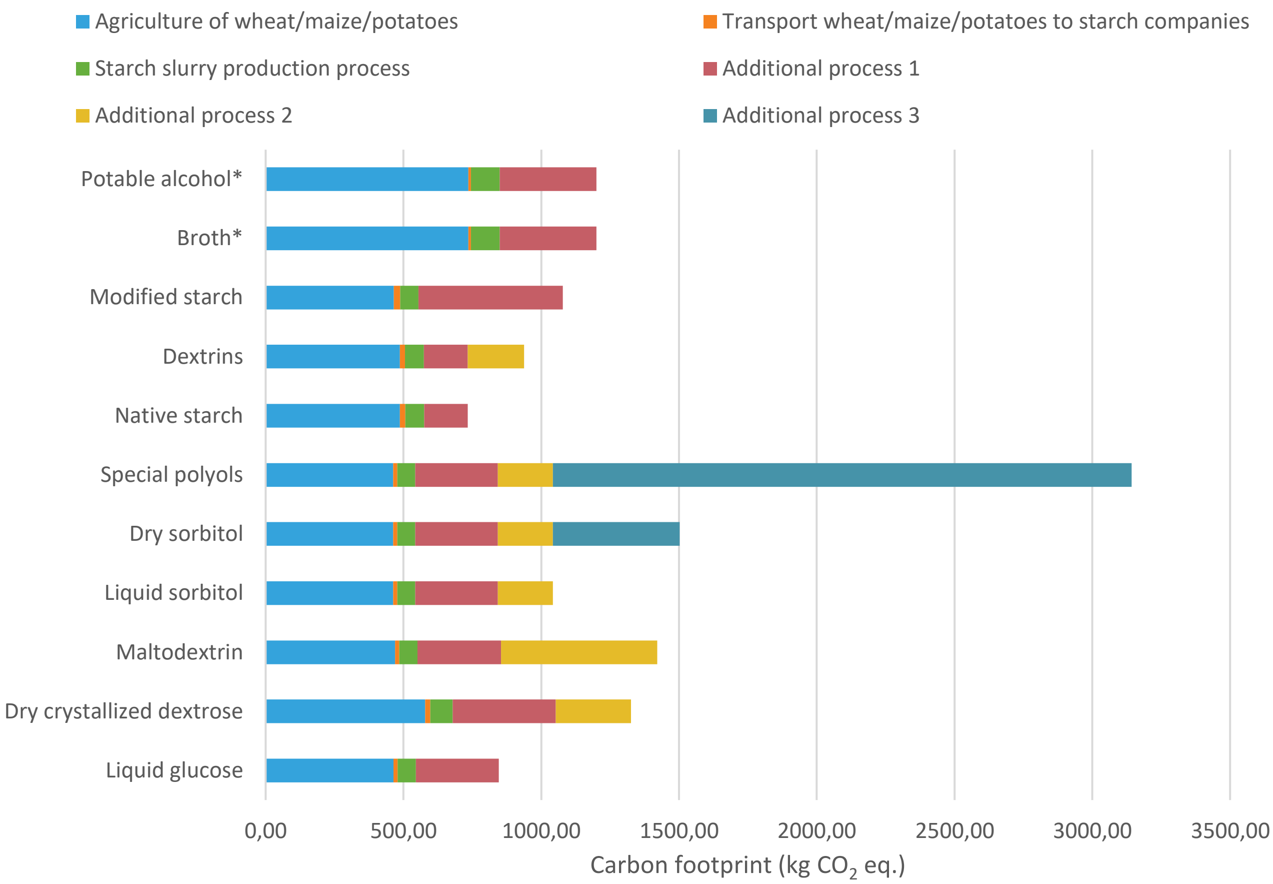
Reference product	Total excl. distribution (kg CO_2 eq.)	Agriculture of potatoes	Transport potatoes to companies	Starch slurry production process	Additional process 1	Additional process 2
Starch slurry from potatoes	474,2	401,4	17,01	55,8		
Wet pulp	474,2	401,4	17,01	55,8		
Fruit juice	474,2	401,4	17,01	55,8		
Protein paste - juice	1264,3	401,5	17,01	55,8	Protein separation:790,0	
Potato proteins	1744,0	401,3	17,00	55,8	Protein separation:789,6	Protein drying: 480,4
Concentrated fruit juice	1574,9	402,1	17,04	55,9	Protein separation:791,1	Evaporation: 308,7
Dry pulp (fibres)	2560,8	403,6	17,10	56,1	Pulp drying: 2084,0	
Native starch	632,4	401,3	17,00	55,8	Native starch production: 158,3	
Dextrins	836,0	400,7	16,98	55,7	Native starch production: 158,1	Drying: 204,5
Modified starch	998,7	402,1	17,04	55,9	Modified starch production: 523,7	

Figure 25: Comparative carbon footprint profile per tonne DS reference/co-product from potatoes

Of all processes, the protein separation process (additional process 1 for products protein paste/juice, potato proteins and concentrated fruit juice) and the drying process (additional process 1 for dry pulp) make the largest contribution to the carbon footprint of all processes. It is the steam input in these processes which makes them so significant. The additional processing steps for the products native starch, dextrins and modified starch are identical to the additional processing steps to produce these products from wheat and maize. For most products the agricultural life cycle phase contributes quite significantly to the carbon footprint. This contribution results for approximately 50% from lime, dolomite and fertiliser emissions on the field and for approximately 50% from the production of fertilisers, energy use from agricultural machinery and the potato raw material itself.

4.3.4. CLIMATE CHANGE IMPACT OF PRODUCTS STARTING FROM A WEIGHTED AVERAGE INPUT

The weighted average is calculated from reported amounts by the member companies. The relative amounts per raw material are different for each of the 11 final products. Broth and potable alcohol are only produced from wheat and therefore the crop cultivation represents for those two products only the cultivation of wheat. Liquid glucose and its derivatives are only produced from wheat and maize, so the crop cultivation is only referring to these crops.



Reference product	Total excl. distribution (kg CO_2 eq.)	Agriculture of wheat/ maize/ potatoes	Transport wheat/ maize/ potatoes to starch companies	Starch slurry production process	Additional process 1	Additional process 2	Additional process 3
Liquid glucose	845,5	464,3	15,13	65,9	Liquid glucose production: 300,1		
Dry crystallised dextrose	1326,2	578,3	18,85	82,1	Liquid glucose production: 373,8	Crystallisation + drying: 273,2	
Maltodextrin	1421,3	469,4	15,30	66,6	Liquid glucose production: 303,4	Maltodextrins process + drying: 566,6	
Liquid sorbitol	1042,6	462,5	15,08	65,7	Liquid glucose production: 299,0	hydrogenation: 200,4	
Dry sorbitol	1502,2	462,5	15,08	65,7	Liquid glucose production: 299,0	hydrogenation: 200,4	Drying: 459,6
Special polyols	3143,2	462,5	15,07	65,7	Liquid glucose production: 299,0	hydrogenation: 200,4	Special polyol process +

							drying: 2100,5
Native starch	733,9	487,3	19,33	69,0	Native starch production: 158,3		
Dextrins	937,3	486,6	19,30	68,9	Native starch production: 158,1	Drying: 204,5	
Modified starch	1078,3	464,9	23,90	65,8	Modified starch production: 523,7		
Broth*	1199,8	735,5	9,37	104,1	Potable alcohol process: 350,8		
Potable alcohol*	1199,8	735,5	9,37	104,1	Potable alcohol process: 350,8		

Figure 26: Comparative carbon footprint profile per tonne DS reference/co-product from the weighted average mix

The three products with the highest carbon footprint are special polyols, dry sorbitol and maltodextrins. For special polyols, the largest contribution results from the special polyol and drying process. The additional processes to produce dry sorbitol and maltodextrins require mostly energy inputs which is responsible for a significant contribution to the carbon footprint.

4.3.5. Sensitivity analysis

The results of an LCA depend on different factors. Sensitivity analyses assess the influence of the most relevant and most uncertain factors on the results of the study. The results of these sensitivity analyses are compared to the basic scenarios. Sensitivity analyses do not make the basic data of a study more reliable, but allow to assess the effect of a change in inventory data on the results and conclusions of the study.

In this study a sensitivity analysis on economic versus mass allocation for the agricultural production has been done.

4.4. Sensitivity analysis economic versus mass allocation for agriculture

To assess the effect of choosing economic allocation for the raw materials, a comparison of the result with economic and mass allocation was made for 2 products. One wheat-based product (dry wheat gluten) and one maize-based product (dry corn feed) were chosen, as for potatoes the type of allocation does not affect the results. For the starch industry processes, DS mass allocation is always used. The profiles below show that the environmental impact for wheat and maize-based products is a bit larger when economic allocation is chosen. The reason is that a smaller share of the impact of crop growing is allocated to the by-products wheat straw and maize stover if economic allocation is chosen. The difference between economic and mass allocation is the largest for wheat. Using mass allocation instead of economic allocation for the agricultural life cycle stages leads to a lower impact for all the considered impact categories. This study thus applies a worst case situation rather than a best case situation for the modelling of the agricultural life cycle phase.

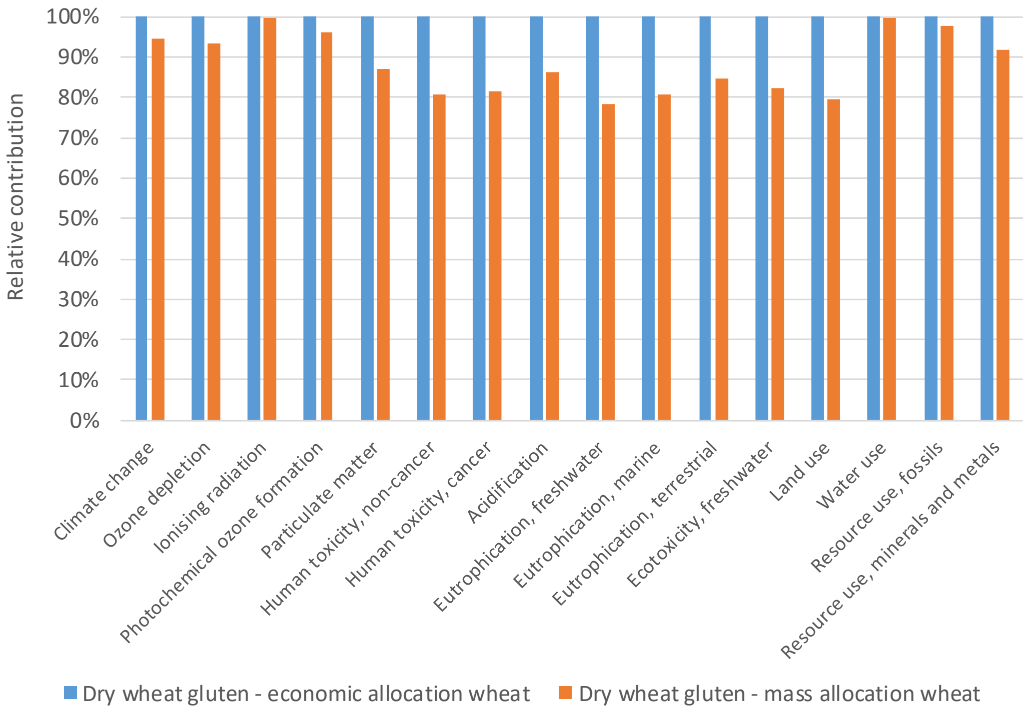


Figure 27: Environmental profile 1 tonne DS dry wheat gluten, economic versus mass allocation for wheat

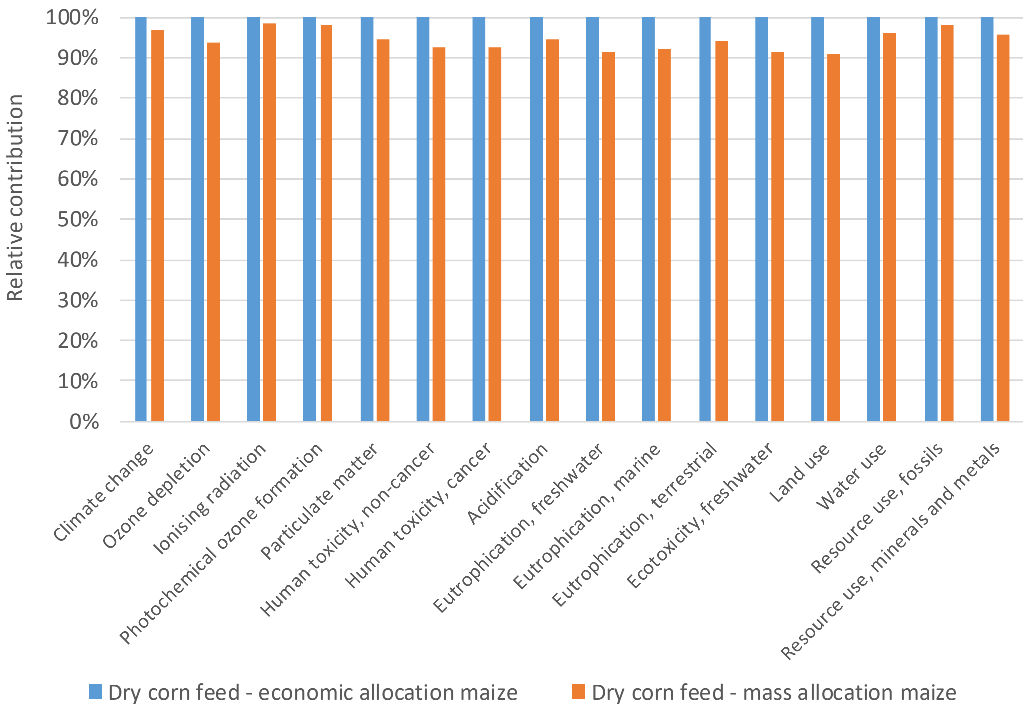


Figure 28: Environmental profile 1 tonne DS dry corn feed, economic versus mass allocation for maize

CHAPTER 5 SUMMARY CONCLUSIONS

The LCA clearly shows the importance of the agricultural life cycle phase in the environmental impact of starch products. The significance of the agricultural phase is high but varies between the impact categories. The agricultural life cycle phase is responsible for the majority of the impact to particulate matter, toxicity (human and ecotoxicity), eutrophication and water use. For climate change, the growing of the crops causes a comparable or higher contribution as the starch industry processes, except for those products where different additional processes (like drying) take place. In these cases the impact of the processes taking place at the starch industry plants is more important. Only to ozone depletion, ionising radiation, photochemical ozone depletion and fossil resource depletion the contribution of agriculture is less to not significant. These impact categories are mainly driven by electricity use and transport. This accounts for all three crops, wheat, maize and potatoes.

Focussing on the production processes that take place at the starch plant, it is the use of electricity and heat that drives the environmental impact. This is of course more distinct for the impact categories that are directly related to energy use like climate change and depletion of fossil fuels, and less important for impact categories such as land use, water use and ozone depletion. The impact of the starch slurry production process is generally lower than the impact of the additional processes. Processes that contribute significantly are for example drying (of dry wheat gluten, dry sorbitol) and separation (of potato proteins).
For some starch products and processes chemicals and other auxiliary materials are needed. The impact of these is of course highly dependent on the product and process, but for some products (like liquid glucose) the use of sodium hydroxide and hydrochloric acid causes a significant contribution to many environmental impact categories.

Looking overall to the carbon footprint of the different starch products, it is clear that the products requiring the most process steps have a higher carbon footprint. As carbon footprint is directly related to the energy use, the carbon footprint is the highest for products that require a drying step (e.g. special polyols, dry sorbitol, maltodextrins).

This LCA also highlights the important contribution of the electricity and heat required for the starch industry processes to the climate change impact of the sector's products. Of note in this context is that important progress has been made in this regard. By comparing the results of the last LCA study conducted by Starch Europe (based on data from 2009), we estimate that GHG emissions from starch plants have declined by 7% in total and by 19% per tonne of dry substance produced between 2009 and 2019.

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