Comparative Life Cycle Assessment of Plant-Based Meats and Conventional Animal Meats

Report

LCA Study Commissioner:

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April 2024

DOI: https://doi.org/10.62468/casv3213

Acknowledgement: This ISO-certified life cycle assessment was supported by data & knowledge from Bühler Environmental Impact Services.

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List of abbreviations

BOD	Biochemical oxygen demand
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
COD	Chemical oxygen demand
DF	Dry fractionation
DOC	Dissolved organic carbon
DQI	Data quality indicator
GFI	The Good Food Institute
HCl	Chlorohydric acid
HME	High moisture extrusion
ISO	International Organization for Standardization
K_2O	Potassium oxide
LCA	Life cycle assessment
LCI	Life cycle inventory
LME	Low moisture extrusion
MAP	Monoammonium phosphate
MRO	Midwest Reliability Organization
MSW	Municipal solid waste
N_2O	Dinitrogen monoxide
NaOH	Sodium hydroxide
NH_3	Ammonia
NH_4	Ammonium
NO_x	Nitrogen oxides
PB	Plant-based
PM	Particulate matter
SO_2	Sulfur dioxide
TOC	Total organic carbon
U.S.	United States of America
WF	Wet fractionation
WFLDB	World Food LCA Database
Wt%	Percentage by wet weight

Note: Being consistent with the WFLDB datasets on conventional meat systems, the term “cattle” refers to the living animal and “beef” refers to the products once the animal has been slaughtered. The same logic is applied to “swine” and “pork” and “broiler” and “chicken.”

Executive summary

The Good Food Institute (GFI) and EarthShift Global conducted a life cycle assessment (LCA) to quantify and compare the environmental impacts of plant-based meat and animal-based meat. This study follows the International Organization for Standardization (ISO) 14040 and 14044 standards for comparative assertion and public disclosure, including critical review by a panel of three independent LCA experts.

A full cradle-to-manufacturing gate analysis of three plant-based and three animal-based meat products is included (Table 0-1). The meat products are compared with a 1 kg ground, ready-to-cook functional unit excluding packaging, storage, and distribution, as the marketed portions, consumption methods, and macronutrient profiles are similar. The plant-based meat recipes are hypothetical approximations chosen for their market representativeness and technological readiness. The life cycle impacts of each product are assessed with mass allocation criteria using the ReCiPe 2016 method and 18 midpoint impact categories, including global warming, land use, and water consumption. The full scope of the study is detailed in Section 3.

Table 0-1. Meat products described in this LCA.

System	Meat Type	Primary Raw Material	Primary Processing Methods
1	Plant-based	Pea	Dry fractionation. Low moisture extrusion.
2		Pea	Wet fractionation. High moisture extrusion.
3		Soy	Wet fractionation. High moisture extrusion.
4	Animal-based	Cattle	Slaughtering. Grinding.
5		Swine	Slaughtering. Grinding.
6		Chicken	Slaughtering. Grinding.

Data from plant-based protein manufacturers, scientific papers, and commercially available LCA datasets are used to model plant-based meat production. Animal-based meat production is modeled using U.S.-based intensive production data from commercially available LCA datasets, namely ecoinvent and the World Food LCA Database. Data used in this study are outlined in Section 4, which includes a full life cycle inventory (LCI). Additional LCI documentation is available in Appendix A.1.

The impact assessment results of this study are presented with full granularity in Section 5, including individual contribution analyses for each ingredient and process to all 18 midpoint impact categories. In addition, anonymized, aggregated results are available in Appendix A.2. The key takeaways from the impact assessment results are:

- On average, plant-based meat shows 89% less environmental impact than animal-based meat in most impact categories, due to the feed basket requirements, emissions, and operations associated with animal husbandry (Figure 0-1).
- Beef and pork show the highest impacts across all meat products. Compared to the plant-based meat average, beef, pork, and chicken show 91%, 88%, and 71% higher environmental impacts, respectively.
- Of the three plant-based meat products, System #2 produced with wet fractionation of peas and high moisture extrusion shows higher impacts in a majority of categories due to the electricity and heat requirements associated with wet fractionation.
- Ingredients used in small amounts in plant-based meat recipes, particularly coconut oil and canola oil, have disproportionately large environmental impacts in certain categories.

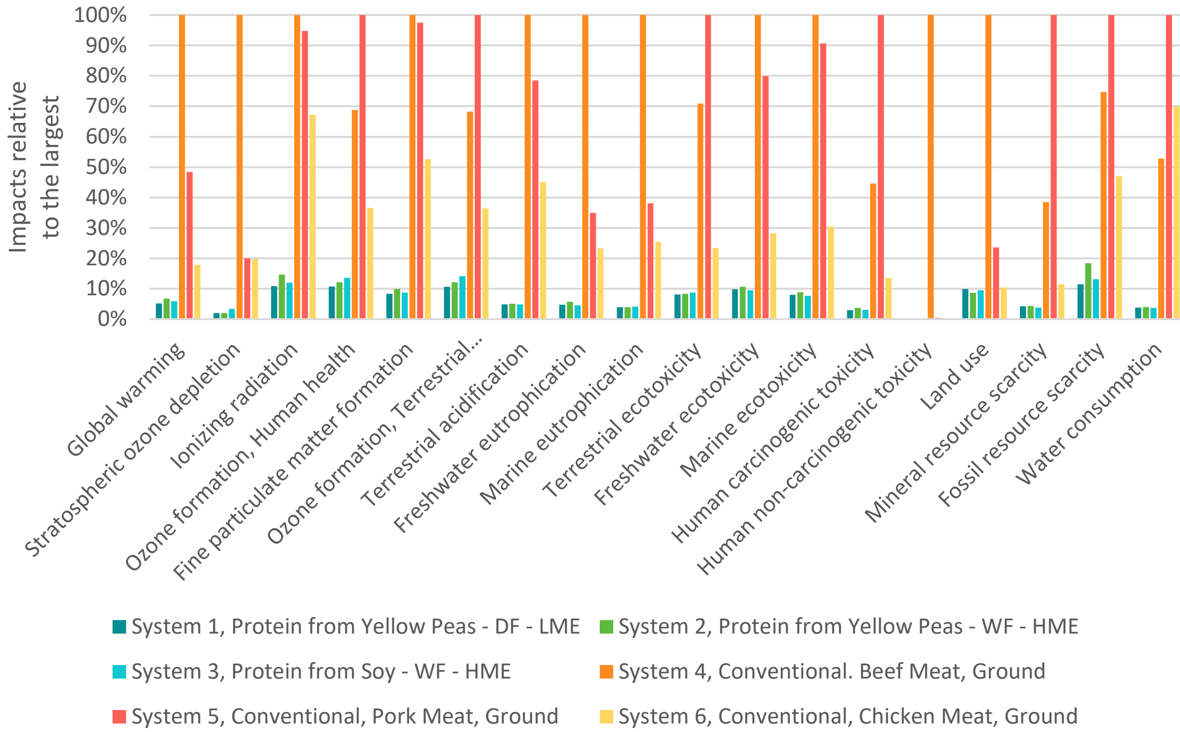

Figure 0-1. Comparison between life cycle impacts for Systems #1-6, 1 kg of ground food with meat or meat alternatives ready to be cooked, from cradle-to-manufacturing gate, before packaging or cooling. Method: ReCiPe 2016 Midpoint (H) V1.03. Data available in Table A-34.

Sensitivity analyses to examine the effect of energy consumption and source, allocation approach, and crop geography are included. Economic allocation is applied to all products, while energy and crop geography sensitivities are applied to plant-based meat only. Animal-based meat shows consistently higher impacts than plant-based meat when the comparisons are expanded to include all scenarios. However, uncertainty analyses reveal that no conclusion can be reached for certain impact categories due to the quality of data available, namely human carcinogenic and non-carcinogenic toxicity and water consumption. In addition, only certain plant-based meat recipes have lower freshwater and marine ecotoxicity and land use impacts than animal meat. Still, plant-based meat shows lower environmental impacts than animal-based meat within a 95% confidence interval for 12 out of 18 impact categories. Sensitivity and uncertainty analyses are described in Section 6, with aggregated results available in Appendix A.3 for the former.

This study provides detailed insight into the environmental impact drivers of plant-based and animal-based meat. Though plant-based meat shows consistently lower environmental impacts than animal-based meat, the former can be further improved by optimizing fractionation, drying, and extrusion processes, exploring alternatives to coconut and canola oil, and promoting a transition to renewable energy.

1. Introduction

The Good Food Institute (GFI) is a nonprofit think tank that researches and promotes plant-based, fermentation-derived, and cultivated alternatives to animal products such as meat, dairy, seafood, and eggs. GFI gathers a large interdisciplinary group of scientists, policymakers, and entrepreneurs to focus on accelerating the growth of the alternative protein sector through science, policy, and industry:

- GFI funds open-access research on plant-based, fermentation-derived, and cultivated meat technologies;
- GFI supports alternative proteins policies by contesting regulations against plant-based, fermentation-derived, and cultivated alternatives, and securing public funding;
- GFI promotes plant-based, fermentation-derived, and cultivated technologies by providing commercial guidance, doing market research, and helping startups connect with industry networks and secure investment.

As part of these efforts, GFI would like to better understand the factors that drive the environmental impacts of plant-based meat and compare the results to conventional meat.

2. Goal of the study

The first phase of a life cycle assessment (LCA) is to define the goal and scope of the study. According to ISO 14044, the goal of the study should specify the following: the intended application, reasons for carrying out the study, the intended audience, and whether the results are intended to be disclosed to the public.

The primary goal of this study is to quantify the environmental impacts of plant-based proteins, considering the current available technologies, and to compare them with the environmental impacts of conventional meat-producing systems (i.e., cattle, pig, and chicken). Moreover, this study aims to identify potential opportunities to reduce environmental impacts and potential environmental tradeoffs between different plant-based meats.

Results of this comparative, ISO-conforming, full LCA and critical review will serve to build internal knowledge at GFI and allow GFI to inform external communications with stakeholders, policymakers, technology developers, and investors.

GFI intends to communicate the results of this study publicly. As the LCA model and report include comparisons that may affect others, it is considered a comparative assertion and follows ISO 14040 (ISO 2006a) and 14044 (ISO 2006b) requirements for comparative LCA studies and is critically reviewed by a panel of experts in LCA, conventional meat production, and alternative protein production.

3. Scope of the study

The scope of the study describes important aspects including the functional unit, system boundaries, cut-off criteria, allocation, impact assessment method, assumptions, and limitations.

The scope of this ISO-conforming LCA includes cradle-to-manufacturing gate modeling of three plant-based protein production systems and three conventional meat production systems. The scope includes:

- Crop cultivation: Farm activities, seed acquisition, upstream fuel, fertilizer, pesticide, and herbicide production, direct emissions from fuel use, and fertilizer and pesticide application.
- Crop pre-processing: Cleaning, milling, dehulling, drying.
- Plant protein production: Fractionation, extrusion.
- Animal raising: Cattle, pig, and chicken.
- Slaughtering and animal meat processing.
- Transportation: Freight, local.
- Recipe preparation: Mixing, grinding, and adding spices, binders, and oils.

Note: Every step and process include material and energy input.

3.1 Function, functional unit, performance characteristics, systems, and reference flow

3.1.1 Function, functional unit, and performance characteristics

A functional unit is the quantified performance of a product system for use as a reference unit (ISO 2006a, 2006b). This facilitates the determination of reference flows for the system being studied. ISO 14044:2006 states that the functional unit (FU) should be: (1) an accurate reflection of the study's goal and scope. This should also reflect whether the study is directly comparing two products, in which case the FU should accurately reflect both products; (2) representative of the product's function to the consumer; (3) clearly defined and measurable.

Mass-based FUs are standard across food products and can provide a reliable comparison between published analyses. Additionally, the marketed portions of plant-based and animal meat products are typically similar and, therefore, consumed at similar masses. As a result, these products function most similarly when comparing masses. Moreover, these products have similar macronutrient profiles as demonstrated in Table 3-1. Composition and structure between different protein products may vary slightly in terms of water, protein, and carbohydrate content, or in texture and mouth-feel. The product is uncooked ground meat that will need further processing into final products, which is typical for both plant-based and animal-based products.

Table 3-1. Nutritional attributes of assessed plant-based and animal meat recipes.

Nutrient	Units	Pea or Soy Meat	Beef Meat	Pork Meat	Chicken Meat
Protein	**g/100g**	19	17	17	17
Fat	**g/100g**	9	20	21	8
Saturated Fat	**g/100g**	4	8	8	2
Cholesterol	**mg/100g**	0	71	72	86
Iron	**mg/100g**	3	2	1	1
Fiber	**g/100g**	2	0	0	0
Calories	**kcal/100g**	179	254	263	143

The *functional unit* is producing 1 kg of conventional animal or plant-based ground meat product, ready to be cooked, from cradle-to-manufacturing gate, before packaging or refrigeration for transportation.

The *function* for this ISO-conforming LCA is producing edible food with a primary protein source of either conventional meat or plant-based meat.

The *performance characteristics* are that the food must be ground and ready to be cooked, and the comparison between the systems is based on mass, specifically 1 kg of product.

3.1.2 Systems description

The systems to be compared are shown in Table 3-2.

Table 3-2. Systems to produce plant-based and conventional meats compared in this LCA.

System	Meat product	Raw material	Processing and product forming methods
System #1	Plant-based meat	Yellow peas	Dry fractionation Low-moisture extrusion
System #2	Plant-based meat	Yellow peas	Wet fractionation High-moisture extrusion
System #3	Plant-based meat	Soybeans	Wet fractionation High-moisture extrusion
System #4	Conventional meat	Cattle	Slaughtering Grinding
System #5	Conventional meat	Swine	Slaughtering Grinding
System #6	Conventional meat	Chicken	Slaughtering Grinding

The reference flow refers to the measure of the outputs from processes in a given product system required to fulfill the function expressed by the functional unit (ISO 2006a, 2006b).

The reference flows for each of the product systems to be compared are:

- 1 kg of plant-based meat, base yellow peas, using dry fractionation and low moisture extrusion.
- 1 kg of plant-based meat, base yellow peas, using wet fractionation and high moisture extrusion.
- 1 kg of plant-based meat, base soybeans, using wet fractionation and high moisture extrusion.
- 1 kg of conventional meat, beef.
- 1 kg of conventional meat, pork.
- 1 kg of conventional meat, chicken.

3.2 System boundaries

System boundaries are established in an LCA to include the significant life cycle stages and unit processes, as well as the associated environmental flows in the analysis. This lays the groundwork for a meaningful assessment where all important life cycle stages and the flows associated with each system are considered. This section describes the main processes and environmental flows included in the system boundaries for plant-based meat systems (i.e., Systems #1–3) and conventional animal meat systems (i.e., Systems #4–6) for this LCA.

This LCA study defines its system boundaries as cradle-to-manufacturing gate, including all the upstream activities related to the production of the main feedstocks (plant or animal production), transport to facilities, further processing or slaughtering, and grinding (for animal meat). Similar to other published LCAs on plant-based meat systems, all downstream activities related to final distribution, retail, and consumer stages are excluded, as we assume these are similar in both types of product systems.

The boundaries established for this study are cradle-to-manufacturing gate with the intent to focus on upstream comparisons between plant- and animal-based systems. While packaging, storage, distribution, and cooking can have important contributions to the environmental impacts of plant-based and animal meat systems, these downstream steps are typically assumed to function similarly (Detzel et al. 2022; Saerens et al. 2021; Smetana et al. 2021). For companies conducting product LCAs, it is recommended to expand the system boundaries of their studies to include packaging, storage, distribution, cooking, and other downstream steps, so they can understand environmental impacts throughout the whole supply chain.

3.2.1 Plant-based systems main processes

Agricultural cultivation

The agricultural stage refers to the cultivation of peas and soybeans, which are used as the main feedstocks for the plant-based meat systems. This stage includes tillage (disk and cultivator), land rolling, seeding, swathing, harrowing, fertilizer application, in-crop herbicide application, foliar fungicide and insecticide application, combining, post-harvest herbicide application, and burndown/desiccant application.

Pre-processing

The feedstock pre-processing stage is composed of separation, cleaning, drying, and milling. In the cleaning stage up to 5% of the total weight of the feedstock is lost, usually due to insect-damaged and undersized feedstock. The clean feedstock is then dehulled and two products are obtained from this process: dehulled product and hulls. The dehulled product is then dry milled and micronized into flour.

Fractionation

Fractionation is a separation process to obtain fractions based on differences in characteristics. This study evaluates dry and wet fractionation processes.

Dry fractionation typically produces protein concentrates, and wet fractionation typically produces protein isolates, which contain a higher protein percentage than concentrates.

Dry fractionation

The dry fractionation technology modeled in this study involves air classification, which relies on the particle size and density difference of the flour obtained from dry milling. Air classification after milling physically separates the feed material (feedstock flour) into a fine (protein-rich) and a coarse (starch-rich) fraction. (De Angelis et al. 2022; Schutyser & van der Goot 2011). Separation occurs according to the aerodynamic properties of the particles, which are dependent on particle density, particle size, and powder dispersibility. When dry fractionation is applied to different crops, the resulting protein-rich fine fraction has a protein content between approximately 37 and 60% (Berghout et al. 2015; Heusala et al. 2020; Saget et al. 2021).

Figure 3-1 presents the dry fractionation process, including the pre-processing stage described above. The final product of dry fractionation is a protein concentrate.

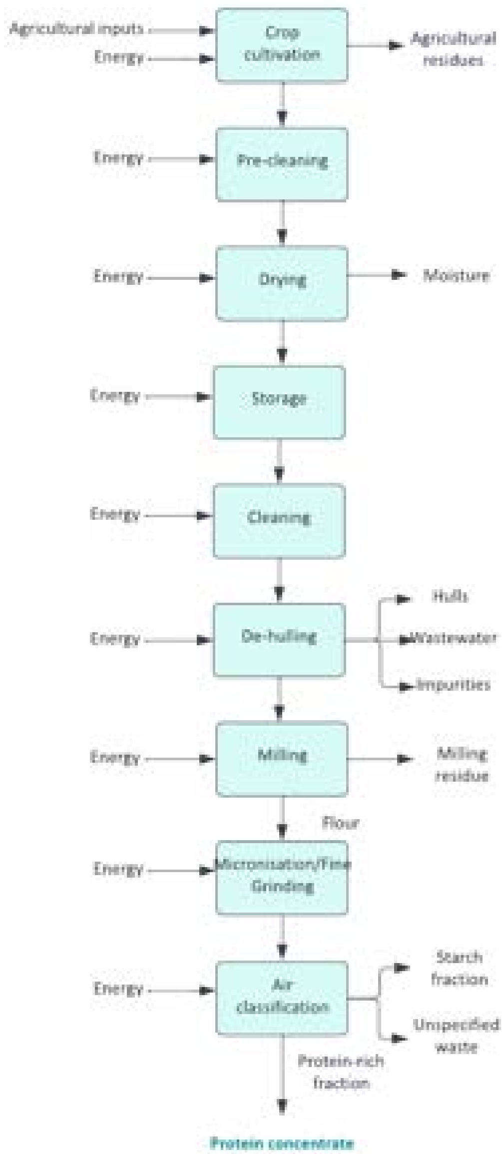

Figure 3-1. Crop cultivation, pre-processing, and dry fractionation process.

Wet fractionation

Wet fractionation technology involves extracting protein in organic or aqueous solvent at alkaline (pH 8-10) or acidic (pH <4) pH depending on the feedstock.

The wet fractionation process begins with preparing a flour suspension, which consists of soaking the feedstock flour in water or ethanol. In this process, proteins are separated based on their differences in solubility in ethanol or under aqueous alkaline or acidic conditions. For the latter, the pH of the suspension is adjusted, and the feedstock protein is separated from the rest of the fractions. Subsequently, the pH is adjusted again to the isoelectric point to precipitate protein that is then suspended and neutralized in the aqueous phase, centrifuged, and dried (Aryee and Boye 2016; Schutyser and van der Goot 2011).

Figure 3-2 presents the wet fractionation process, including the pre-processing stage described above. The final product of wet fractionation is either a protein isolate or protein concentrate, depending on the characteristics of the feedstock and degree of processing. In some instances, the isolate is prepared after multiple rounds of wet fractionation.

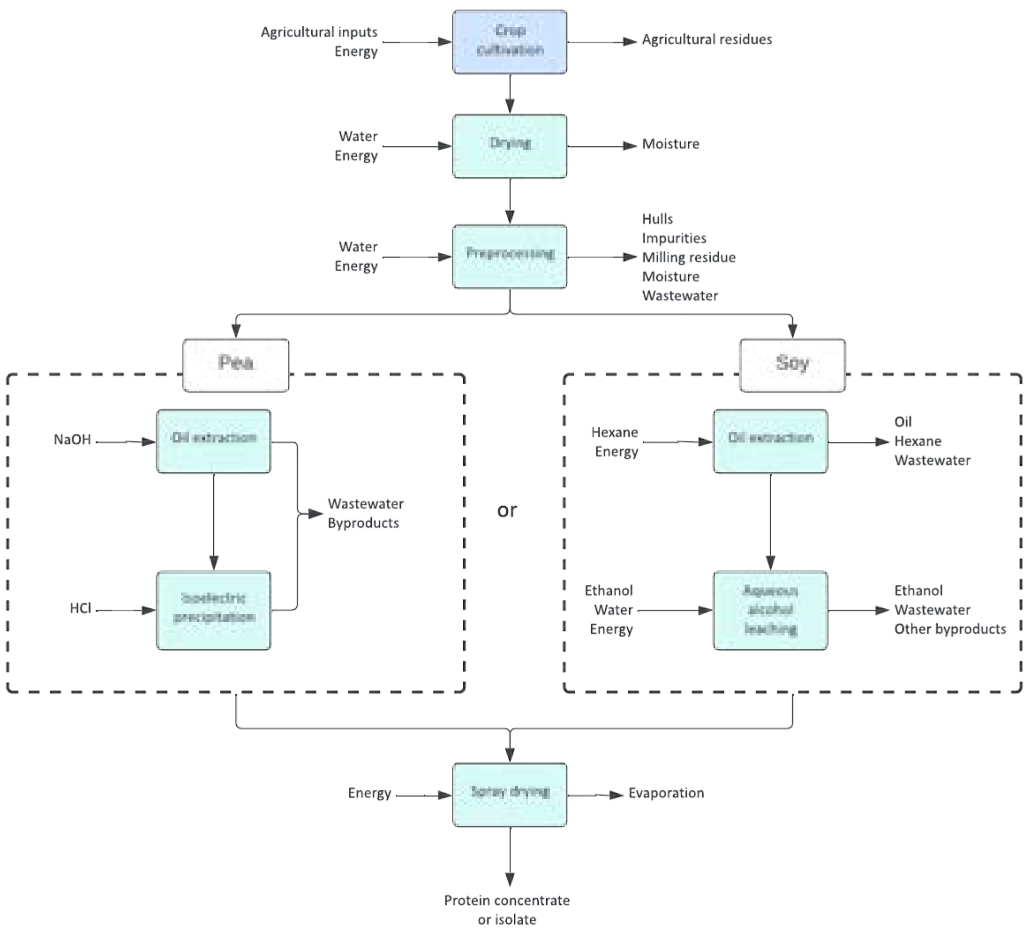

Figure 3-2. Crop cultivation, pre-processing, and wet fractionation process.

Extrusion

The extrusion process is a critical step that gives plant proteins a meat-like texture. In this process, the raw materials, or ingredients (e.g., protein isolate or concentrate), are fed into a horizontal barrel with one or more screws. The inputs are forced through a shaped die with the aid of screws inside the barrel to form the desired product. Water and electricity are the main inputs in this process, as high temperature and pressure are required.

There are two types of extrusion processes: low moisture extrusion (LME) and high moisture extrusion (HME). LME provides a porous structure to the final product, and HME gives a fibrous meat-like structure (Ferawati et al. 2021; GFI India's Technological Review of High-Moisture Extrusion for Creating Whole-Cut Plant-Based Meat 2023). In LME, the moisture content of the final material is <40% (Figure

3-3), while in HME, the product has a high moisture content (>50%), requires low temperature storage, and requires additional water for the final meat analogue (Figure 3-4) (Saerens et al. 2021).

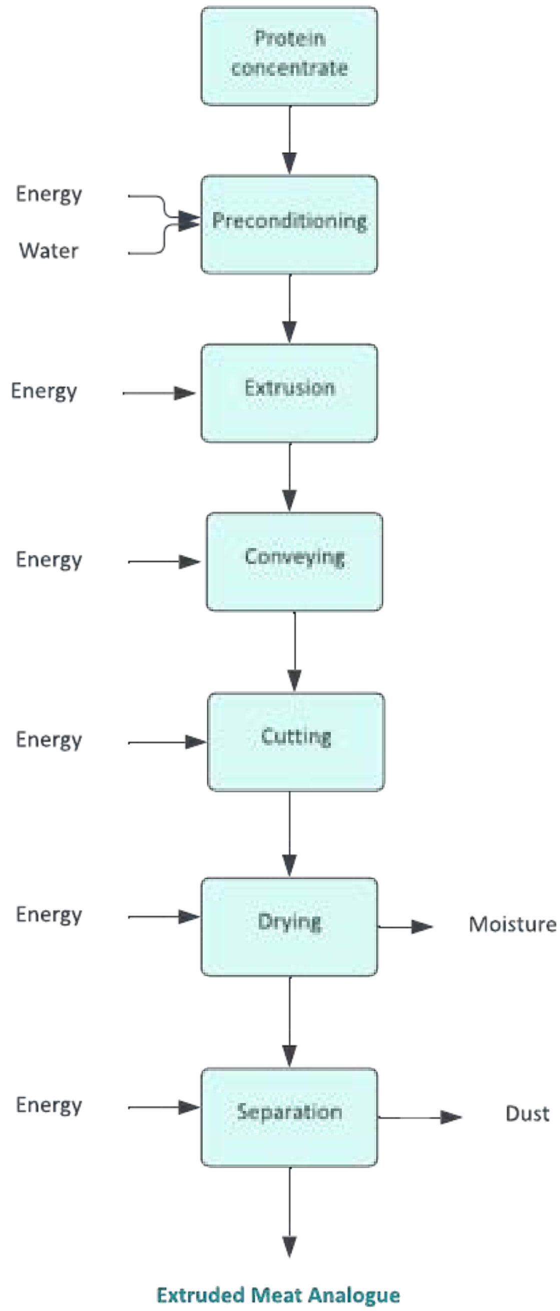

Figure 3-3. Low moisture extrusion process.

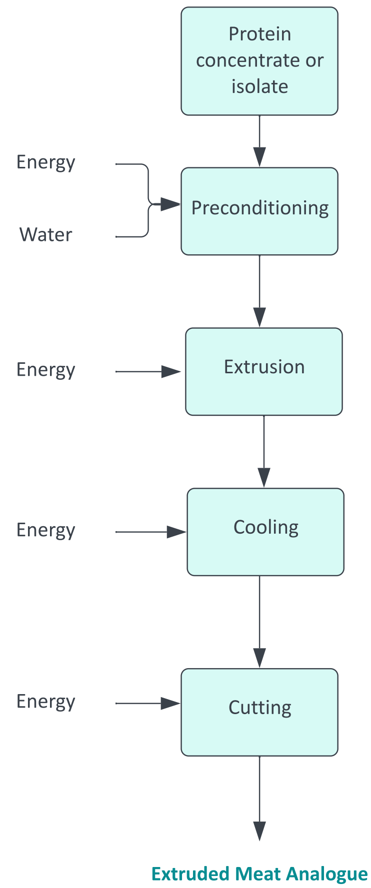

Figure 3-4. High moisture extrusion process.

3.2.2 Animal-based systems main processes

Conventional systems refer to the usual processes for obtaining animal-based meats. These production systems are based on intensive farming practices, such as feedlots for cattle farming, and include all processes from feed basket cultivation to animal husbandry to slaughtering.

These systems start at the animal husbandry stage, consisting of the birth of younglings (calves, piglets, and chicks for beef, pork, and chicken, respectively), nursery subprocess in which younglings are grown and weaned (piglets and calves), and finally the fattening subprocess where animals are fed until they reach live weight ready to be slaughtered. Both the nursery and fattening subprocesses require reception and storage of feed, livestock management operations, manure storage, drinking and cleaning water, energy use and buildings infrastructure. It is important to note that all animal husbandry subprocesses require feed (mostly grains) and each has its own agricultural cultivation system consisting of the necessary inputs required to cultivate the feed (e.g., land use, water, fertilizers, and pesticides) and outputs and emissions.

After the animals have been fattened at the farm, they are sent to the slaughterhouse as live weight. During this stage, the animals are slain requiring consumption of energy, water, several chemical agents, and other inputs. Multiple co-products are obtained from the slaughtering of the animal, including fresh meat, which is ground to be delivered at the manufacturing gate.

Given the chosen functional unit and the associated market for the final product, the conventional systems include the production of animal meat from three sources: beef, pork, and chicken. Secondary data from available database modules were used to model farm activities, animal slaughtering, and meat processing.

3.2.3 System #1

- Feedstock: Yellow peas
- Processing: Dry fractionation, resulting in a pea protein concentrate
- Product Forming: Low moisture extrusion

Background data for the agricultural production for peas is taken from the latest version of ecoinvent (3.9.1) (Wernet et al. 2016), from Canada. The peas are dried and pre-processed, which requires energy and produces pea hulls (15% of input) and pea flour (85% of input) (Saget et al. 2021, Figure 3-5).

The flour obtained from pre-processing is micronized in a mill and then dry fractionated with an air classifier. The resulting protein concentrate represents around 23% of the processed pea flour, and the starch-rich fraction and losses equal around 77%. The protein concentrate is then extruded, where 5% of the total input is lost. Finally, the extruded protein is cut, dried, and mixed with other ingredients into a plant-based patty for taste, texture, color, fortification, cooking experience, and shelf life. See Assumptions for a list of all ingredients.

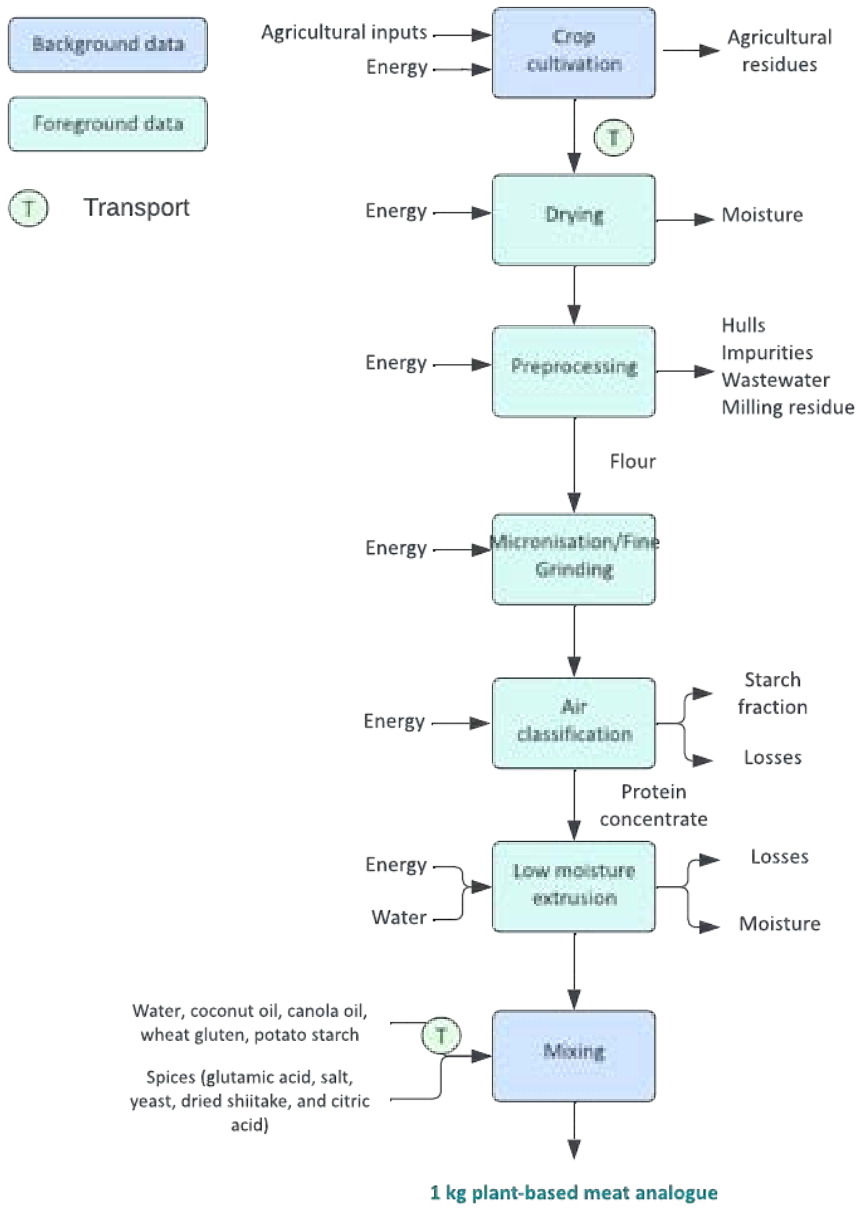

Figure 3-5. Diagram of System #1 plant-based meat production.

3.2.4 System #2

- Feedstock: Peas
- Processing: Wet fractionation, resulting in a pea protein isolate
- Product Forming: High-moisture extrusion

Background data for the agricultural production for peas is taken from the latest version of ecoinvent (3.9.1) (Wernet et al. 2016), from Canada. The peas are dried and pre-processed, which requires energy and produces pea hulls (15% of input) and pea flour (85% of input) (Saget et al. 2021, Figure 3-6).

The pea flour is then steeped in water (25 wt% solution). In this step, approximately 3% of the input is lost and considered waste. The pH is then adjusted in the protein-rich fraction to obtain an alkaline solution and facilitate protein separation. This step is followed by isoelectric precipitation, where the pH of the protein rich fraction is adjusted to the isoelectric point.

After precipitating the protein, the solution is neutralized by adjusting the pH to 7, and then the protein is spray dried. In this process, the protein solution is atomized into small droplets and then passed through a hot air stream (provided by compressed air) to obtain a fine dry protein isolate powder. Protein isolate is mixed with water and then extruded via HME; this process assumes no losses. The extruded protein is cut and mixed with other ingredients to give taste and texture to the plant-based patty. Figure 3-6 presents the production process of System #2.

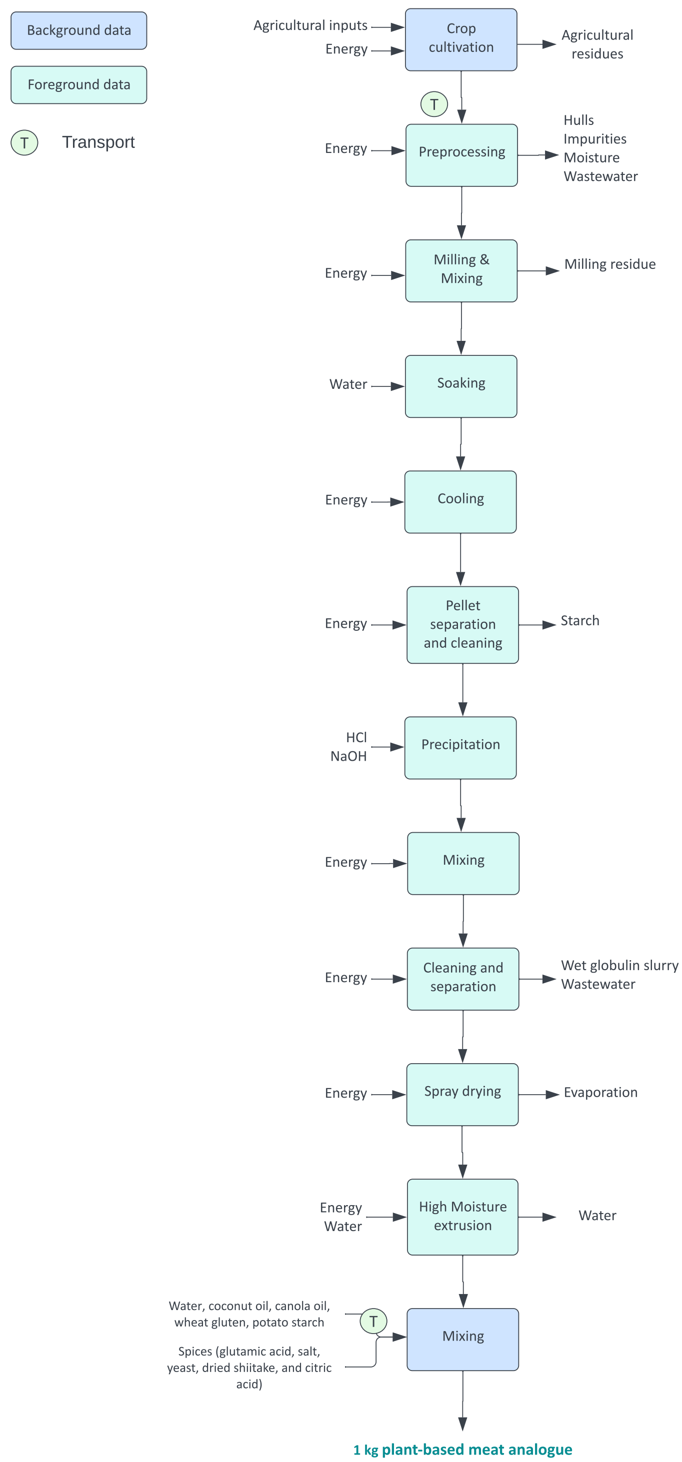

Figure 3-6. Diagram of System #2 plant-based meat production.

3.2.5 System #3

- Feedstock: Soybean
- Processing: Wet fractionation, resulting in a soy protein concentrate
- Product Forming: High moisture extrusion

Data for U.S. soybean agricultural production is taken from the latest version of ecoinvent (3.9.1) (Wernet et al. 2016). Soybeans are cleaned and dehulled using compressed air. Hulls represent 8% of the total input and are currently used for animal feed production but have the potential for high-value applications in alternative protein products (GFI's Cultivating alternative proteins from commodity crop sidestreams 2023). The soybean meal and oil are then separated (yields of 0.805 and 0.195 kg/kg of soybean as input, respectively) by subjecting the dehulled soybeans to a flake rolling process, where they are flattened by going through heated rollers (Johnson 2008).

Next, the soy full-fat flakes enter the oil extraction stage which uses hexane as the main solvent. Most of the oil available in the flakes is removed as a mixture of oil and solvent to be further distilled. The remaining solvent-laden meal goes through a vacuum desolventizing process, in which residual solvents from the meal are evaporated and removed (Veličković et al. 2023). Then, superheated stripping steam is introduced into the desolventizing chamber to eliminate any remaining solvents; the hexane and steam vapor is condensed to be reused. The extracted oil is further processed for cooking, biodiesel, and other uses. The defatted white flakes obtained from this process are subsequently cooled down and ground.

Defatted soy flakes then go into the aqueous alcohol leaching process, in which they are mixed with water and ethanol and heated to solubilize their proteins in a precipitate (Figure 3-7). The precipitate undergoes a washing process to isolate the proteins, and the protein is spray dried. In this process, the protein solution is atomized into small droplets and passed through a hot air stream (compressed air) to obtain a fine dry protein concentrate powder. Protein concentrate is mixed with water and then processed via HME. The extruded protein is cut and mixed with other ingredients to give taste and texture to the plant-based meat recipe. Figure 3-7 presents the production process of System #3.

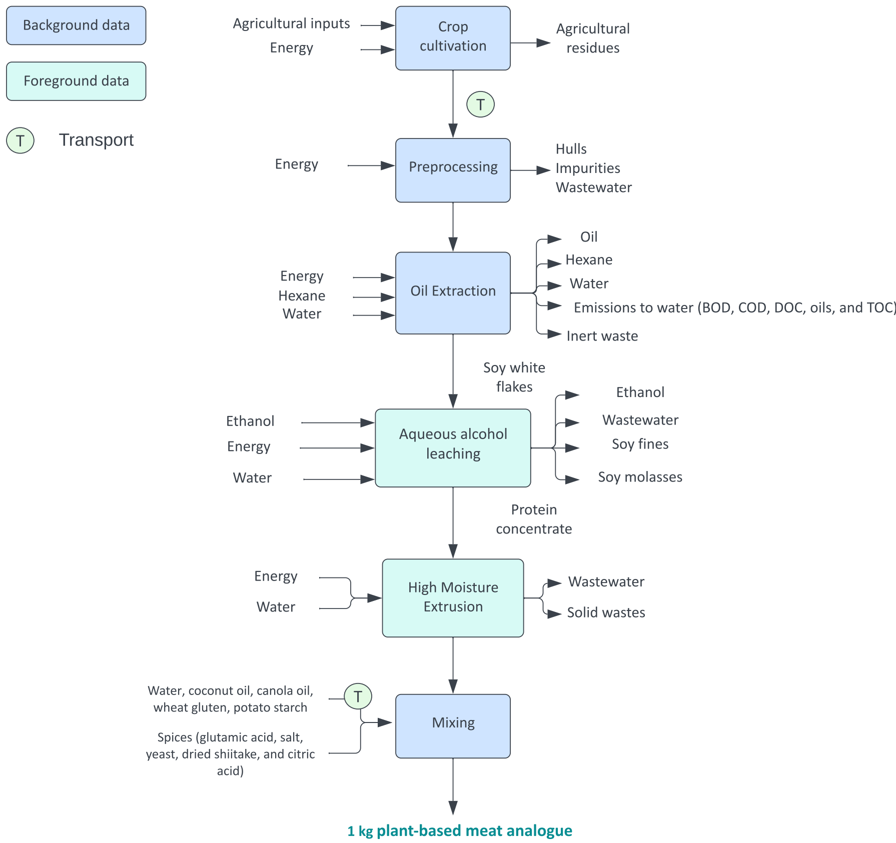

Figure 3-7. Diagram of System #3 plant-based meat production.

3.2.6 System #4

- Feedstock: Cattle
- Processing: Slaughtering
- Product Forming: Grinding

Data for beef were taken from the ecoinvent 3.9.1 database considering a cattle production system for the U.S. based on intensive production practices on pasture. The system starts with the weaned calves' animal husbandry subprocess, in which they consume maize grain and soybean meal as the main external feed inputs (cultivated in the U.S.); grass is also provided to the cattle as feed. Pasture maintenance also requires fertilizer consumption. This subprocess uses energy and water, while emitting grazing, manure management, and enteric-related emissions. Once the weaned calves reach a weight of 230 kg, they go through the feedlot subprocess until they reach 485 kg and are ready to be slaughtered. The feedlot subprocess has a more complex feed basket, which is composed of alfalfa-grass silage, defatted maize germ, maize chop, rape meal, maize grain and silage, and wheat bran (Figure 3-8); these agricultural feedstocks are modeled as sourced from the U.S., Canada, or rest of world (RoW) (without U.S.-specific data). The feedlot operation process includes water and energy use for cattle housing and manure management, and generates grazing, enteric, and manure management emissions. Once the cattle leave the farm, they are taken to the slaughterhouse. The slaughtering process involves consumption of heat, electricity, different foam cleaning agents and disinfectants, as well as biowaste and wastewater generation. Note that the animal slaughtering stage includes the use of cleaning chemicals not included in the plant-based meat systems due to data availability; the animal meat cleaning agents were left unchanged because of their adherence to background datasets. Slaughtering is a multifunctional process, since it produces meat, bones, fat, hides and skins, category 1/2 wastes (animal by-products unfit for human consumption), and category 3 wastes (carcasses and parts of slaughtered animals fit for human consumption but not intended for direct commercial consumption). Finally, fresh beef is ground and mixed to form a ground meat product, a process which primarily consumes electricity.

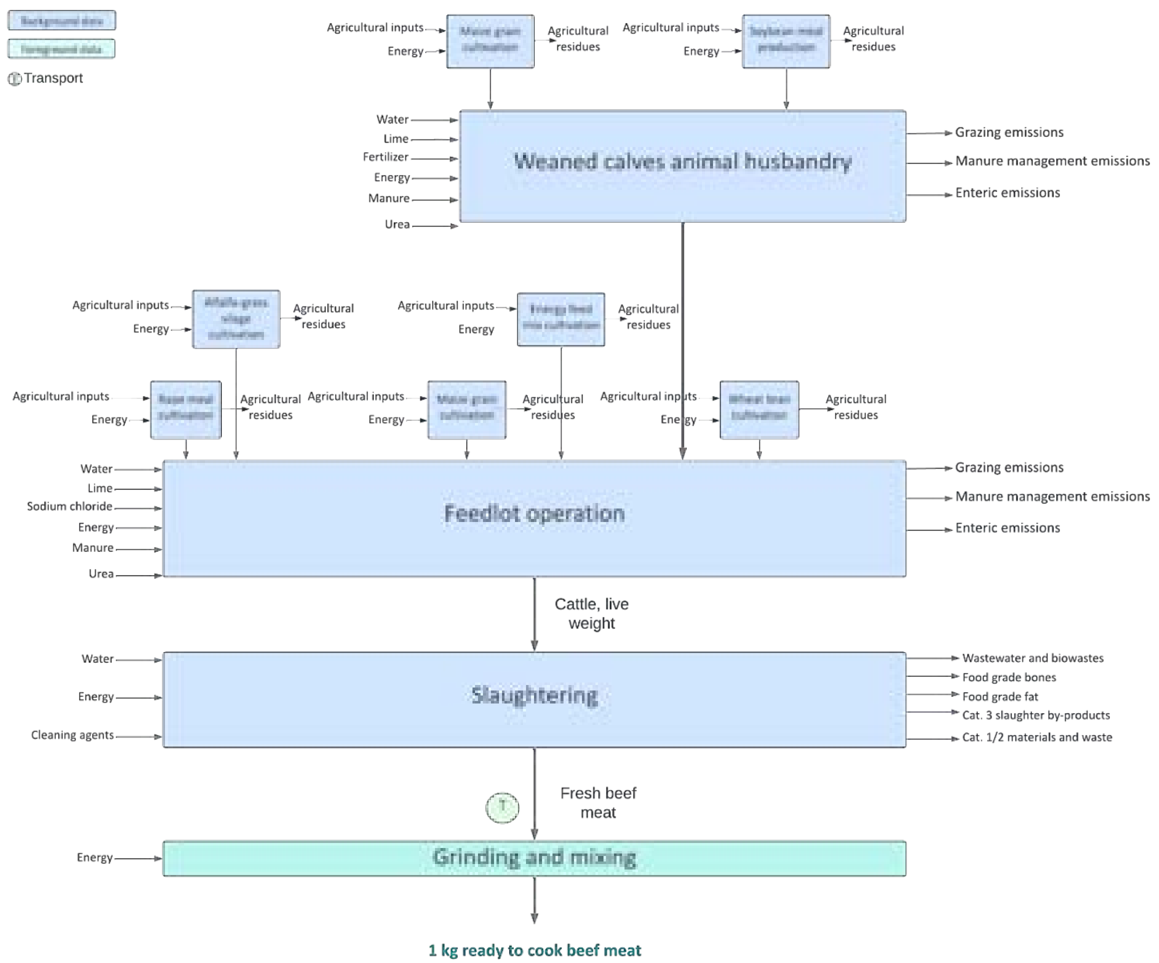

Figure 3-8. Beef meat process (based on ecoinvent 3.9.1 dataset).

3.2.7 System #5

- Feedstock: Swine
- Processing: Slaughtering
- Product Forming: Grinding

Data for pork were taken from the ecoinvent 3.9.1 database considering an average industrial system. This system starts with the agricultural cultivation of the feed basket and overall diet supplements (barley grain, oat grain, whey, rape meal, maize grain, soybean feed and meal, and wheat grain) (Figure 3-9); these agricultural feedstocks are modeled as sourced from the U.S., Canada, and RoW (without U.S.-specific data). Other processes included in the industrial swine system are heat and electricity use, water use, wastewater generation, manure management, and enteric emissions. The live weight swine are taken to the slaughterhouse, which involves different materials and energy carriers such as heat, electricity, water, disinfectants, and foam cleaning agents as inputs, and biowaste and wastewater as emissions. The slaughterhouse produces four different products: fresh meat, food grade bones, food grade fat, and category 3 byproducts. Afterward, fresh pork is ground and mixed to form a ground meat product, a process that primarily consumes electricity.

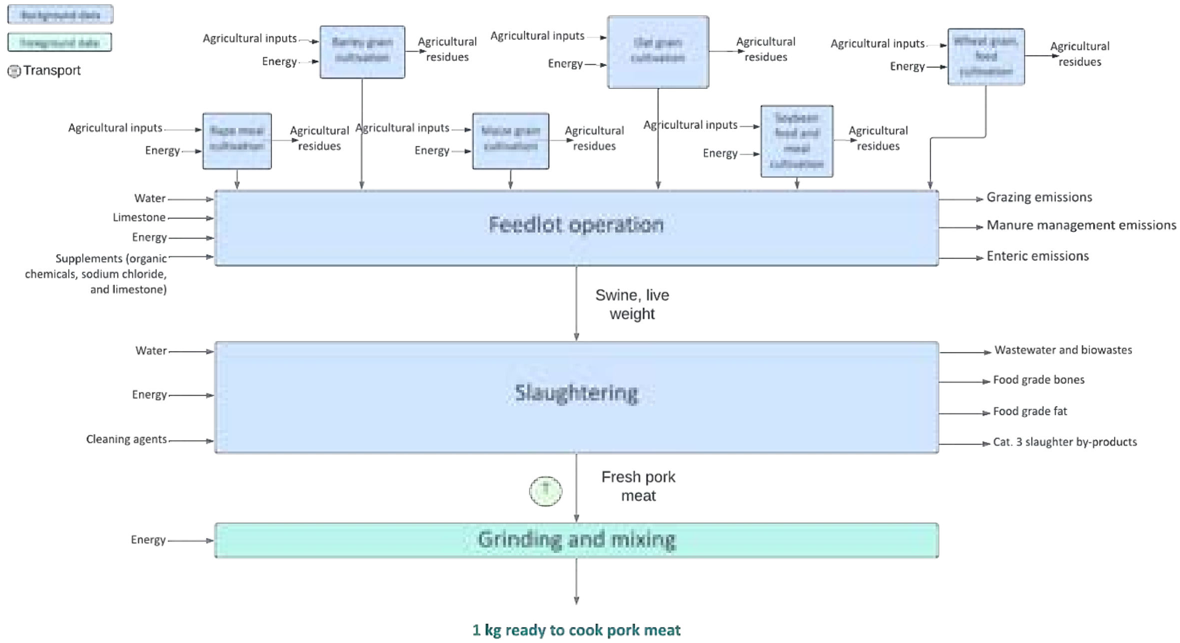

Figure 3-9. Pork meat process (based on ecoinvent 3.9.1 dataset).

3.2.8 System #6

- Feedstock: Chicken
- Processing: Slaughtering
- Product Forming: Grinding

Data for chicken meat were taken from the ecoinvent 3.9.1 database considering an intensive chicken production system in the U.S. This system includes the broiler husbandry, which includes sand, electricity, heat, and water consumption, as well as feed basket production, manure management, enteric emissions, and treatment of biowaste (Figure 3-10). The feed basket includes mixes of oilseeds (sunflower, rapeseed, soybean, and palm kernel), grains (maize and soybean), proteins (soybean), and feed additives, as well as fishmeal and limestone. Once the chickens have matured on the farm, they are taken to a slaughterhouse, where numerous products are obtained: fresh meat, food grade offal, feathers, category 1 and 2 materials, and category 3 byproducts. The slaughterhouse process requires heat, electricity, water, and disinfectant and foam agents, and generates biowastes and wastewater. Finally, fresh chicken meat is ground and mixed to form a ground meat product, which primarily consumes electricity.

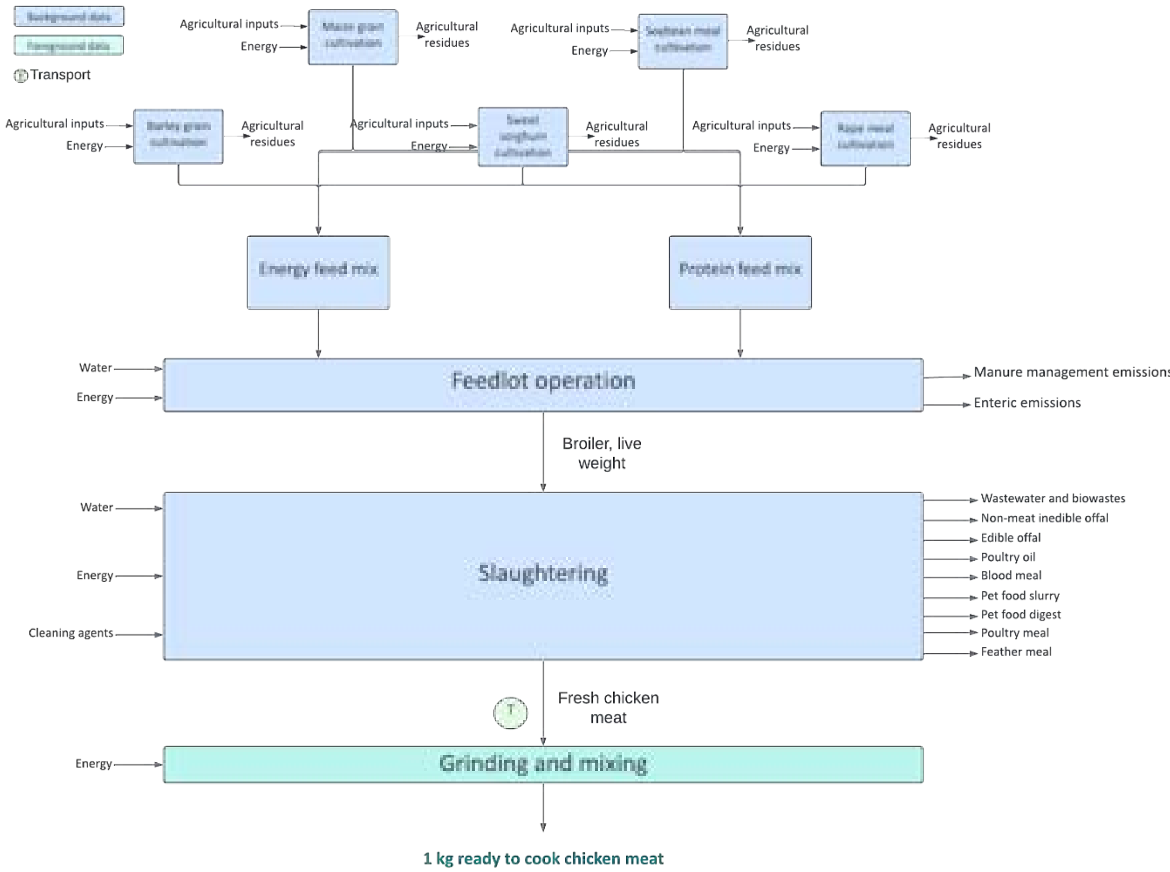

Figure 3-10. Chicken meat process (based on ecoinvent 3.9.1 dataset).

3.3 Cut-off criteria

Cut-off criteria are crucial in LCA practice to guide the selection of processes or flows within the system boundary. Processes or flows below these predefined cut-offs or thresholds are typically excluded from the study. Various criteria, such as mass, energy, and environmental relevance, are employed in LCA practice to determine the inclusion of specific inputs.

For this study, a 1% mass cut-off was applied. Instances of missing data were evaluated via proxies, depending on the nature of the inventory, and a justification is provided in each case.

During the interpretation phase and when building the model, 1% of the environmental relevance criterion, as calculated by the impact assessment method, was used to test the results' sensitivity to assumptions and data substitutions made (Section 4.2). Environmental impact relevance was also used when selecting proxies and prioritizing data refinements.

3.4 Excluded processes

In an LCA, some aspects within the set boundaries are typically excluded due to statistical insignificance or irrelevancy to the goal and scope. The following impacts were excluded from the scope and boundaries of this study:

- Infrastructure for foreground processes (e.g., buildings and auxiliary plant equipment). High quality data were not available for considering these inputs into the foreground models. However, background processes in plant-based and animal-based systems do include infrastructure impacts.
- Other operation-related activities such as work activities (e.g., employee travel to and from work), research and development (i.e., the laboratory and inputs related to the development of the technologies) and services (e.g., marketing, consultancy services, business travel).

3.5 Co-product allocation

While conducting an LCA, allocation scenarios occur when the life cycles of different production systems are connected, or when multiple co-products are produced from the same system. According to ISO 14044, allocation of the process inputs should be avoided by using the system boundary expansion approach. If allocation cannot be avoided, an allocation method—based on physical causality (e.g., mass or energy content) or any other relationship such as economic value—should be used (ISO 2022). Baseline results for plant- and animal-based meat systems are based on mass allocation criteria, while economic allocation scenarios are explored for the sensitivity analysis. Table 3-3 summarizes allocation factors for plant-based meat systems (#1–3), while Table 3-4 summarizes allocation factors for animal meat systems (#4–6). Unit prices are shown in the confidential appendix (Table A-49).

For background processes, which come from the ecoinvent 3.9.1 database (Wernet et al. 2016), such as electricity and raw materials, the cut-off approach is applied, and co-products are allocated based on economic or physical relationships. No change in allocation is made to the background data from ecoinvent.

Table 3-3. Mass and economic allocation factors used per co-products in plant-based meat systems (Systems #1–3).

System	Stage	Process	Co-products[1]	Mass allocation factor (%)[2]	Economic allocation factor (%)[2]
System #1	Pre-processing	Dehulling	**Dehulled peas**	**82.80**	**89.06**
			Hulls	17.20	10.94
	Dry fractionation	Air classification	**Protein concentrate**	**23.38**	**52.90**
			Starch	76.62	47.10
System #2	Pre-processing	Dehulling	**Dehulled peas**	**73.14**	**89.06**
			Hulls	26.86	10.94
	Wet fractionation	Precipitation	**Pea protein slurry**	**21.73**	**54.97**

			Starch slurry	34.33	37.07
			Wet globulin slurry	43.94	7.96
System #3	Pre-processing	Soybean oil extraction	**Soybean meal**	**19.49**	**35.87**
			Soybean oil	80.51	64.13
	Wet fractionation		**Soy protein concentrate**	**62.54**	**97.41**
			Soy fines	7.24	1.76
			Soy molasses	30.22	0.82

Notes: [1]Bolded co-products are of direct interest in the production of plant-based meat recipes. [2]Economic allocation factors are taken from (Blonk et al. 2023; Durlinger et al. 2017; van Veghel 2017; Wernet et al. 2016). Mass allocation factors are calculated from mass balances considering average values from available industry data, LCI datasets, and scientific papers (Section 4).

Table 3-4. Mass and economic allocation factors used per co-products in animal meat systems (Systems #4–6).

System	Stage	Co-products[1]	Mass allocation factor (%)	Economic allocation factor (%)
System #4	Cattle slaughtering[2]	**Fresh beef meat**	**49.0**	**92.9**
		Food grade bones	8.0	1.0
		Food grade fat	7.0	1.8
		Category 3 slaughter by-products	7.0	0.8
		Hides and skins	7.0	3.5
		Category 1 and 2 material and waste	22.0	0.0
System #5	Swine slaughtering[2]	**Fresh pork meat**	**67.0**	**98.67**
		Food grade bones	11.0	0.47

		Food grade fat	3.0	0.09
		Category 3 slaughter byproducts	19.0	0.77
System #6	Broiler slaughtering[3]	**Fresh chicken meat**	**65.7**	**86.6**
		Non-meat inedible offal	20.8	10.7
		Edible offal	1.9	0.4
		Poultry oil	1.5	0.5
		Blood meal	0.3	0.2
		Pet food slurry	5.0	0.5
		Pet food digest	0.5	0.2
		Poultry meal	1.6	0.5
		Feather meal	2.7	0.4

Notes: [1]Bolded co-products are of direct interest in the production of animal-based meat recipes. [2]Mass and economic allocation factors for beef (System #4) and pork (System #5) are taken from European Commission (2021). [3]Mass and economic allocation factors for chicken (System #6) are taken from FAO (2016).

3.6 Assumptions

Based on data availability, the report makes and tests several assumptions if they exceeded the 1% cut-off. The following are the general study assumptions:

- Datasets: A comprehensive list of the common datasets used to model all the different material and energy inputs, as well as waste generation and treatment, is shown in Appendix A, and is assumed to be representative of the processes modeled herein.
- Geography: U.S., focusing on the Midwest region since this is an agriculturally intensive area with available data for production of plant-based meats. When U.S. agricultural data are not available in databases, Canada and RoW are taken as the closest proxies.
- Electricity: Midwest Reliability Organization (MRO) electricity grid. This dataset is used to align with the geographical boundary of the Midwest. Background datasets used for modeling plant-based and animal-based meat systems with electricity as an input were modified to include this particular grid mix.
- Transport: The transport distance can vary, depending on the location of the suppliers. For the plant-based pathways, an average distance of 50 km was included based on the assumptions that most agricultural inputs were sourced from the U.S. (only pea was sourced from Canada), and that all the plant-based meat processing is assumed to be done at the same plant and location (no intermediate transport needed). Animal-based meat is assumed to be transported by a distance of 200 km from the animal husbandry site to the slaughterhouse (Ge et al. 2022; Kannan et al. 2016).
- Use of background and foreground data: Background data refers to available LCA datasets provided by commercial databases that include upstream processes—also referred to as secondary data throughout this LCA. The animal-based systems, as well as the agricultural feedstocks and main processing inputs (electricity, water, heat, etc.) of the plant-based systems are based on background data. In contrast, foreground data refers to primary data gathered specifically for an LCA study provided by direct operators and the literature; the plant-based meat processes are based on foreground data.

For plant-based systems, the following are the main assumptions considered in this study:

- Cultivation: peas cultivated in Canada (Manitoba) and soybeans cultivated in the U.S.
- Spice mix: the dataset was created based on glutamic acid, salt, yeast, dried shiitake, and citric acid (Appendix 3). This spice mix was chosen as a representation of common natural flavor agents in the sector.

Protein content per intermediate and final products:

- Pea protein concentrate: 58%.
- Extruded meat analogue from pea protein concentrate: 53%.
- Pea protein isolate: 80%.
- Extruded meat analogue from pea protein isolate: 34%.
- Soy protein concentrate: 70%.
- Extruded meat analogue from soy protein concentrate: 21%.

Average plant-based ground meat recipe:

- Water: 9.6-52.7% (66% water total).
- Extruded meat analogue: 28.3-71.4% (15% protein total, water contents vary).
- Wheat gluten: 5%.
- Coconut oil: 4%.
- Canola oil: 4%.
- Potato starch: 3%.
- Spices: 3% (though the ingredients for the spice mix are less than 1% of the cut-off criteria, we decide to include them to account for the totality of the final meat recipe).

For the conventional system, the following are the assumptions considered in this study:

- Databases: To model the conventional animal meat systems, a hybrid approach between ecoinvent and WFLDB databases was applied. The ecoinvent 3.9.1 database was used as the main source of data for the animal husbandry stage, while the WFLDB datasets on cattle, swine, and broiler slaughtering processes were used. The multiproduct output from each system's slaughterhouse was built based on the European Union Product Environmental Footprint method-derived allocation factors for beef and pork (European Commission 2021), while data taken from FAO were used to model the outputs from chicken slaughtering (FAO 2016).
- Cattle farming: Due to ecoinvent 3.9.1 having a limited number of geographies for cattle farming, a South African dataset was modified to account for U.S.-sourced feed and grains.
- Swine farming: An ecoinvent 3.9.1 dataset for swine production from the Canadian region of Quebec was used as main proxy for modeling swine farming from background datasets.
- Broiler husbandry: Similar to cattle farming, a global broiler production dataset from ecoinvent 3.9.1 was modified to account for U.S.-sourced feed and grains.
- The datasets from ecoinvent 3.9.1 used for modeling animal husbandry processes include nutritional supplements, though only swine and broiler production indicate them explicitly. These same datasets indicate that antibiotics are excluded because of their small mass contribution (less than 1%).
- The original WFLDB datasets for cattle, swine, and broiler slaughtering include low density polyethylene consumption as packaging film. Since the packaging stage is excluded from this LCA study, packaging film consumption was excluded from the slaughtering datasets.
- The energy consumption for grinding meat (0.489 kWh/kg meat) is taken from Smetana et al. 2021 and assumed to be the same for all three animal-based meat systems.

Finally, throughout the report, numerous contribution analyses related to stages and processes are explained and discussed with the assistance of percentages. In the event of one impact category showing negative values (available in the individual results tables in the Appendix A.2 section), the percentage values discussed in text and shown in the graphs are based on the absolute sum of impacts, as opposed to the arithmetical sum of impacts normally shown when all individual impact values show positive values. The graphs that use this "absolute" approach for calculating contribution percentages indicate this approach in their notes.

3.7 Data quality requirements

Primary measured, metered, or calculated data are required for an LCA and have been used for pea and soy processing. Primary data from GFI's industry partners were also gathered and checked to guarantee consistency.

Secondary data from peer-reviewed scientific papers and available LCA datasets were used to fill in data gaps where needed. These data were chosen to represent the North American geography, particularly for electricity consumption, agricultural practices, animal raising, and slaughterhouse practices. When North American resolution was not available, the global or the RoW resolution was chosen. The latest available technology in the ecoinvent database was used as the time frame for the study is 2021.

Moreover, in comparative and single product assertions, it is important to provide a description of the data quality used for each of the systems to identify limitations (ISO 14044 section 4.2.3.6.2). Aspects of data quality considered below are time-related coverage, geographic coverage, technology coverage, precision, completeness, representativeness, consistency, reproducibility, data sources, and uncertainty of information.

3.7.1 Data quality assessment of conventional systems

Time-related coverage: The quantity of inputs and energy required for animal-based systems is from 2019 and 2022. Secondary data were obtained from ecoinvent 3.9.1 (updated in 2023) and WFLDB (updated in 2019), as described in the general information of the databases library. Overall, time coverage is estimated to be very good.

Geographic coverage: Secondary data representative of U.S. processes have been used to the extent possible. Global and RoW inventories were used where specific U.S. data were not available. Overall, geographic coverage is estimated to be good.

Technology coverage: Agricultural machinery, slaughterhouse technology, and meat processing are represented by the fuel consumption, electricity, natural gas, and water consumption in each stage, as well as the machinery reported in ecoinvent and WFLDB. Overall, technology coverage is estimated to be acceptable.

Precision and completeness: This dataset can be considered complete with emissions reported in every unit process. The datasets are represented by secondary data retrieved from ecoinvent and the literature, as reported in the LCI data.

Representativeness: The system is representative of the intended geography and technology.

Consistency and reproducibility: The data gathered follow the same approach as performed by ecoinvent, therefore the same datasets can be accessed by other LCA practitioners, making the results reproducible. Modeling is consistent across all products. Proxies and assumptions are reported in section 3.6. Ecoinvent processes used for raw materials and to model the products are presented in sections 4.3.4, 4.3.5, and 4.3.6.

Data sources: All the background data comes from ecoinvent and literature.

3.7.2 Data quality assessment of plant-based systems

Time-related coverage: Inputs, quantities, and processing for the plant-based system is from 2015 to 2022, from data gathered from GFI partners and literature. Secondary data were obtained from ecoinvent 3.9.1 and the WFLDB. Overall, time coverage is estimated to be very good.

Geographic coverage: Inputs and processing primary data are from different geographies, including U.S. and Europe. However, background processes for the national electricity grid, agricultural inputs, and other ingredients representative of U.S. processes were used to the extent possible. Global and RoW inventories and background processes were used where specific data for the U.S. were not available. Overall, geographic coverage is estimated to be good.

Technology coverage: Agricultural machinery and crops processing are represented by the fuel consumption, electricity, natural gas, and water consumption in each stage, as well as the machinery reported in ecoinvent and WFLDB. Data on energy consumption were retrieved from the literature and information shared by GFI partners. Overall, technology coverage is estimated to be acceptable.

Precision and completeness: This dataset can be considered complete with emissions reported in every unit process. The dataset is represented by primary data for the plant-based ingredients and processing (energy and water) inputs. The foreground system for these products is represented by primary information provided by GFI partnerships and secondary information based on the literature.

Representativeness: The system is representative of the intended geography and technology.

Consistency and reproducibility: Modeling is consistent across all products, and proxies and assumptions are reported in section 3.6. The ecoinvent process used for the raw materials and to model the products are presented in sections 4.3.1, 4.3.2, and 4.3.3

Data sources: All background data come from ecoinvent and literature.

3.8 Sensitivity analysis

Per the ISO 14044 guidelines, analysis was conducted to determine the sensitivity of the study results to key assumptions and parameters. This full LCA includes the following sensitivity checks to test the robustness of assumptions and modeling choices to inform a general case:

3.8.1 Energy source and quantity for plant-based production

Plant-based meat production companies are optimizing their process to reduce environmental impacts, among other activities. This analysis evaluates the effect of first moving to 100% renewable energy in the manufacturing plants or reducing total energy consumption by 5 and 10%.

3.8.2 Allocation approach

While conducting an LCA, allocation scenarios occur when multiple co-products are produced from the same system. According to ISO standards, when system boundary expansion is not possible or practical, then direct allocation must be applied by either substitution or based on relationships between the co-products (e.g., mass, economic value). Baseline results for all systems are based on mass allocation criteria, meaning that the impacts of the process are assigned according to their relative mass flows.

The impact of economic allocation was evaluated via sensitivity analysis for all systems, given that the co-products produced by all systems have disparate economic value. This sensitivity analysis also facilitates evaluating the robustness of the comparative results of plant-based vs. animal-based meat systems, as well as the study's overall conclusions.

Background processes such as electricity and raw materials, which in this case are from the ecoinvent 3.9.1 database, use a cut-off approach for recycling, and co-products are allocated based on economic or physical relationships. No change in allocation is made to the background data from ecoinvent.

3.8.3 Geography of crops being used for plant-based meat production

Agricultural practices for soy and pea cultivation vary between countries, affecting yield, emissions, and resource consumption. For that reason, this analysis evaluates how changing the crop geography affects the environmental performance of the plant-based systems and the comparison with the animal systems. Due to lack of data availability in the ecoinvent 3.9.1 datasets, pea provision was evaluated by comparing baseline Canadian-Manitoba systems to French and German systems, while soybean provision was evaluated by comparing baseline U.S. systems to Canadian and Brazilian systems. Switching the geography for agricultural production systems implies changes in different key parameters, e.g., agricultural yields, soil conditions, fertilizer and pesticide rates, types of fertilizers and pesticides.

3.9 Impact assessment method

Impact assessment methods are used to convert LCI data (environmental emissions and raw material extractions) into a set of environmental impacts.

Table 3-5 presents the midpoint impact categories from ReCiPe 2016 (H) (Huijbregts et al. 2017). ReCiPe 2016 is currently the most well-known and globally used assessment method, and it includes major midpoint impact categories such as global warming, land use, and water consumption. The hierarchist perspective (H) is based on the most common policy principles concerning the timeframe and other issues. Each impact category is characterized by a unit of measure to which the resource and emission flows have been normalized. To aggregate the substances into the impact categories, substances were multiplied by their characterization factor to convert into an equivalent substance (e.g., CO_2) and then added together to create a total for each impact category (e.g., global warming).

Table 3-5. Impact categories and units of measure from ReCiPe 2016 (H).

Impact Category	Unit
Global warming*	kg CO_2 eq.
Stratospheric ozone depletion	kg CFC-11 eq.
Ionizing radiation	kg kBq Co-60 eq.
Ozone formation, human health	kg NO_x eq.
Fine particulate matter formation	kg $PM_{2.5}$ eq.
Ozone formation, terrestrial ecosystems	kg NO_x eq.
Terrestrial acidification	kg SO_2 eq.
Freshwater eutrophication	kg P eq.
Marine eutrophication	kg N eq.
Terrestrial ecotoxicity	kg 1,4-DCB eq.
Freshwater ecotoxicity	kg 1,4-DCB eq.
Marine ecotoxicity	kg 1,4-DCB eq.
Human carcinogenic toxicity	kg 1,4-DCB eq.
Human non-carcinogenic toxicity	kg 1,4-DCB eq.
Land use	m^2a crop eq.
Mineral resource scarcity	kg Fe eq.
Fossil resource scarcity	kg oil eq.

Impact Category	Unit
Water consumption	m^3

*Considers Global Warming Potential 100a from IPCC report 2014, feedback included.

3.10 Calculation tool

After the required data were obtained and the associated flows were normalized to the reference flows (based on the chosen functional unit), system modeling was carried out by using the commercial LCA software SimaPro 9.5, developed by PRé Sustainability, Netherlands (www.pre.nl). This software allows the calculation of LCIs and impact assessments, contribution analysis, parameterization, and related sensitivity analysis and uncertainty analysis. To exclude infrastructure from the assessment, foreground models were all built using unit-level processes and assessed with infrastructure excluded. Background dataset assessments do include infrastructure for all plant-based and animal-based meat recipes. The ecoinvent 3.9.1 cut-off database was used for secondary data.

3.11 Limitations of LCA methodology

The ability of an LCA to consider the entire life cycle of a product makes it an attractive tool to assess potential environmental impacts. Nevertheless, like other environmental management analysis tools, LCAs have several limitations, which are typically related to data quality and the unavailability of potentially relevant data. While all known flows above the 1% cut off have been included, production, distribution, and waste management systems are complex, and some flows may have been inadvertently omitted.

Furthermore, LCA is based on a linear extrapolation of emissions with the assumption that all the emissions contribute to an environmental effect. This is contrary to threshold-driven environmental and toxicological mechanisms. Thus, while linear extrapolation may be a reasonable approach for global and regional impact categories such as Global Warming Potential and acidification, it may not accurately represent the human and ecotoxicity-related impacts. Some specific environmental impacts not included are noise and light pollution, plastics leakage, and barriers to species migration.

Even if a study has been critically reviewed, the impact assessment results are relative expressions and do not predict impacts on category midpoints (e.g., categories used throughout the report such as global warming, freshwater eutrophication, among others) and endpoints (e.g., human health, wildlife species), the exceedance of thresholds, or risks. Plus, even with critical reviews, the impact assessment results are relative expressions, and model predictions on category endpoints have high uncertainty. LCA is also a linear framework and does not account for the exceedance of thresholds or risks that are not considered in the inventory (Huijbregts et al. 2016, RIVM 2020).

3.12 Critical review

ISO 14044 requires a critical review for comparative assertions intended for public dissemination. Critical review ensures consistency between an LCA and ISO requirements for carrying out an LCA. The review of this comparative LCA was carried out by a panel of experts and stakeholders to decrease the likelihood of misunderstandings and negative effects on external interested parties.

As outlined by ISO 14044, the role of the critical review is to determine if:

- The methods used to carry out the LCA are consistent with this International Standard.

- The methods used to carry out the LCA are scientifically and technically valid.
- The data used are appropriate and reasonable in relation to the goal of the study.
- The interpretations reflect the limitations identified and the goal of the study.
- The study report is transparent and consistent.

The critical review panel members for this study are specified in Table 3-6. Members of the committee were not engaged or contracted as official representatives of their organizations. Their comments should not be construed as official opinions from their organizations.

Table 3-6. Critical Review Panel Members.

Member	Role	Affiliation(s)
Terrie Boguski	Chair	Harmony Environmental
Sophie Saget	Reviewer	Researcher Trinity College Dublin
Richard Venditti	Reviewer	Professor Dept. of Forest Biomaterials North Carolina State University

4. Life cycle inventory

After defining study scope and related details, the second phase of an LCA is to collect life cycle inventory (LCI) data. LCI data contain the details of the resources flowing into a process, the outputs or products of the process, and the emissions flowing from a process to air, soil, and water.

4.1 LCI data collection

This study uses a combination of primary and secondary data. Primary LCI data were collected directly from companies that produce plant-based proteins. The data were averaged with secondary published data and peer-reviewed sources. For the animal-based systems, data reported in the ecoinvent 3.9.1 cut off database are used (Wernet et al. 2016). Secondary data are used for complementary ingredients for the plant-based meat recipes, electricity production, transportation processes, and raw material inputs, among others.

To build the unit processes for each system, data from industry and scientific papers were processed to show the input and output data per kg of main product (e.g., per kg of protein concentrate, per kg of meat alternative). Then, average values, as well as maximum, minimum, and standard deviation were calculated for each input and output. Finally, minor adjustments were made to each inventory to maintain mass balance.

4.2 Data quality assessment

In practice, all data used in an LCA study are a mixture of measured, estimated, and calculated data. To evaluate the quality of the data used for modeling the meat alternative systems, data quality indicators (DQI) were used to assess each flow using a data quality matrix approach. These scores were also used to assess data uncertainties and the results and evaluate the significance of differences.

Five types of DQI were evaluated by the selected Pedigree matrix (Frischknecht et al. 2007), by using scores from 1 to 5 for the following parameters:

1. Reliability (reliability of the collected primary data).
2. Completeness (completeness of the primary data).
3. Temporal correlation (temporal correlation of the primary data).
4. Geographic correlation (geographic correlation of the secondary data used).
5. Further technological correlation (technological correlation of the secondary data used).

Scores were assigned to the data based on the previous criteria. These scores were then combined with basic uncertainty factors to develop squared geometric standard deviations for use in Monte Carlo analysis to determine the influence of data quality on the reliability of the study results.

Data quality was assessed using the Pedigree matrix approach, and data quality scores were used to generate standard deviation values for Monte Carlo analysis (section 6.2). Assessments are based on 1,000 Monte Carlo runs for each system. This analysis is referred to as a discernibility analysis (Heijungs & Kleijn 2001) and is applied to the results of the uncertainty analysis to evaluate, per run, the number of times one formulation is larger than another. This is done by subtracting one value from the other and counting the number of times there is a negative/positive result. When this value reaches 95% of the runs or higher, then it can be said the formulations are statistically different. Therefore, the formulation with the smallest mean (less impact) can be considered superior despite uncertainties. Discernibility analysis was used in this study to filter the comparative results to limit discussion to those impact categories with significant differences. It is important to consider that the discernibility analysis does not consider the magnitude of a difference; rather, it applies a smaller-larger dichotomy.

The LCI was built based on averages for each input and output in the case of Systems #1–3. These averages were calculated based on confidential industry and scientific paper data sources for each system (Table 4-1).

Table 4-1. Number of sources per system, scientific papers.

System	Process	Number of Scientific Paper Sources	References
System 1	Dry fractionation	5	• Saget et al. 2021 • Berghout et al. 2015 • Lie-Piang et al. 2021 • Van Veghel et al. 2017, cited by Blonk et al. 2023 • Schutyser et al. 2015
	Low moisture extrusion	1	• Saget et al. 2021
System 2	Wet fractionation	6	• Pelgrom et al. 2015 • Berghout et al. 2015 • Lie-Piang et al. 2021 • Van Veghel et al. 2017, cited by Blonk et al. 2023 • Geerts et al. 2018

			• Schutyser et al. 2015
	High moisture extrusion	0	
System 3	Wet fractionation	1	• Van Veghel et al. 2017, cited by Blonk et al. 2023
	High moisture extrusion	1	• Saerens et al. 2021

4.3 Life cycle inventory data

A summary of the materials and energy inputs relative to producing 1 kg of ground food with the protein content of each system is provided in Table 4-2. to Table 4-24.

4.3.1 System 1, yellow pea, dry fractionation, low moisture extrusion

This system starts with the agricultural cultivation of fresh peas in Manitoba, Canada. This process is taken directly from the ecoinvent 3.9.1 database and includes everything from the production of crop inputs (seeds, fertilizers, crop protection products, fuels) to direct agricultural activities and emissions from fertilizer and pesticide use. The next process, pea drying, involves extracting moisture from fresh peas via drying and pre-processing (Table 4-2).

Table 4-2. Life cycle inventory data for pea drying.

Components	Consumption	Unit	Note
Pea drying			
Inputs			
Peas, fresh	1.748	kg	Average value from available industry data, LCI datasets, and scientific papers
Transport, ground freight, 7.5-16 ton	87.4	kg.km	1.748 kg of harvested peas transported for 50 km
Electricity, pre-cleaning	0.002	kWh	Average value from available industry data, LCI datasets, and scientific papers
Electricity, drying	0.006	kWh	Average value from available industry data, LCI datasets, and scientific papers
Heat, from natural gas	0.350	MJ	Average value from available industry data, LCI datasets, and scientific papers
Outputs			

Pea, dried	1.589	kg	Average value from available industry data, LCI datasets, and scientific papers
Moisture	0.159	kg	Average value from available industry data, LCI datasets, and scientific papers

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

Once the peas are dried, they are pre-processed through the dehulling process to extract hulls and other impurities (Table 4-3), and further milled to obtain dehulled pea flour. Dehulled peas and hulls are the two main products from this process.

Table 4-3. Life cycle inventory data for pea pre-processing.

Components	Consumption	Unit	Note
Pea pre-processing			
Inputs			
Peas, dried	1.589	kg	Average value from available industry data, LCI datasets, and scientific papers
Electricity, storage	0.001	kWh	Average value from available industry data, LCI datasets, and scientific papers
Electricity, cleaning	0.033	kWh	Average value from available industry data, LCI datasets, and scientific papers
Electricity, dehulling	0.082	kWh	Average value from available industry data, LCI datasets, and scientific papers
Heat, from natural gas	0.769	MJ	Average value from available industry data, LCI datasets, and scientific papers
Electricity, milling	0.149	kWh	Average value from available industry data, LCI datasets, and scientific papers
Outputs			
Pea flour	1.055	kg	Co-product. Average value from available industry data, LCI datasets, and scientific papers
Hulls	0.221	kg	Co-product. Average value from available industry data, LCI datasets, and scientific papers

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Impurities	0.120	kg	Average value from available industry data, LCI datasets, and scientific papers
Wastewater	0.155	Kg	Average value from available industry data, LCI datasets, and scientific papers
Milling residue	0.038	kg	Average value from available industry data, LCI datasets, and scientific papers

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

The dry fractionation process is based on air classification, which involves electricity and heat consumption (Table 4-4). This process produces pea protein concentrate and starch.

Table 4-4. Life cycle inventory data for dry fractionation through air classification.

Components	Consumption	Unit	Note
Air classification			
Inputs			
Pea flour	1.055	kg	Average value from available industry data, LCI datasets, and scientific papers
Electricity, micronization/fine grinding	0.175	kWh	Average value from available industry data, LCI datasets, and scientific papers
Electricity, air classification	0.282	kWh	Average value from available industry data, LCI datasets, and scientific papers
Heat, air classification	1.021	MJ	Average value from available industry data, LCI datasets, and scientific papers
Outputs			
Pea protein concentrate	0.291	kg	Average value from available industry data, LCI datasets, and scientific papers
Starch	0.718	kg	Average value from available industry data, LCI datasets, and scientific papers
Losses, to disposal	0.046	kg	Average value from available industry data, LCI datasets, and scientific papers

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

Once the protein concentrate is obtained, it is mixed with water to go through the LME process to produce meat alternatives (Table 4-5).

Table 4-5. Life cycle inventory data for low moisture extrusion.

Components	Consumption	Unit	Note
Low moisture extrusion			
Inputs			
Pea protein concentrate	0.291	kg	Average value from available industry data, LCI datasets, and scientific papers
Water	0.058	kg	Average value from available industry data, LCI datasets, and scientific papers
Steam	0.026	kg	Average value from available industry data, LCI datasets, and scientific papers
Electricity, pre-conditioning	0.005	kg	Average value from available industry data, LCI datasets, and scientific papers
Heat, from natural gas	0.289	MJ	Average value from available industry data, LCI datasets, and scientific papers
Electricity, extrusion	0.017	kWh	Average value from available industry data, LCI datasets, and scientific papers
Electricity, conveying	0.008	kWh	Average value from available industry data, LCI datasets, and scientific papers
Electricity, cutting	0.008	kWh	Average value from available industry data, LCI datasets, and scientific papers
Electricity, drying	0.005	kWh	Average value from available industry data, LCI datasets, and scientific papers
Electricity, separation	0.000	kWh	Average value from available industry data, LCI datasets, and scientific papers
Outputs			
Meat analogue	0.283	kg	Average value from available industry data, LCI datasets, and scientific papers

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Losses	0.008	kg	Average value from available industry data, LCI datasets, and scientific papers
Moisture	0.101	kg	Average value from available industry data, LCI datasets, and scientific papers

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

Finally, the meat alternative is mixed along with the rest of the recipe's ingredients to be cooked and consumed as ground food (Table 4-6).

Table 4-6. Life cycle inventory data for ground meat alternative, System 1.

Components	Consumption	Unit	Origin of Ingredient	Note
1 kg of ground food with protein content, known in the market as meat or meat alternative ready to be cooked, from cradle-to-manufacturing gate, before packaging or cooling				
Inputs				
Meat analogue	0.283	kg	U.S.	0.15 kg of protein content, 0.13 kg of water
Water	0.527	kg	U.S.	
Wheat gluten	0.050	kg	U.S.	
Coconut oil	0.040	kg	Philippines and Indonesia	
Canola oil	0.040	kg	Canada	
Potato starch	0.030	kg	Germany	
Spices	0.030	kg	Global mix and U.S.	
Transport	9.50	kg.km	U.S.	Transport, freight, lorry 7.5-16 metric ton, EURO5 for wheat gluten, coconut oil, canola oil, potato starch, and spices. Distance of 50 km.
Outputs				
1 kg of plant-based meat product ready to be cooked, from cradle-to-	1.000	kg		

manufacturing gate, before packaging or cooling				

4.3.2 System 2, yellow pea, wet fractionation, high moisture extrusion

Similar to System 1, the agricultural cultivation of fresh peas in Manitoba, Canada is the first stage of the system. This process is taken directly from the ecoinvent 3.9.1 database and includes everything from the production of crop inputs (seeds, fertilizers, crop protection products, fuels) to direct agricultural activities and emissions from fertilizer and pesticide use.

The next process, pea drying, requires the consumption of fresh peas, which need to be dried and pre-processed to extract moisture (Table 4-7).

Table 4-7. Life cycle inventory data for pea drying.

Components	Consumption	Unit	Note
Pea drying			
Inputs			
Peas, fresh	1.416	kg	Average value from available industry data, LCI datasets, and scientific papers
Transport, ground freight, 7.5-16 ton	70.8	kg.km	1.416 kg of harvested peas transported for 50 km
Electricity, pre-cleaning	0.003	kWh	Average value from available industry data, LCI datasets, and scientific papers
Electricity, drying	0.010	kWh	Average value from available industry data, LCI datasets, and scientific papers
Heat, from natural gas	0.219	MJ	Average value from available industry data, LCI datasets, and scientific papers
Outputs			
Pea, dried	1.273	kg	Average value from available industry data, LCI datasets, and scientific papers
Evaporation	0.143	kg	Average value from available industry data, LCI datasets, and scientific papers

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

Once the peas are dried, they need to be dehulled and milled (Table 4-8).

Table 4-8. Life cycle inventory data for pea pre-processing.

Components	Consumption	Unit	Note
Pea pre-processing			
Inputs			
Peas, dried	1.273	kg	Average value from available industry data, LCI datasets, and scientific papers
Electricity, storage	0.000	kWh	Average value from available industry data, LCI datasets, and scientific papers
Electricity, cleaning	0.056	kWh	Average value from available industry data, LCI datasets, and scientific papers
Electricity, dehulling	0.065	kWh	Average value from available industry data, LCI datasets, and scientific papers
Electricity, milling and mixing	0.085	kWh	Average value from available industry data, LCI datasets, and scientific papers
Heat, from natural gas	0.481	MJ	Average value from available industry data, LCI datasets, and scientific papers
Outputs			
Dehulled pea flour	0.725	kg	Co-product. Average value from available industry data, LCI datasets, and scientific papers
Hulls	0.266	kg	Co-product. Average value from available industry data, LCI datasets, and scientific papers
Impurities	0.127	kg	Average value from available industry data, LCI datasets, and scientific papers
Wastewater	0.155	kg	Average value from available industry data, LCI datasets, and scientific papers

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

Pea flour is the main input of the wet fractionation process, where it is mixed with water, sodium hydroxide (NaOH), and chlorohydric acid (HCl) to obtain multiple types of slurry, in which pea protein slurry is the main product of the system (Table 4-9).

Table 4-9. Life cycle inventory data for obtaining pea protein slurry.

Components	Consumption	Unit	Note
Wet fractionation - Obtaining pea protein slurry			
Inputs			
Dehulled pea flour	0.725	kg	Average value from available industry data, LCI datasets, and scientific papers
Water	3.417	kg	Average value from available industry data, LCI datasets, and scientific papers
NaOH	0.003	kg	Average value from available industry data, LCI datasets, and scientific papers
HCl	0.006	kg	Average value from available industry data, LCI datasets, and scientific papers
Electricity, pellet separation	0.033	kWh	Average value from available industry data, LCI datasets, and scientific papers
Electricity, precipitation	0.036	kWh	Average value from available industry data, LCI datasets, and scientific papers
Electricity, mixing	0.011	kWh	Average value from available industry data, LCI datasets, and scientific papers
Electricity, cleaning, and separation	0.043	kWh	Average value from available industry data, LCI datasets, and scientific papers
Electricity, cooling	0.285	kWh	Average value from available industry data, LCI datasets, and scientific papers
Outputs			
Pea protein slurry	0.518	kg	Co-product. Average value from available industry data, LCI datasets, and scientific papers
Starch slurry	0.819	kg	Co-product. Average value from available industry data, LCI datasets, and scientific papers
Wet globulin slurry	1.048	kg	Co-product. Average value from available industry data, LCI datasets, and scientific papers

Wastewater	1.766	kg	Average value from available industry data, LCI datasets, and scientific papers
Impurities/Losses	0.138	kg	Average value from available industry data, LCI datasets, and scientific papers

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

Finally, the pea protein slurry undergoes a spray drying process to remove moisture (Table 4-10).

Table 4-10. Life cycle inventory data for spray drying of pea protein slurry.

Components	Consumption	Unit	Note
Wet fractionation - spray drying			
Inputs			
Pea protein slurry	0.518	kg	Average value from available industry data, LCI datasets, and scientific papers
Heat from natural gas	2.980	MJ	Average value from available industry data, LCI datasets, and scientific papers
Electricity, spray drying	0.086	kWh	Average value from available industry data, LCI datasets, and scientific papers
Outputs			
Pea protein isolate	0.190	kg	Average value from available industry data, LCI datasets, and scientific papers
Evaporation	0.328	kg	Co-product. Average value from available industry data, LCI datasets, and scientific papers

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

The HME process has the pea protein isolate from wet fractionation as its main input (Table 4-11). The protein isolate is mixed with water to produce a meat alternative.

Table 4-11. Life cycle inventory data for high moisture extrusion of pea protein isolate.

Components	Consumption	Unit	Note
High moisture extrusion			
Inputs			

Pea protein isolate	0.190	kg	Average value from available industry data, LCI datasets, and scientific papers
Water, mainstream	0.251	kg	Average value from available industry data, LCI datasets, and scientific papers
Water, side stream	0.545	kg	Average value from available industry data, LCI datasets, and scientific papers
Heat from natural gas	0.020	MJ	Average value from available industry data, LCI datasets, and scientific papers
Electricity, water heating	0.006	kWh	Average value from available industry data, LCI datasets, and scientific papers
Electricity, pre-conditioning	0.005	kWh	Average value from available industry data, LCI datasets, and scientific papers
Electricity, extrusion	0.155	kWh	Average value from available industry data, LCI datasets, and scientific papers
Electricity, cooling	0.001	kWh	Average value from available industry data, LCI datasets, and scientific papers
Electricity, cutting	0.011	kWh	Average value from available industry data, LCI datasets, and scientific papers
Outputs			
Meat alternative	0.441	kg	Average value from available industry data, LCI datasets, and scientific papers
Water, side stream wastewater treatment	0.545	kg	Average value from available industry data, LCI datasets, and scientific papers

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

Finally, the meat alternative is mixed along with the rest of the recipe's ingredients to be ready for cooking and consumption as ground food (Table 4-12).

Table 4-12. Life cycle inventory data for ground meat alternative, System 2.

Components	Consumption	Unit	Origin of Ingredient	Note
1 kg of ground food with protein content, known in the market as meat or meat alternatives ready to be cooked, from cradle-to-manufacturing gate, before packaging or cooling				
Inputs				
Meat alternative	0.441	kg	U.S.	0.15 kg of protein content, 0.29 kg of water content
Water	0.369	kg	U.S.	
Wheat gluten	0.050	kg	U.S.	
Coconut oil	0.040	kg	Philippines and Indonesia	
Canola oil	0.040	kg	Canada	
Potato starch	0.030	kg	Germany	
Spices	0.030	kg	Global mix and U.S.	
Transport	9.50	kg.km	U.S.	Transport, freight, lorry 7.5-16 metric ton, EURO5 for wheat gluten, coconut oil, canola oil, potato starch, and spices. Distance of 50 km.
Outputs				
1 kg of plant-based meat product ready to be cooked, from cradle-to-manufacturing gate, before packaging or cooling	1.000	kg		

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

4.3.3 System 3, soybeans, wet fractionation, high moisture extrusion

The process starts with soybean processing from the agricultural cultivation stage into soybean white flakes and oil (Table 4-13).

Table 4-13. Life cycle inventory data for processing of soybeans.

Components	Consumption	Unit	Note
Soybean oil and white flakes extraction			
Inputs			

Hexane	2.40E-04	kg	Taken from ecoinvent 3.9.1 original dataset for soybean oil and meal extraction {U.S.}
Oil mill infrastructure	7.36E-11	p	Taken from ecoinvent 3.9.1 original dataset for soybean oil and meal extraction {U.S.}
Soybeans	0.42	kg	Taken from ecoinvent 3.9.1 original dataset for soybean oil and meal extraction {U.S.}
Water	0.21	kg	Taken from ecoinvent 3.9.1 original dataset for soybean oil and meal extraction {U.S.}
Transport, ground freight, 7.5–16 ton	21.18	kg.km	Taken from ecoinvent 3.9.1 original dataset for soybean oil and meal extraction {U.S.} 0.42 kg of soybean transported for 50 km
Electricity, medium voltage	0.02	kWh	Taken from ecoinvent 3.9.1 original dataset for soybean oil and meal extraction {U.S.}
Heat, from natural gas	0.51	MJ	Taken from ecoinvent 3.9.1 original dataset for soybean oil and meal extraction {U.S.}
Outputs			
Soy white flakes	0.334	kg	Co-product. Taken from ecoinvent 3.9.1 original dataset for soybean oil and meal extraction {U.S.}
Soybean oil	0.081	kg	Co-product. Taken from ecoinvent 3.9.1 original dataset for soybean oil and meal extraction {U.S.}
Hexane, to air	2.40E-04	kg	Taken from ecoinvent 3.9.1 original dataset for soybean oil and meal extraction {U.S.}
Water, to air	3.09E-05	m3	Taken from ecoinvent 3.9.1 original dataset for soybean oil and meal extraction {U.S.}
BOD, to water	4.53E-06	kg	Taken from ecoinvent 3.9.1 original dataset for soybean oil and meal extraction {U.S.}

COD, to water	2.27E-05	kg	Taken from ecoinvent 3.9.1 original dataset for soybean oil and meal extraction {U.S.}
DOC, to water	8.50E-06	kg	Taken from ecoinvent 3.9.1 original dataset for soybean oil and meal extraction {U.S.}
Oils, biogenic, to water	1.13E-05	kg	Taken from ecoinvent 3.9.1 original dataset for soybean oil and meal extraction {U.S.}
TOC, to water	8.50E-06	kg	Taken from ecoinvent 3.9.1 original dataset for soybean oil and meal extraction {U.S.}
Water, to water	1.75E-04	m3	Taken from ecoinvent 3.9.1 original dataset for soybean oil and meal extraction {U.S.}
Inert waste, for final disposal	7.04E-04	kg	Taken from ecoinvent 3.9.1 original dataset for soybean oil and meal extraction {U.S.}

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

Then, the soy white flakes go through the wet fractionation process to obtain soy protein concentrate (Table 4-14).

Table 4-14. Life cycle inventory data for wet fractionation of soy white flakes.

Components	Consumption	Unit	Note
Wet fractionation of soy white flakes			
Inputs			
Soy white flakes	0.334	kg	Average value from available industry data, LCI datasets, and scientific papers
Water	0.058	kg	Average value from available industry data, LCI datasets, and scientific papers
Ethanol	0.002	kg	Average value from available industry data, LCI datasets, and scientific papers
Electricity, wet fractionation	0.032	MJ	Average value from available industry data, LCI datasets, and scientific papers

Heat from natural gas	1.511	MJ	Average value from available industry data, LCI datasets, and scientific papers
Outputs			
Soy protein concentrate	0.215	kg	Co-product. Average value from available industry data, LCI datasets, and scientific papers
Soy fines	0.025	kg	Co-product. Average value from available industry data, LCI datasets, and scientific papers
Soy molasses	0.104	kg	Co-product. Average value from available industry data, LCI datasets, and scientific papers
Wastewater	0.048	kg	Average value from available industry data, LCI datasets, and scientific papers
Ethanol	0.002	kg	Average value from available industry data, LCI datasets, and scientific papers

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

Once the soy protein concentrate is obtained, it is mixed with water through an HME process to produce a meat alternative as a main product (Table 4-15).

Table 4-15. Life cycle inventory data for high moisture extrusion of soy protein concentrate.

Components	Consumption	Unit	Note
High moisture extrusion of soy protein concentrate			
Inputs			
Soy protein concentrate	0.215	kg	Average value from available industry data, LCI datasets, and scientific papers
Water	0.520	kg	Average value from available industry data, LCI datasets, and scientific papers
Water, side stream	6.100	kg	Average value from available industry data, LCI datasets, and scientific papers
Electricity, pre-conditioning	0.021	kWh	Average value from available industry data, LCI datasets, and scientific papers

Electricity, extrusion	0.120	kWh	Average value from available industry data, LCI datasets, and scientific papers
Electricity, cooling	0.004	kWh	Average value from available industry data, LCI datasets, and scientific papers
Electricity, cutting	0.042	kWh	Average value from available industry data, LCI datasets, and scientific papers
Electricity, water heating	0.010	kWh	Average value from available industry data, LCI datasets, and scientific papers
Heat from natural gas	0.013	MJ	Average value from available industry data, LCI datasets, and scientific papers
Outputs			
Meat alternative	0.714	kg	Average value from available industry data, LCI datasets, and scientific papers
Side stream water	6.100	kg	Average value from available industry data, LCI datasets, and scientific papers
Solid wastes	0.021	kg	Average value from available industry data, LCI datasets, and scientific papers

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

Finally, the meat alternative is mixed along with the rest of the recipe's ingredients to be ready for its cooking and consumption as ground food (Table 4-16).

Table 4-16. Life cycle inventory data for ground meat alternative, System 3.

Components	Consumption	Unit	Origin of Ingredient	Note
1 kg of ground food with protein content, known in the market as meat or meat alternatives ready to be cooked, from cradle-to-manufacturing gate, before packaging or cooling				
Inputs				
Meat alternative	0.714	kg	U.S.	0.15 kg of protein content, 0.56 kg of water content
Water	0.096	kg	U.S.	
Wheat gluten	0.050	kg	U.S.	

Coconut oil	0.040	kg	Philippines and Indonesia	
Canola oil	0.040	kg	Canada	
Potato starch	0.030	kg	Germany	
Spices	0.030	kg	Global mix and U.S.	Mix of spices available in Section 3.6 and in Appendix 3
Transport	9.50	kg.km	U.S.	Transport, freight, lorry 7.5–16 metric ton, EURO5 for wheat gluten, coconut oil, canola oil, potato starch, and spices. Distance of 50 km.
Outputs				
1 kg of plant-based meat product ready to be cooked, from cradle-to-manufacturing gate, before packaging or cooling	1.000	kg		

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

4.3.4 System 4, animal-based meat, beef

This system starts with the upstream production of cattle, live weight, including cultivation of the feed basket. This process is modeled after an ecoinvent 3.9.1 dataset based on cattle production originally modeled accounting for a RoW market mix (Table 4-17).

Table 4-17. Summarized life cycle inventory data for cattle, live weight production (2.04 kg) based on cattle for slaughtering, live weight U.S.; fattening of calves for beef production, feedlot; cut-off, U from ecoinvent 3.9.1.

Components	Consumption	Unit	Geographic origin	Notes
Cattle for slaughtering, live weight U.S.| fattening of calves for beef production, feedlot | Cut-off, U				
Inputs				
Water, natural origin	0.01	m3	U.S.	Taken from original ecoinvent 3.9.1 dataset
Occupation, natural grassland, for livestock grazing	0.38	m2a		
Occupation, manmade, pasture	0.09	m2a		

Occupation, unspecified	0.01	m2a		
Transformation, from natural grassland for livestock grazing	1.32	m2		
Transformation, to natural grassland for livestock grazing	1.04	m2		
Transformation to man-made pasture	0.25	m2		
Transformation, to unspecified	0.02	m2		
Alfalfa-grass silage	1.515	kg	Québec, CA	
Energy feed mix	0.010	kg	Modified to account for U.S. when available datasets; original dataset based after RoW	Composed of maize (68%), barley (8%), soybean meal (9%), sweet sorghum (4%), rape meal (2%), sugar beet pulp (1%), distilled dried grains (1%), wheat bran (1%), skimmed milk (1%), and remaining grains (5%)
Irrigation	0.02	m3	U.S.	
Lime	0.05	kg	Québec, CA	
Maize	3.85	kg	U.S.	
Manure, liquid	-0.80	kg	Global	Negative value due to cut-off approach for original ecoinvent 3.9.1 dataset
Manure, solid	-7.24	kg	Global	Negative value due to cut-off approach for original ecoinvent 3.9.1 dataset
Rape meal	0.28	kg	Global	
Sodium chloride	0.02	kg	Global	
Water	0.60	kg	Global	
Transport, tractor, and trailer (tkm=tonne-km)	0.02	tkm	Global	
Urea	0.07	kg	Global	

Weaned calves, live weight, U.S. market mix	0.97	kg	U.S.	Original market mix adjusted to account for U.S. market mix (77% intensive systems, 23% mixed and extensive). Source: Bengoa et al., 2019
Wheat bran	0.40	kg	Global	
Electricity, low voltage	0.01	kWh	U.S., MRO	
Operation, housing system, cattle, loose	1.57E-03	p	U.S.	
Outputs				
Cattle for slaughtering, live weight {US}	2.04	kg	U.S.	
Ammonia, to air	4.10E-02	kg		
Dinitrogen monoxide, to air	3.61E-03	kg		
Methane, biogenic, to air	9.31E-02	kg		
Water, to air	1.36E-03	kg		
Cadmium, to water	1.00E-09	kg		
Chromium, to water	1.19E-06	kg		
Copper, to water	4.08E-07	kg		
Lead, to water	9.82E-09	kg		
Mercury, to water	1.43E-10	kg		
Phosphate, to water	8.80E-03	kg		
Phosphorus, to water	5.14E-03	kg		
Water, to water	7.73E-03	kg		
Zinc, to water	2.06E-06	kg		
Cadmium, to soil	1.45E-08	kg		
Copper, to soil	1.12E-06	kg		
Lead, to soil	3.33E-07	kg		
Mercury, to soil	2.45E-08	kg		
Nickel, to soil	3.41E-07	kg		
Zinc, to soil	8.04E-06	kg		

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

The cattle, live weight, are then slaughtered; an original slaughtering dataset from WFLDB was modified to use the same electricity, heat from natural gas, and water datasets used in Systems 1-3 (Table 4-18).

Table 4-18. Life cycle inventory data for beef cattle slaughtering (2.04 kg).

Components	Consumption	Unit	Note
Slaughtering, beef cattle (WFLDB)/GLO U			
Inputs			
Occupation, industrial area	6.73E-03	m2a	Original dataset and consumption from WFLDB
Building, hall {GLO}| market for | Cut-off, S	1.15E-04	m2	Original dataset and consumption from WFLDB
Industrial machine, heavy, unspecified {RER}| production | Cut-off, S	3.20E-03	kg	Original dataset and consumption from WFLDB
Heat, natural gas {US}	2.79	MJ	Modified dataset from ecoinvent
Phosphoric acid, industrial grade, without water, in 85% solution state {GLO}| market for | Cut-off, S	9.02E-04	kg	Original dataset and consumption from WFLDB
Water, general use {US} ESG	33.86	kg	Modified dataset from ecoinvent
Sodium hydroxide, without water, in 50% solution state {RER}| chlor-alkali electrolysis, membrane cell | Cut-off, S	3.69E-03	kg	Original dataset and consumption from WFLDB
Potassium hydroxide {GLO}| market for | Cut-off, S	3.69E-04	kg	Original dataset and consumption from WFLDB
Sodium hypochlorite, without water, in 15% solution state {RoW}| market for sodium hypochlorite, without water, in 15% solution state | Cut-off, S	2.04E-03	kg	Original dataset and consumption from WFLDB
Soap {GLO}| market for | Cut-off, S	2.59E-05	kg	Original dataset and consumption from WFLDB
Electricity, medium voltage {US} ESG	2.65	kWh	Modified dataset from ecoinvent
Outputs			
Slaughtering, beef cattle (WFLDB)/GLO U - ESG	2.04	kg	Original dataset and consumption from WFLDB
Water	4.13	kg	Original dataset and consumption from WFLDB

Wastewater from potato starch production {CH}| treatment of, capacity 1.1E10l/year | Cut-off, S	0.03	m3	Original dataset and consumption from WFLDB; this is a proxy for slaughterhouse wastewater treatment
Biowaste {GLO}| treatment of biowaste, municipal incineration | Cut-off, S	1.80	kg	Original dataset and consumption from WFLDB
Municipal solid waste {CH}| treatment of, municipal incineration with fly ash extraction | Cut-off, S	0.09	kg	Original dataset and consumption from WFLDB
Core board (waste treatment) {GLO}| recycling of core board | Cut-off, S	0.01	kg	Original dataset and consumption from WFLDB

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

During the slaughtering stage, multiple co-products are obtained from the live weight cattle, such as fresh beef meat, bones, and fat (Table 4-19).

Table 4-19. Life cycle inventory data for fresh beef meat (1 kg).

Components	Consumption	Unit	Note
Fresh beef meat, slaughtered cattle {US}| cattle production | Cut-off, U			
Inputs			
Cattle for slaughtering, live weight {US}| fattening of calves for beef production, feedlot | Cut-off, U	2.04	kg	Dataset from ecoinvent 3.9.1
Slaughtering, beef cattle WFLDB/GLO U - ESG	2.04	kg	Modified dataset from WFLDB
Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO3 | Cut-off, S - Copied from ecoinvent	0.41	tkm	Assumption: 200 km between farm and slaughterhouse (tkm=tonne-km)
Outputs			
Fresh beef meat, slaughtered cattle {US}| cattle production | Cut-off, U	1.00	kg	Allocation factors in Section 3.5 Source: European Commission 2021
Food grade bones, slaughtered cattle {US}| cattle production | Cut-off, U - ESG	0.16	kg	Allocation factors in Section 3.5 Source: European Commission 2021

Food grade fat, slaughtered cattle {US}| cattle production | Cut-off, U - ESG	0.14	kg	Allocation factors in Section 3.5 Source: European Commission 2021
Category 3 slaughter by-products, slaughtered cattle {US}| cattle production | Cut-off, U - ESG	0.14	kg	Allocation factors in Section 3.5 Source: European Commission 2021
Hides and skins, slaughtered cattle {US}| cattle production | Cut-off, U - ESG	0.14	kg	Allocation factors in Section 3.5 Source: European Commission 2021
Category 1/2 material and waste, slaughtered cattle {US}| cattle production | Cut-off, U - ESG	0.45	kg	Allocation factors in Section 3.5 Source: European Commission 2021

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

Finally, the fresh beef meat is ground to be delivered at the manufacturing gate, before packaging or cooling (Table 4-20).

Table 4-20. Life cycle inventory data for animal-based meat, from beef, at the manufacturing gate.

Components	Consumption	Unit	Note
1 kg of ground animal-based meat, from beef, at the manufacturing gate			
Inputs			
Fresh beef meat, slaughtered cattle {US}| cattle production | Cut-off, U	1.00	kg	
Electricity, medium voltage {US}	0.49	kWh	Data taken from Smetana et al. 2021. Custom-made dataset from ecoinvent
Outputs			
Beef, ground meat, at manufacturing gate {US} U	1.00	kg	

4.3.5 System 5, animal-based meat, pork

This system starts with the upstream production of swine, live weight, including cultivation of the feed. This process is modeled after an ecoinvent 3.9.1 dataset based on industrial swine production from Québec, Canada (Table 4-21).

Table 4-21. Summarized life cycle inventory data for swine, live weight production (1.49 kg) based on Swine for slaughtering, live weight {US}| swine production | Cut-off, U from ecoinvent 3.9.1.

Components	Consumption	Unit	Geographic origin	Notes
Swine for slaughtering, live weight {US}| swine production | Cut-off, U				
Inputs				
Barley grain, feed	0.66	kg	Québec, CA	
Organic chemical	0.01	kg	Global	Diet supplement
Limestone	0.04	kg	Global	Diet supplement
Liquid manure storage and processing facility	0.01	m3	Global	
Maize grain, feed	2.21	kg	U.S.	
Manure, liquid	-12.99	kg	Global	Negative value due to cut-off approach for original ecoinvent 3.9.1 dataset
Oat grain	0.40	Kg	Québec, CA	
Operation, pig housing system	0.02	p	Global	
Rape meal	0.23	kg	Global	
Sodium chloride	0.01	kg	Global	
Soybean meal	0.52	kg	U.S.	
Soybean, feed	0.22	kg	U.S.	
Wheat grain, feed	0.16	kg	U.S.	
Whey	0.01	kg	Global	
Outputs				
Swine for slaughtering, live weight {US}	1.49	kg	U.S.	
Carbon dioxide, biogenic, to air	4.12E-03	kg		
Dinitrogen monoxide, to air	3.69E-04	kg		
Hydrogen sulfide, to air	8.39E-02	kg		
Methane, biogenic, to air	7.92E-02	kg		
Particulates <2.5 um, to air	2.75E-03	kg		
Particulates <10 um, to air	2.64E-02	kg		
Particulates <2.5 and <10 um, to air	2.83E-03	kg		

Slaughterhouse waste	0.05	kg	Global	Dead animals sent to rendering market

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

Then, the swine, live weight, are slaughtered; an original slaughtering dataset from WFLDB was modified to account for the same electricity, heat from natural gas, and water mixes and providers as those used in Systems 1-3 (Table 4-22).

Table 4-22. Life cycle inventory data for swine slaughtering (1.49 kg).

Components	Consumption	Unit	Note
Slaughtering, swine (WFLDB)/GLO U			
Inputs			
Building, hall {GLO}| market for | Cut-off, S	1.34E-05	m2	Original dataset and consumption from WFLDB
Industrial machine, heavy, unspecified {RER}| production | Cut-off, S	1.11E-03	kg	Original dataset and consumption from WFLDB
Water, general use {US}	15.05	kg	Modified dataset from ecoinvent
Carbon dioxide, liquid {RER}| market for | Cut-off, S	7.15E-03	kg	Original dataset and consumption from WFLDB
Phosphoric acid, fertilizer grade, without water, in 70% solution state {GLO}| market for | Cut-off, S	5.24E-04	kg	Original dataset and consumption from WFLDB
Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, S	2.15E-03	kg	Original dataset and consumption from WFLDB
Potassium hydroxide {GLO}| market for | Cut-off, S	2.15E-04	kg	Original dataset and consumption from WFLDB
Sodium hypochlorite, without water, in 15% solution state {RoW}| market for sodium hypochlorite, without water, in 15% solution state | Cut-off, S	1.18E-03	kg	Original dataset and consumption from WFLDB
Fatty alcohol sulfate {RER}| production, coconut oil | Cut-off, S	1.52E-05	kg	Original dataset and consumption from WFLDB
Electricity, Medium Voltage {US}	0.74	kWh	Modified dataset from ecoinvent
Heat, natural gas {US}	2.19	MJ	Modified dataset from ecoinvent
Outputs			

Slaughtering, swine (WFLDB)/GLO U	1.49	kg	Original dataset and consumption from WFLDB
Water	1.84	kg	Original dataset and consumption from WFLDB
Wastewater from potato starch production {CH}| treatment of, capacity 1.1E10l/year | Cut-off, S	1.32E-02	m3	Original dataset and consumption from WFLDB; this is a proxy for slaughterhouse wastewater treatment
Municipal solid waste {CH}| treatment of, municipal incineration with fly ash extraction | Cut-off, S	2.67E-02	kg	Original dataset and consumption from WFLDB
Biowaste {CH}| treatment of biowaste by anaerobic digestion | Cut-off, S	1.11E-03	kg	Original dataset and consumption from WFLDB
Biowaste {GLO}| treatment of biowaste, municipal incineration | Cut-off, S	2.18E-01	kg	Original dataset and consumption from WFLDB
Core board (waste treatment) {GLO}| recycling of core board | Cut-off, S	6.18E-04	kg	Original dataset and consumption from WFLDB

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

During the slaughtering stage, multiple co-products are obtained from the live weight swine, such as fresh pork meat (Table 4-23).

Table 4-23. Life cycle inventory data for fresh pork meat (1 kg).

Components	Consumption	Unit	Note
Fresh pork meat, slaughtered swine {US}|			
Inputs			
Swine for slaughtering, live weight {US}	1.49	kg	Modified dataset from ecoinvent 3.9.1
Slaughtering, swine (WFLDB)/GLO U - ESG	1.49	kg	Modified dataset from WFLDB
Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO3 | Cut-off, S	0.30	tkm	Assumption: 200 km between farm and slaughterhouse (tkm=tonne-km)
Outputs			

Fresh pork meat, slaughtered swine {US}| swine production | Cut-off, U	1.00	kg	Allocation factors in Section 3.5 Source: European Commission 2021
Food grade bones, slaughtered swine {US}	0.16	kg	Allocation factors in Section 3.5 Source: European Commission 2021
Food grade fat, slaughtered swine {US}	0.04	kg	Allocation factors in Section 3.5 Source: European Commission 2021
Category 3 slaughter by-products, slaughtered swine {US}	0.28	kg	Allocation factors in Section 3.5 Source: European Commission 2021

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

Finally, the fresh pork meat is ground at the manufacturing gate, before packaging or cooling (Table 4-24).

Table 4-24. Life cycle inventory data for animal-based meat, from pork, at the manufacturing gate.

Components	Consumption	Unit	Note
1 kg of ground animal-based meat, from pork, at the manufacturing gate			
Inputs			
Fresh pork meat, slaughtered swine {US}| swine production | Cut-off, U	1.00	kg	
Electricity, Medium Voltage {US} ESG	0.49	kWh	Data taken from Smetana et al. 2021. Custom-made dataset from ecoinvent
Outputs			
Pork, ground meat, at manufacturing gate {US} U	1.00	kg	

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

4.3.6 System 6, animal-based meat, chicken

This system starts with the upstream production of broiler, live weight, including feed cultivation. This process is modeled after an ecoinvent 3.9.1 dataset based on intensive broiler production from the U.S. (Table 4-25).

Table 4-25. Summarized life cycle inventory data for broiler, live weight production (1.52 kg) based on Chicken for slaughtering, live weight {US}| chicken production | Cut-off, U from ecoinvent 3.9.1.

Components	Consumption	Unit	Geographic origin	Notes
Chicken for slaughtering, live weight {US}| chicken production | Cut-off, U				
Inputs				
Water	7.88E-03	kg	Global	
Energy feed mix	1.64	kg	Modified to account for U.S. when available datasets; original dataset based after RoW.	Composed of maize (68%), barley (8%), soybean meal (9%), sweet sorghum (4%), rape meal (2%), sugar beet pulp (1%), distilled dried grains (1%), wheat bran (1%), skimmed milk (1%), and remaining grains (5%)
Poultry manure, fresh	-2.94	kg	Global	Negative value due to cut-off approach for original ecoinvent 3.9.1 dataset
Protein feed	0.46	kg	Modified to account for U.S. when available datasets; original dataset based after RoW.	Composed by maize (40%), soybean meal (27%), sweet sorghum (9%), barley (6%), rape meal (4%), skimmed milk (4%), distilled dried grains (2%), cottonseed (2%), meat and bone meal (2%), wheat bran (1%), and remaining grains (4%)
Shed	8.03E-08	m2	Global	
Electricity	0.81	kWh	U.S.	
Heat, from natural gas	0.47	MJ	U.S.	
Broiler house	2.04E-05	p	U.S.	
Outputs				
Chicken for slaughtering, live weight {US}	1.52	kg	U.S.	
Ammonia, to air	2.23E-02	kg		
Dinitrogen monoxide, to air	1.65E-03	kg		
Methane, biogenic, to air	8.68E-04	kg		

Water, to air	1.18E-03	kg		
Nitrate, to water	6.28E-02	kg		
Phosphate, to water	3.44E-04	kg		
Water, to water	6.70E-03	kg		

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

Then, the live weight broilers are slaughtered; inventory is shown in Table 4-26. The original slaughtering dataset from WFLDB was modified to use the same electricity, heat from natural gas, and water datasets used in the plant-based meat systems.

Table 4-26. Life cycle inventory data for broiler slaughtering (1.52 kg).

Components	Consumption	Unit	Note
Slaughtering, poultry (WFLDB)/GLO U			
Inputs			
Building, hall {GLO}| market for | Cut-off, S	1.73E-05	m2	Original dataset and consumption from WFLDB
Industrial machine, heavy, unspecified {RER}| production | Cut-off, S	1.69E-03	kg	Original dataset and consumption from WFLDB
Heat, natural gas {US}	2.13	MJ	Modified dataset from ecoinvent
Water, general use {US}	20.67	kg	Modified dataset from ecoinvent
Phosphoric acid, industrial grade, without water, in 85% solution state {GLO}| market for | Cut-off, S	3.54E-04	kg	Original dataset and consumption from WFLDB
Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, S	3.22E-03	kg	Original dataset and consumption from WFLDB
Potassium hydroxide {GLO}| market for | Cut-off, S	3.22E-04	kg	Original dataset and consumption from WFLDB
Sodium hypochlorite, without water, in 15% solution state {RoW}| market for sodium hypochlorite, without water, in 15% solution state | Cut-off, S	1.43E-03	kg	Original dataset and consumption from WFLDB
Soap {GLO}| market for | Cut-off, S	1.81E-05	kg	Original dataset and consumption from WFLDB
Electricity, Medium Voltage {US}	1.21	kWh	Modified dataset from ecoinvent

Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, S	5.49E-03	kg	Original dataset and consumption from WFLDB
Iron (III) chloride, without water, in 40% solution state {GLO}| market for | Cut-off, S	5.32E-03	kg	Original dataset and consumption from WFLDB
Outputs			
Slaughtering, poultry (WFLDB)/GLO	1.52	kg	Original dataset and consumption from WFLDB
Water	2.52	kg	Original dataset and consumption from WFLDB
Biowaste {GLO}| treatment of biowaste, municipal incineration | Cut-off, S	0.00E+00	kg	Original dataset and consumption from WFLDB
Municipal solid waste {CH}| treatment of, municipal incineration with fly ash extraction | Cut-off, S	3.22E-02	kg	Original dataset and consumption from WFLDB
Biowaste {CH}| treatment of biowaste by anaerobic digestion | Cut-off, S	8.03E-02	kg	Original dataset and consumption from WFLDB
Core board (waste treatment) {GLO}| recycling of core board | Cut-off, S	1.16E-03	kg	Original dataset and consumption from WFLDB
Mixed plastics (waste treatment) {GLO}| recycling of mixed plastics | Cut-off, S	4.46E-03	kg	Original dataset and consumption from WFLDB
Wastewater from potato starch production {CH}| treatment of, capacity 1.1E10l/year | Cut-off, S	1.82E-02	m3	Original dataset and consumption from WFLDB; this is a proxy for slaughterhouse wastewater treatment

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

During the slaughtering stage, multiple co-products are obtained from the live weight broilers, such as fresh chicken meat (Table 4-27).

Table 4-27. Life cycle inventory data for fresh chicken meat (1 kg).

Components	Consumption	Unit	Note
Fresh chicken meat, slaughtered broiler {US}| broiler production | Cut-off, U			

Inputs			
Chicken for slaughtering, live weight {US}	1.52	kg	Dataset from ecoinvent 3.9.1
Slaughtering, poultry (WFLDB)/GLO	1.52	kg	Modified dataset from WFLDB
Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO3 | Cut-off, S - Copied from ecoinvent	0.30	tkm	Assumption: 200 km between farm and slaughterhouse (tkm=tonne-km)
Outputs			
Fresh chicken meat, slaughtered broiler {US}	1.00	kg	Allocation factors on Section 3.5 Source: FAO 2016
Non-meat inedible offal in carcass, slaughtered broiler {US}	0.32	kg	Allocation factors on Section 3.5 Source: FAO 2016
Edible offal, slaughtered broiler {US}	0.03	kg	Allocation factors on Section 3.5 Source: FAO 2016
Poultry oil, slaughtered broiler {US}	0.02	kg	Allocation factors on Section 3.5 Source: FAO 2016
Blood meal, slaughtered broiler {US}	0.01	kg	Allocation factors on Section 3.5 Source: FAO 2016
Pet food slurry, slaughtered broiler {US}	0.08	kg	Allocation factors on Section 3.5 Source: FAO 2016
Pet food digest, slaughtered broiler {US}	0.01	kg	Allocation factors on Section 3.5 Source: FAO 2016
Poultry meal, slaughtered broiler {US}	0.02	kg	Allocation factors on Section 3.5 Source: FAO 2016
Feather meal, slaughtered broiler {US}	0.04	kg	Allocation factors on Section 3.5 Source: FAO 2016

Notes: For each table, the main product of interest is highlighted in green. Inventory is scaled to 1 kg of functional unit (final product for each system).

Finally, the fresh chicken meat is ground to be delivered at the manufacturing gate, before packaging or cooling (Table 4-28).

Table 4-28. Life cycle inventory data for animal-based meat, from chicken, at the manufacturing gate.

Components	Consumption	Unit	Note
1 kg of ground animal-based meat, from chicken, at the manufacturing gate			
Inputs			
Fresh chicken meat, slaughtered broiler {US}	1.00	kg	

Electricity, Medium Voltage {US} ESG	0.49	kWh	Data taken from Smetana et al. 2021. Custom-made dataset from ecoinvent
Outputs			
Chicken, ground meat, at manufacturing gate {US} U	1.00	kg	

5. Life cycle impact assessment results

5.1 System #1 (yellow peas, DF, LME) results

5.1.1 Ingredient contribution analysis

Figure 5-1 shows the contribution of each ingredient and stage to the environmental impacts of 1 kg of plant-based meat recipe, LME, DF, pea-sourced. The extruded meat analogue (28% of the product) accounts for -22 to 61% of overall impacts, with a higher contribution to ionizing radiation (61%), freshwater eutrophication (57%), human carcinogenic toxicity (52%), fossil resource scarcity (48%), marine ecotoxicity (41%), mineral resource scarcity (40%), fine particulate matter formation (38%), land use (40%), freshwater ecotoxicity (29%), and global warming (29%). The processes that drive the impacts for the extruded meat analogue are evaluated in greater detail in the next subsection.

Coconut and canola oil have disproportionally high contributions to certain impact categories, while accounting for 8% of the recipe, combined. Coconut oil contributes between 0 and 38% of the impact, while it accounts for only 4% of the recipe. Coconut oil production is identified as the main driver for impacts in global warming (38%), as well as a key driver for impacts on land use (35%), freshwater ecotoxicity (27%), stratospheric ozone depletion (23%), fine particulate matter formation (21%), and marine eutrophication (21%). In this analysis, coconut oil is sourced from coconuts cultivated in Indonesia and the Philippines. These countries have agricultural yields of around 1 ton/ha, involve land use change, emit large amounts of CO_2 from peat oxidation, and release of metolachlor from herbicide application-related emissions. Further, the processing of coconut oil requires high electricity consumption from the Southeast Asia grids, which rely heavily on fossil fuels (PM2.5 from lignite power plants).

Canola oil, which represents 4% of the recipe, contributes between 3 and 51% of the total product impact: marine eutrophication (51%), terrestrial acidification (49%), stratospheric ozone depletion (43%), human non-carcinogenic toxicity (43%), and ozone formation—human health and terrestrial ecosystems (21%, for both). Upstream emissions related to rapeseed cultivation based in Canada are the main sources of impact (fertilizer and pesticide applications cause zinc and nitrate leaching to water, and NH_4 and N_2O emissions to air). Canadian rapeseed yields are, on average, around 1.9 tons/ha.

Potato starch accounts for 2 to 49% of total impacts (49% of total water consumption and 23% of terrestrial ecotoxicity) while representing only 3% of the recipe. The average potato agricultural systems have a yield of 41 tons/ha, involve a high consumption of irrigated water (around 100 L/kg), and cause copper emissions from truck brake wear involved in transport. Although spice production was not identified as a top contributor for any impact category, its contribution to overall impacts remains noticeable (6–27%) considering it represents only 3% of the recipe. Its highest contributions are for terrestrial ecotoxicity (27%), marine ecotoxicity (21%), and mineral resource scarcity (19%), caused by upstream emissions of copper to air, copper to water, and mining of iron and copper (to both air and water) related to upstream citric acid manufacturing. Even though direct water consumption represents 53% of the alternative meat recipe, its contribution to overall impacts is insignificant (less than 3%). Finally, the contribution of overall transport to environmental impacts is minimal (less than 2%).

The negative contribution for the extruded meat analogue to the human non-carcinogenic toxicity category (-22%) is caused by upstream direct emissions of zinc from air and water to soils and plant biomass during the agricultural cultivation stage (Nemecek & Schnetzer 2011). According to the ecoinvent 3.9.1 dataset, these emissions, which were calculated based on the SALCA-heavy metal model (Freiermuth 2006), show negative values. This tool models a balance of heavy metal leaching into soils including net changes from environmental drivers such as erosion, leaching, crop removal, fertilizer and manure application, planting, and deposition. According to ecoinvent reports, it is possible (and common) for crop cultivation datasets to show negative values (Nemecek & Schnetzer 2011) and can be explained via the calculation method for the heavy metal soil leaching. The net value (which is the one shown in the LCI for each substance on each dataset) is the result of a balance between inputs (heavy metal content in fertilizers, pesticides, seeds, and deposition) and outputs (exported biomass, leaching, and erosion); negative values mean that more heavy metals leave the system embedded in biomass or into a different reservoir (e.g., groundwater) than come into the system via chemicals, seeds, and deposition (Nemecek & Schnetzer 2011).

Figure 5-1. Contribution analysis dashboard for System #1, 1 kg of plant-based meat recipe, LME, DF, pea-sourced, cradle-to-manufacturing gate. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Built based on Figure 5-1 to Figure 5-8.

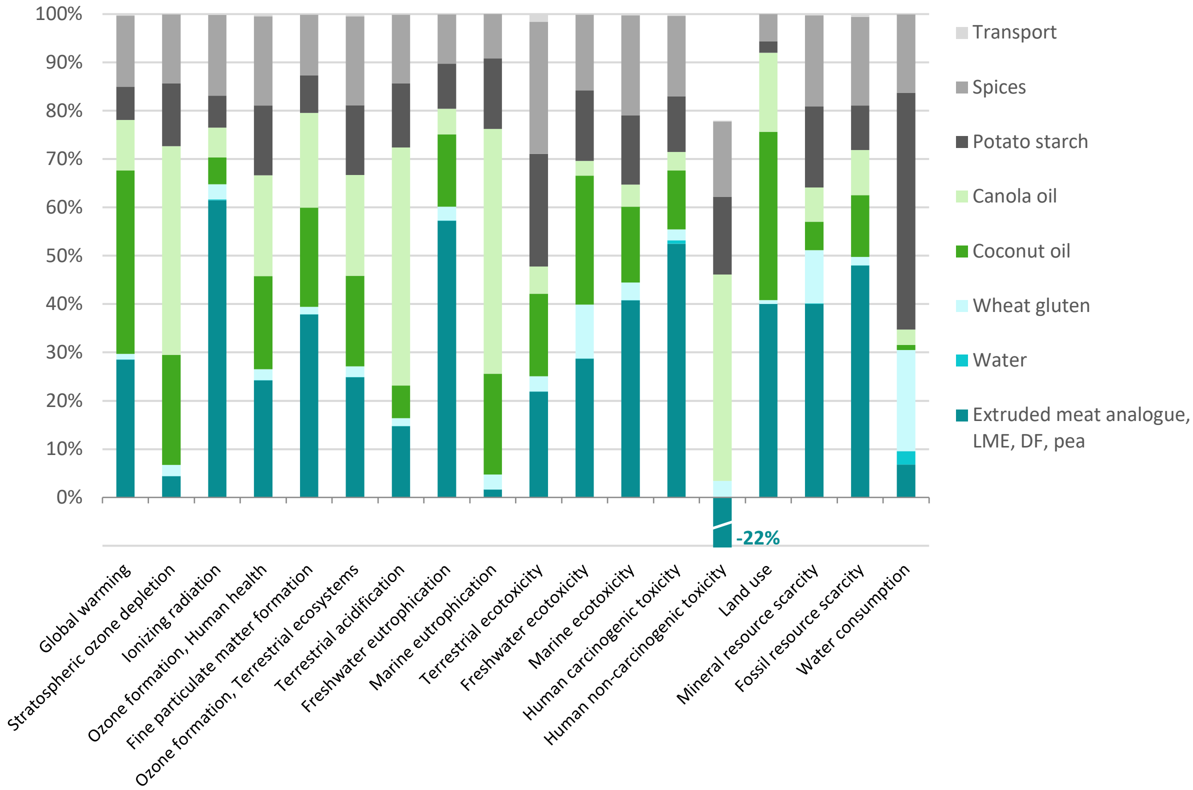

Figure 5-2. Contribution analysis for System #1, 1 kg of plant-based meat recipe, pea, DF, LME, pea-sourced, cradle-to-manufacturing gate. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-4.

5.1.2 Extruded meat analogue contribution analysis

Zooming into the extruded meat analogue contribution analysis (Figure 5-3), the dry fractionation process has the highest overall contribution (range of 44 to 71%, except land use), with the highest share of impacts for ionizing radiation (71%), fine particulate matter formation (68%), marine eutrophication (63%), water consumption (62%), global warming (60%), fossil resource scarcity (59%), freshwater eutrophication (54%), human carcinogenic toxicity (51%), terrestrial acidification (46%), stratospheric ozone depletion (45%), ozone formation—human health and terrestrial ecosystems (44% for both), and marine and freshwater ecotoxicity (44% for both).

The agricultural production of peas shows the highest contribution to land use (100%), mineral resource scarcity (80%), and terrestrial ecotoxicity (65%), while showing a negative contribution to human non-carcinogenic toxicity (-67%) caused by upstream direct emissions of zinc. Finally, the LME process shows a range of 0 to 27% of total impacts.

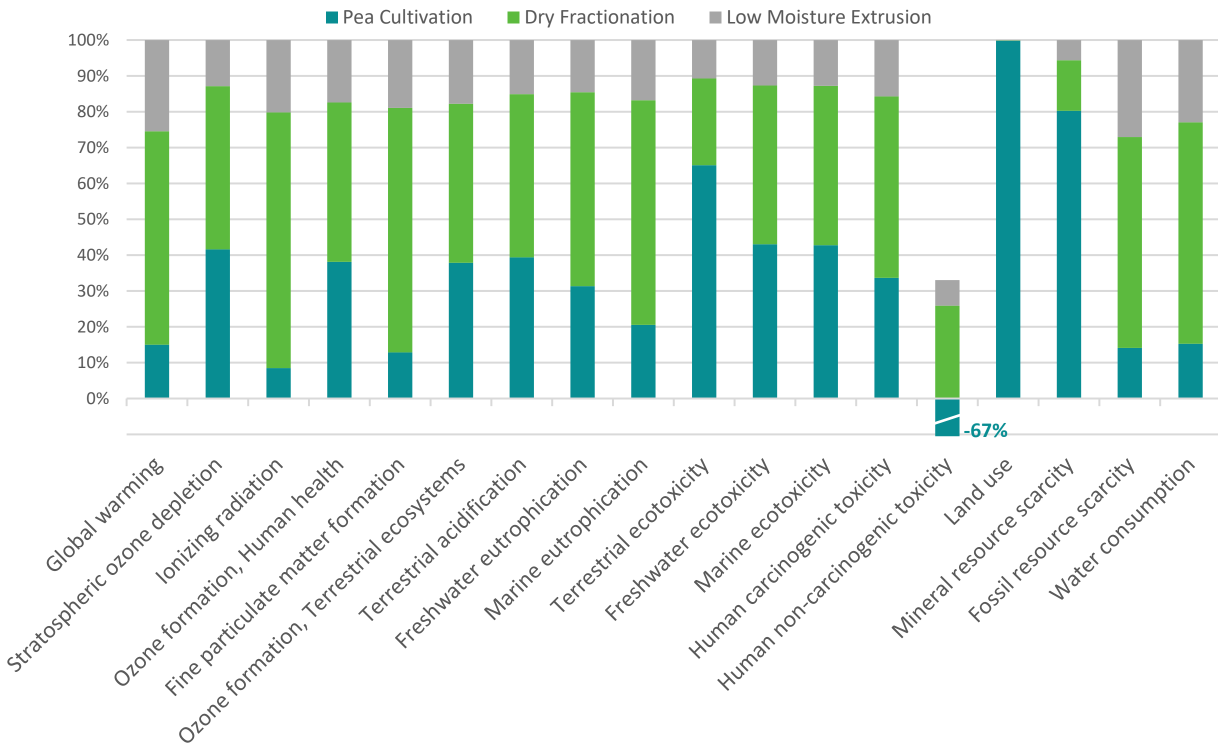

Figure 5-3. Contribution analysis for System #1, 0.283 kg of extruded meat analogue, pea, DF, LME, pea-sourced, cradle-to-manufacturing stage. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-5.

Agricultural cultivation stage impacts

Figure 5-4 shows the contribution analysis for the Canada-sourced pea cultivation stage. Direct land use and field emissions derived from fertilizer and pesticide application have a high contribution to overall impacts. Direct land use for pea cultivation represents 100% of the impact on land use. Direct emissions related to fertilizer application cause high impacts for freshwater eutrophication (85%, phosphorus run-offs to water as major contributor), stratospheric ozone depletion (75%, direct N_2O air emissions as major contributor), terrestrial acidification (51%, direct NH_4 emissions to air as main contributor), marine eutrophication (49%, nitrate run-offs to water as main contributor), and fine particulate matter formation (20%, direct NH_4 emissions to air as main contributor). Freshwater and marine ecotoxicity impacts (46% each) are mainly caused by direct zinc emissions to water. The negative values of human non-carcinogenic toxicity (-88%), that are shown from the start of the whole System #1 contribution analysis, are caused by direct emissions of zinc to soils (full explanation in Section 5.1.1).

The tillage from the rotary cultivator accounts for 0 to 38% of overall impacts, in large part due to its high diesel consumption (1.74 kg/ha). Specifically, this process contributes significantly to human carcinogenic toxicity (38%), global warming (21%), fossil resource scarcity (19%), fine particulate matter formation (19%), mineral resource scarcity (19%), terrestrial ecotoxicity (18%), and ozone formation—human health and ecosystems (20% each). This process involves upstream extraction and refining of fossil fuels. The production of monoammonium phosphate, the fertilizer with the highest consumption across the entire crop, accounts for 48% of mineral resource scarcity, 35% of ionizing radiation, and 35% of water consumption impacts (this agricultural system does not require irrigation in the Manitoba region). This process involves the extraction of phosphate rock, which requires heavy amounts of water and electricity. Finally, transport of peas from the farm to the facility gate accounts for 0–20% of total impacts, with its higher contributions in the terrestrial ecotoxicity (20%), fossil resource scarcity (15%), and global warming (13%) categories; these impacts are caused by copper emissions from brake wearing, upstream oil consumption, and direct fossil CO_2 emissions from freight trucks, respectively.

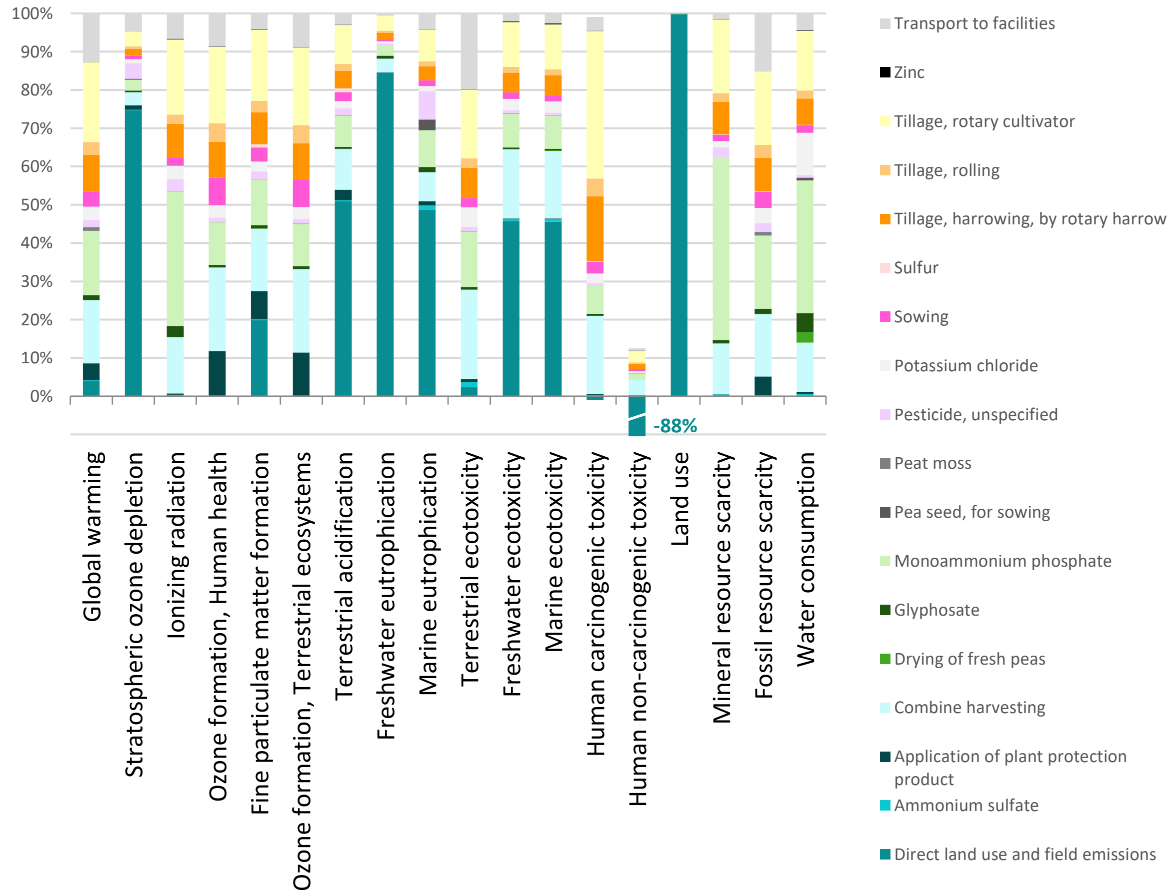

Figure 5-4. Contribution analysis for System #1, 0.339 kg of fresh peas cultivation, agricultural cultivation stage, pea-sourced, farm to facilities. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-6.

Dry fractionation stage impacts

Figure 5-5 shows the contribution analysis of the dry fractionation process. The electricity consumption has the highest overall contribution (52–98%) across all impact categories, especially freshwater eutrophication (98%), ionizing radiation (97%), fine particulate matter formation (96%), marine eutrophication (93%), human non-carcinogenic toxicity (91%), freshwater and marine ecotoxicity (90% each), human carcinogenic toxicity (88%), water use (89%), land use (84%), terrestrial acidification (84%), and terrestrial ecotoxicity (78%). The impacts are mainly caused by upstream emissions derived from fossil fuel production and direct use in power generation. The overall heating by natural gas contribution is less than 35% in all the categories, with its highest contributions to fossil resource scarcity (35%), global warming (29%), and mineral resource scarcity (28%). Biowaste disposal accounts for less than 9% of impacts, except for stratospheric ozone depletion (38%), caused by the downstream emissions of dinitrogen monoxide from municipal waste incineration. Finally, the contribution from wastewater treatment is lower than 2% in all impact categories, with a particular effect on water consumption, where the treatment of water gives negative values (-6%). This can be interpreted as an avoided burden, related to environmental benefits derived from delivering water back into the environment.

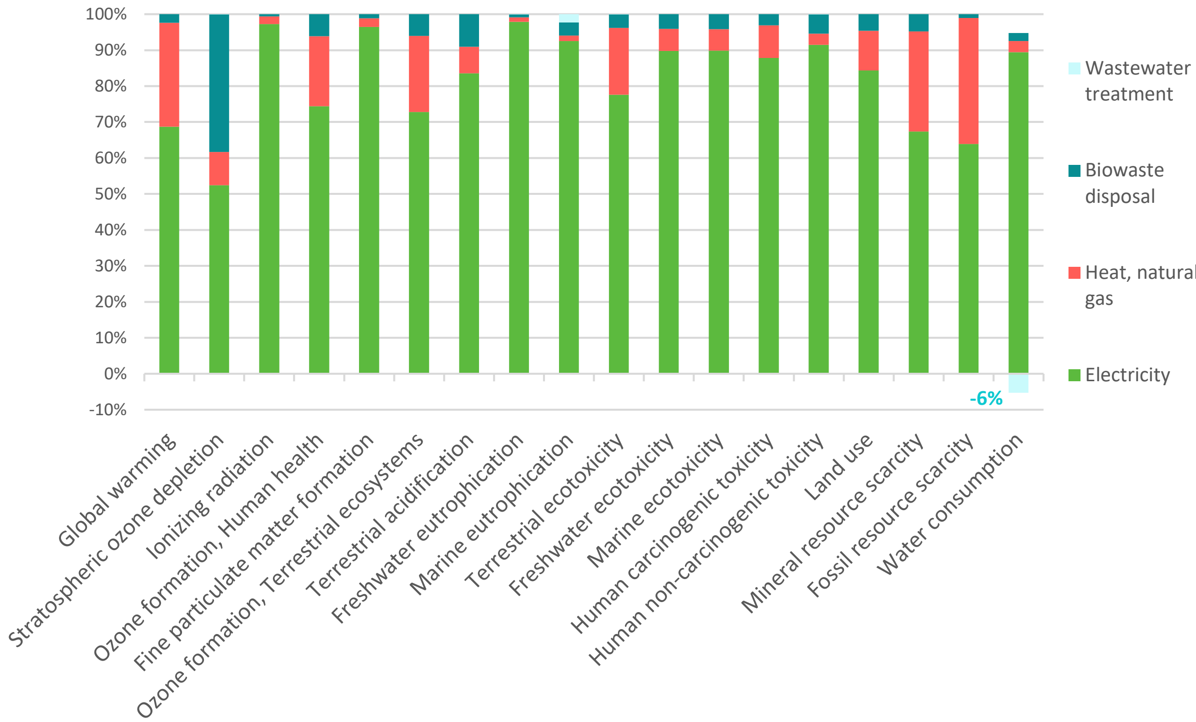

Figure 5-5. Contribution analysis for System #1, 0.291 kg of pea protein concentrate, dry fractionation stage, pea-sourced, utilities-only. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-7. Note: To focus only on the dry fractionation utilities impacts, this graph excludes the accumulated impacts from pea agricultural cultivation and transport, hence the contributions shown only account for the disaggregated utilities.

Analysis of dry fractionation from a process perspective (excluding the pea cultivation) (Figure 5-6) shows that fine grinding and air classification processes account for more than half of the environmental impacts. These processes are the top contributors to water consumption (67%), ionizing radiation (64%), freshwater eutrophication (64%), fine particulate matter formation (64%), freshwater ecotoxicity (62%), human carcinogenic toxicity (62%), human non-carcinogenic toxicity (62%), marine ecotoxicity (62%), marine eutrophication (61%), land use (61%), terrestrial ecotoxicity (61%), terrestrial acidification (60%), global warming (60%), fossil resource scarcity (60%), and ozone formation—human health and ecosystems (60% each).

Fine grinding and air classification require the highest electricity consumption across the whole dry fractionation process (1.571 kWh/kg), as well as natural gas consumption for heating (3.51 MJ/kg). Cleaning and dehulling contributes to 10 to 31% of overall impacts, with a high contribution to the stratospheric ozone depletion impact category (31%). Milling and drying contribute to 14 to 22% and 1 to 6% of total impacts, respectively. The overall contribution to impacts per process is proportional to its electricity consumption.

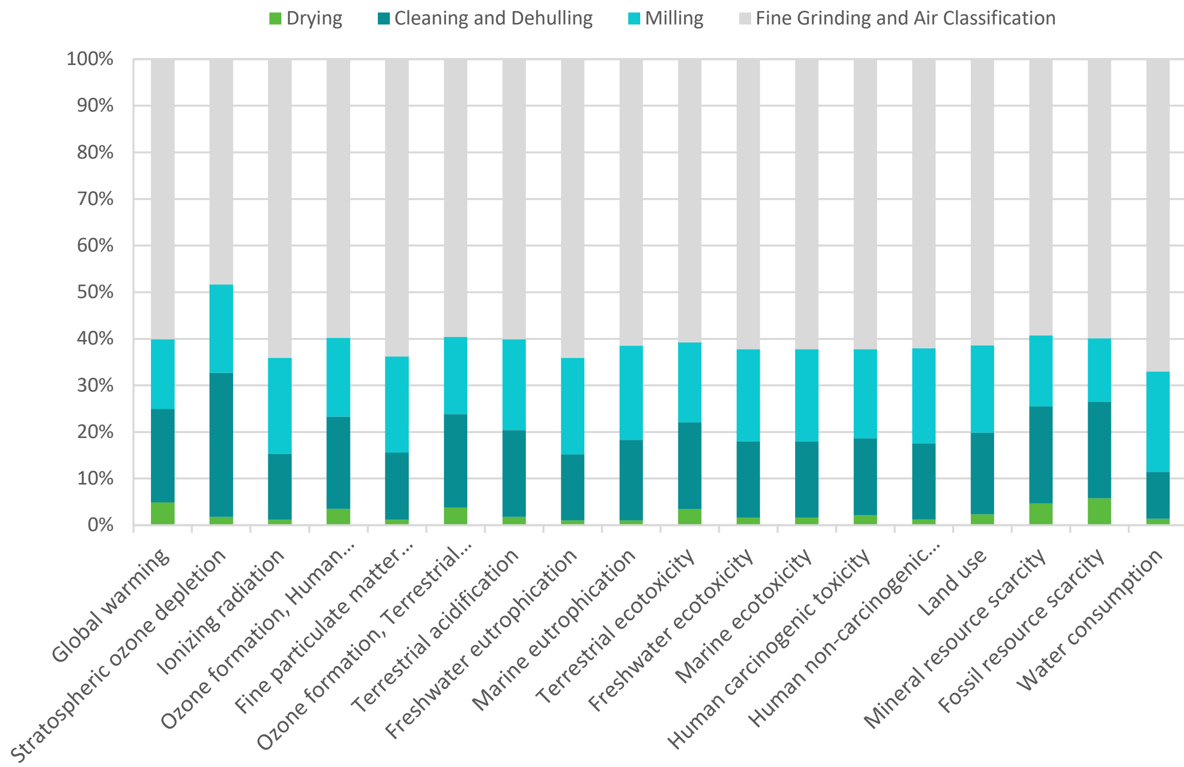

Figure 5-6. Contribution analysis for System #1, 0.291 kg of pea protein concentrate, dry fractionation stage, pea-sourced, subprocesses-only. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-8. Note: To focus only on the dry fractionation utilities impacts, this graph excludes the accumulated impacts from pea agricultural cultivation and transport, hence the contributions shown only account for the disaggregated subprocesses.

Low moisture extrusion stage impacts

Figure 5-7 shows the contribution analysis of only the LME process. Direct electricity consumption contributes to 36–93% of LME impacts, which makes it the main source of impacts in 15 out of 18 categories, with its highest contributions to freshwater eutrophication (93%), marine eutrophication and fine particulate matter formation (89% for both), ionizing radiation (88%), human non-carcinogenic toxicity (85%), and freshwater and marine ecotoxicity (80% for both). Heat from natural gas contributes the most to fossil resource scarcity (48%), mineral resource scarcity (43%), and global warming (41%); all three impact categories are closely related to fossil fuel consumption. As for the other inputs, biowaste disposal contributes to less than 5% of impacts except for stratospheric ozone depletion (25%), steam production contributes to 3–26% of impacts (highest contribution for terrestrial ecotoxicity, 26%); upstream copper emissions to air from furnaces involved in heat production and water production contribute to less than 1% in all categories except for water consumption (20%).

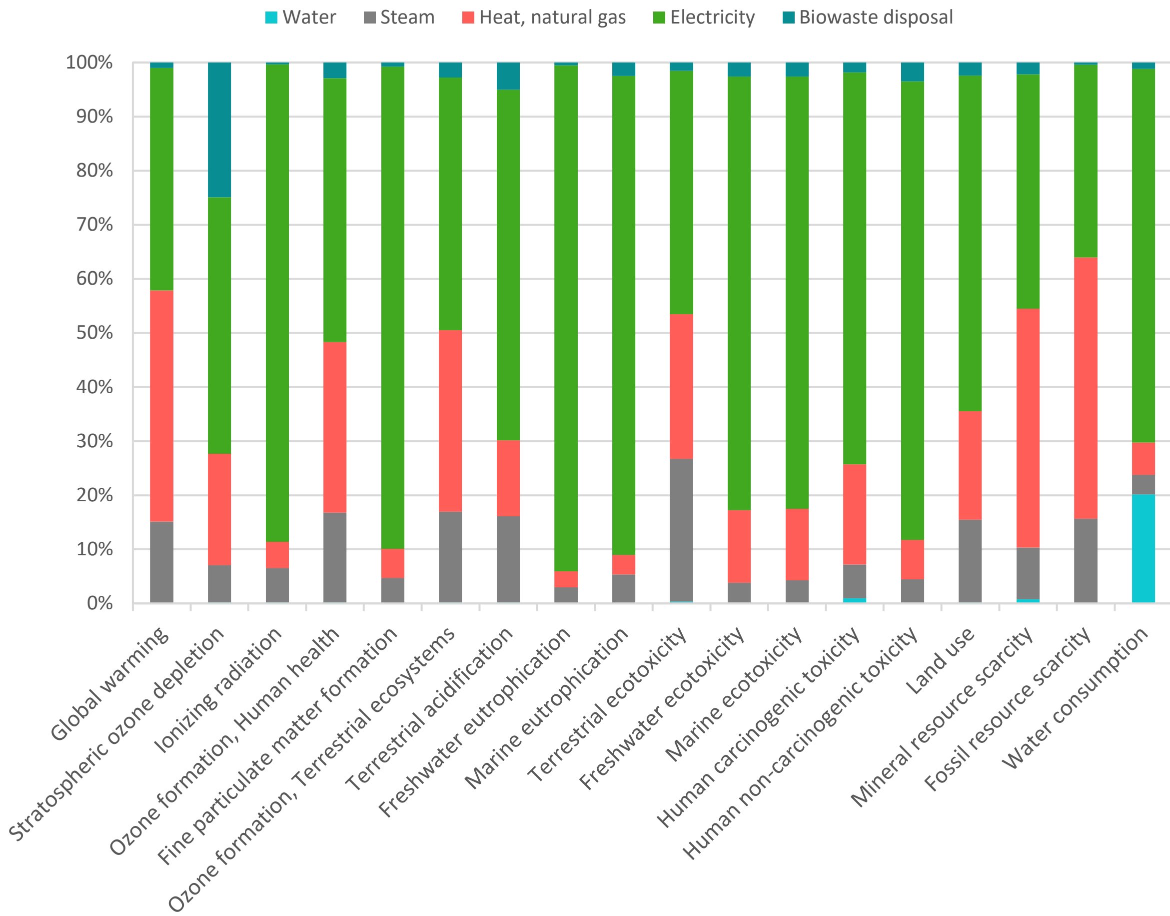

Figure 5-7. Contribution analysis for System #1, 0.283 kg of extruded meat analogue, low moisture extrusion stage, pea-sourced, utilities-only. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-9. Note: To focus only on the low moisture extrusion utilities impacts, this graph excludes the accumulated impacts from pea protein concentrate dry fractionation, hence the contributions shown only account for the disaggregated utilities.

Analysis of the extruded meat analogue from a process perspective (and excluding the pea protein concentrate) shows that pre-conditioning, extrusion, and drying processes have the overall highest contribution to LME impacts (range of 12–31%, 15–39%, and 14–52%, respectively) (Figure 5-8). These three processes have higher electricity consumption, which proves to be a key driver for environmental impacts (upstream emissions from fuel and electricity generation in the MRO mix). Also, the drying process has a high contribution to impacts because of its consumption of natural gas (direct fossil CO_2 emissions and consumption of fossil fuels). Finally, the disposal of extrusion losses (3% of input mass) contributes to stratospheric ozone depletion (25%) because of the N_2O emissions derived from downstream biowaste incineration.

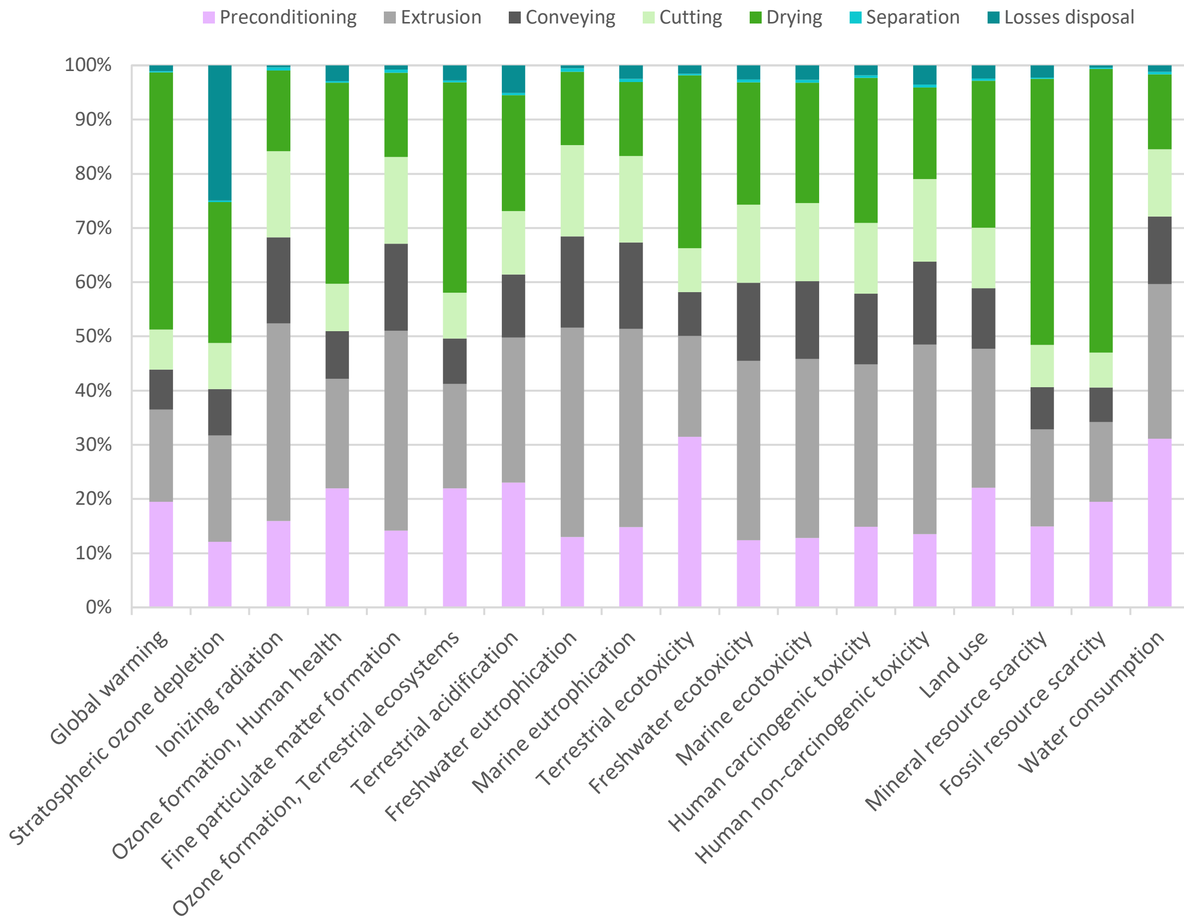

Figure 5-8. Contribution analysis for System #1, 0.283 kg of extruded meat analogue, low moisture extrusion stage, pea-sourced, subprocesses-only. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-10. Note: To focus only on the LME utilities impacts, this graph excludes the accumulated impacts from pea protein concentrate dry fractionation; the contributions shown only account for the disaggregated utilities.

5.2 System #2 (yellow peas, WF, HME) results

5.2.1 Ingredient contribution analysis

Figure 5-9 shows the environmental impacts caused by the production of 1 kg of plant-based meat recipe, HME, WF, pea-sourced. The production of the extruded plant-based meat analogue accounts for 3 to 71% of overall impacts, with the higher contributions being to ionizing radiation (71%), fossil resource scarcity (68%), freshwater eutrophication (64%), human carcinogenic toxicity (62%), fine particulate matter formation (48%), marine ecotoxicity (47%), global warming (46%), mineral resource scarcity (41%), freshwater ecotoxicity (34%), ozone formation—human health and ecosystems (34% for both) (Figure 5-10). The high-moisture extrudate represents 44% of the total weight of the plant-based meat recipe.

Like System #1, other ingredients have a high contribution to the overall impacts. The production of coconut oil contributes between 0 to 40% of impacts (while accounting for only 4% of the recipe), and this process is identified as the main driver for impacts in the land use category (40%) (Figure 5-10). Canola oil, which represents 4% of the meat recipe, has the highest contribution to marine eutrophication (50%), human non-carcinogenic toxicity (50%), terrestrial acidification (47%), and stratospheric ozone depletion (43%). For more details on the sources of upstream impacts from the production of additional ingredients for the recipe, see above. Potato starch accounts for 3 to 47% of total impacts (47% of total water consumption and 23% of terrestrial ecotoxicity) while representing only 3% of the recipe. Spices (3% of the recipe) contribute to 6–27% of overall impacts, mainly in the terrestrial ecotoxicity impact category (27%). Even though it represents 37% of the meat recipe, the direct water consumption contribution to overall impacts is insignificant (less than 2%). Similarly, the contribution of transport to environmental impacts is minimal (less than 2%).

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Figure 5-9. Contribution analysis dashboard for System #2, 1 kg of plant-based meat recipe, HME, WF, pea-sourced, cradle-to-manufacturing gate. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Built based on Figure 5-10 to Figure 5-15.

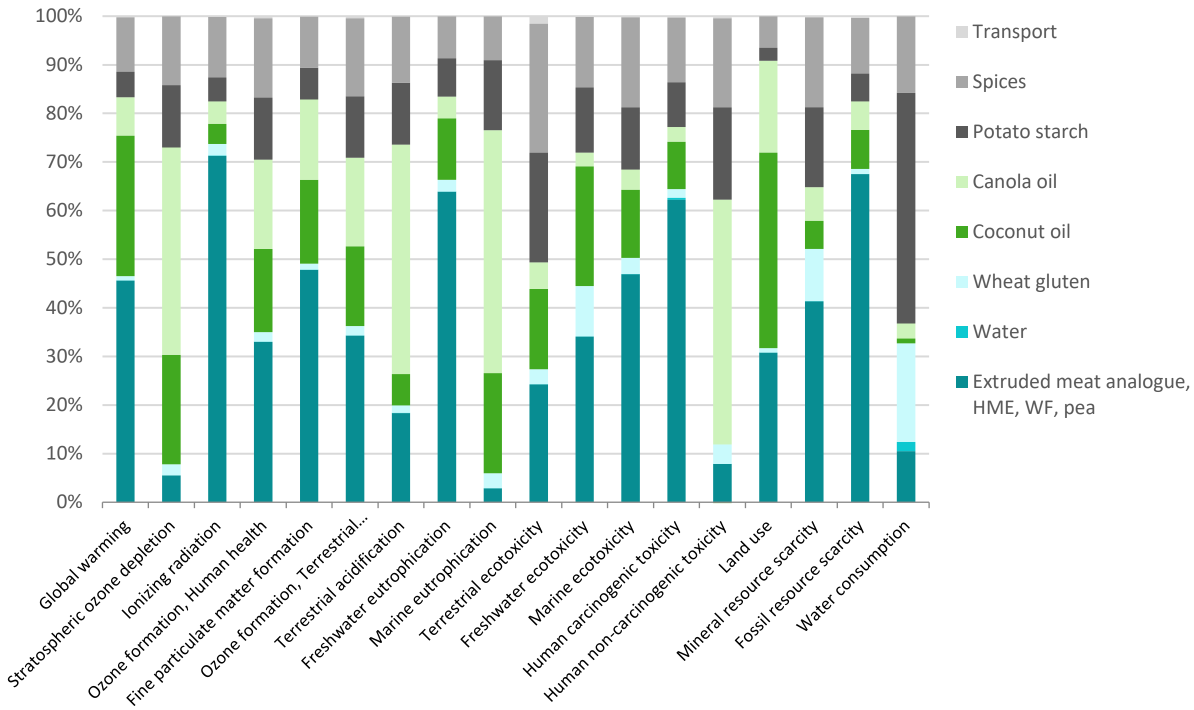

Figure 5-10. Contribution analysis for System #2, 1 kg of plant-based meat recipe, pea, WF, HME, pea-sourced, cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-11.

5.2.2 Extruded meat analogue contribution analysis

The extruded meat analogue contribution analysis (Figure 5-11) shows that the wet fractionation process accounts for the highest overall contribution (up to 77%) in 14 out of 18 impact categories, with the highest share of impacts for fossil resource scarcity (77%), global warming (74%), ozone formation—terrestrial ecosystems (62%) and human health (60%), stratospheric ozone depletion (57%), water consumption (52%), human carcinogenic toxicity (51%), ionizing radiation (48%), fine particulate matter formation (47%), terrestrial acidification (48%), marine and freshwater ecotoxicity (44% for both), freshwater eutrophication (40%), and terrestrial ecotoxicity (44%). The agricultural production of peas shows the highest contribution to land use (99%) and mineral resource scarcity (51%). In contrast, the LME process represents about a quarter of the environmental impacts.

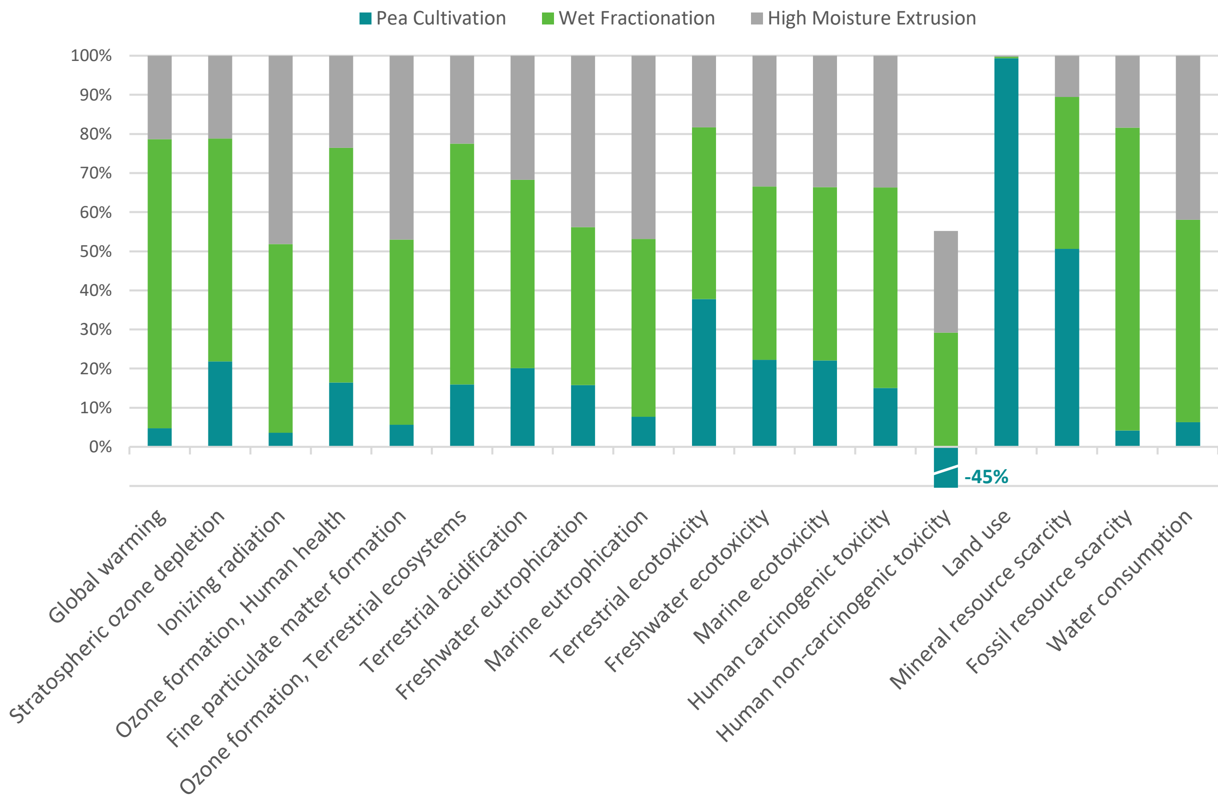

Figure 5-11. Contribution analysis for System #2, 0.441 kg of extruded meat analogue, pea, WF, HME, pea-sourced, cradle-to-manufacturing stage. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-12.

Agricultural cultivation stage impacts

The environmental impacts from the agricultural cultivation of peas follow the same contribution patterns as for System #1 (Figure 5-4), since both systems use peas as feedstock. The exact values for the agricultural cultivation of 1.416 kg of peas (reference flow for System #2) are shown in Table A-13. For a detailed explanation on the contribution analysis of impacts from the agricultural stage, please go to Section 5.1.2.

Wet fractionation stage impacts

Figure 5-12 shows the contribution analysis of the wet fractionation process.

Electricity consumption has the highest overall contribution in 10 out of 18 impact categories, especially for freshwater eutrophication (88%), ionizing radiation (83%), fine particulate matter formation (82%), human non-carcinogenic toxicity (73%), marine eutrophication (64%), marine ecotoxicity (62%), freshwater ecotoxicity (62%), terrestrial acidification (54%), human carcinogenic toxicity (52%), and land use (47%). Upstream emissions derived from fossil fuels production and direct use in power generation explain these high electricity impacts.

Heat produced by natural gas has the highest contributions to fossil resource scarcity (80%), global warming (75%), mineral resource scarcity (65%), ozone formation—terrestrial ecosystems and human health (66% and 63%, respectively), and terrestrial ecotoxicity (61%) due to natural gas consumption and related CO_2 emissions during use.

Water consumption accounts for less than 2% in most impact categories, except for water consumption, where it contributes to 32% of impacts. Wastewater treatment contributes to less than 1% in most categories, except for marine eutrophication (24%), in which downstream nitrate release to water has a significant effect; as in the previous system, wastewater treatment has a negative contribution to water consumption (-27%). As for the rest of materials, the biowaste disposal contribution only surpasses the 5% threshold in the stratospheric ozone depletion (28%) impact category, while the joint contribution for HCl and NaOH accounts for less than 2% of the overall impacts except for mineral resource scarcity, where the joint contribution for HCl and NaOH accounts for 12%.

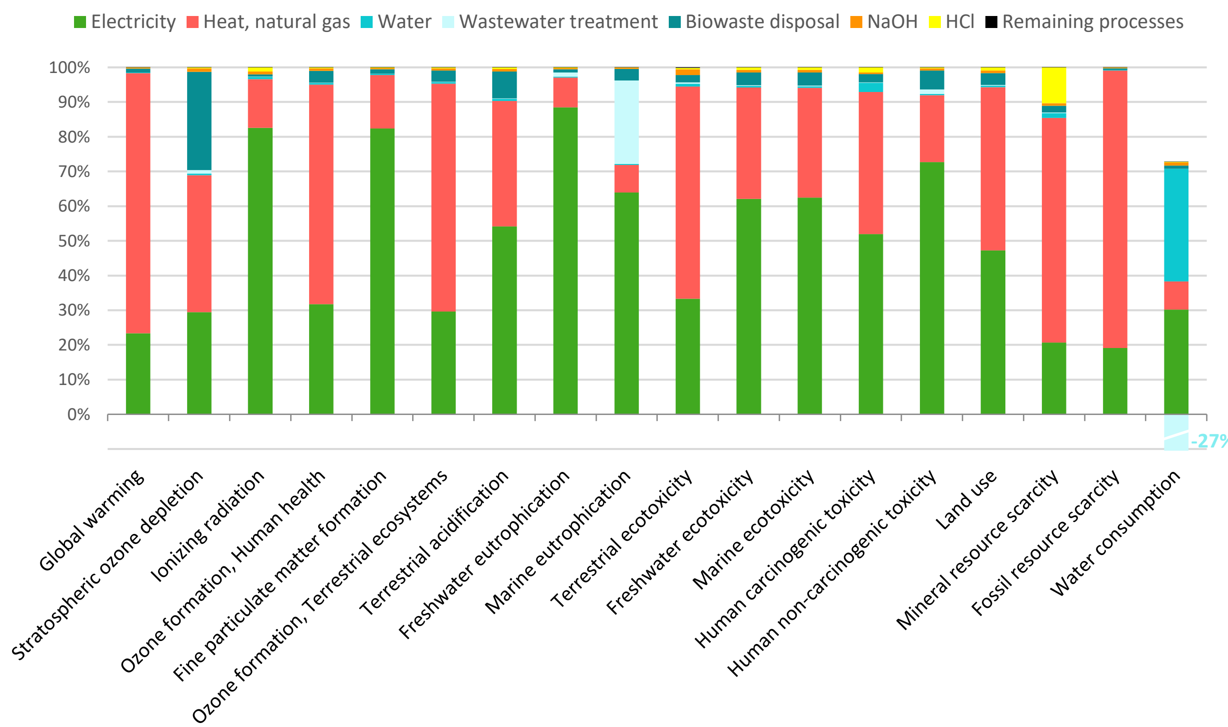

Figure 5-12. Contribution analysis for System #2, 0.190 kg of pea protein isolate, wet fractionation stage, pea-sourced, utilities-only. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-14. Note: To focus only on the wet fractionation utilities impacts, this graph excludes the accumulated impacts from pea agricultural cultivation and transport; the contributions shown only account for the disaggregated utilities.

Analysis of the wet fractionation of peas from a process perspective (Figure 5-13) shows that the spray drying process is the top contributor to the environmental impacts (45–88%), mainly in the fossil resource scarcity (88%), global warming (86%), ozone formation—human health and ecosystems (79% and 81%, respectively), mineral resource scarcity (74%), terrestrial ecotoxicity (78%), land use (73%), human carcinogenic toxicity (70%), terrestrial acidification (66%) and freshwater and marine ecotoxicity (67% each). Spray drying has the highest electricity consumption across the whole wet fractionation process (0.451 kWh/kg), as well as the highest natural gas consumption for heating (15.69 MJ/kg).

Precipitation and mixing account for 4 to 37% of total impacts with high contributions to marine eutrophication (37%) and water consumption (31%). This stage requires huge amounts of water (17.99 kg/kg) and consumption of electricity for different subprocesses. The remaining processes—drying fresh peas, and cleaning and dehulling—contribute less than 1% and 20%, respectively.

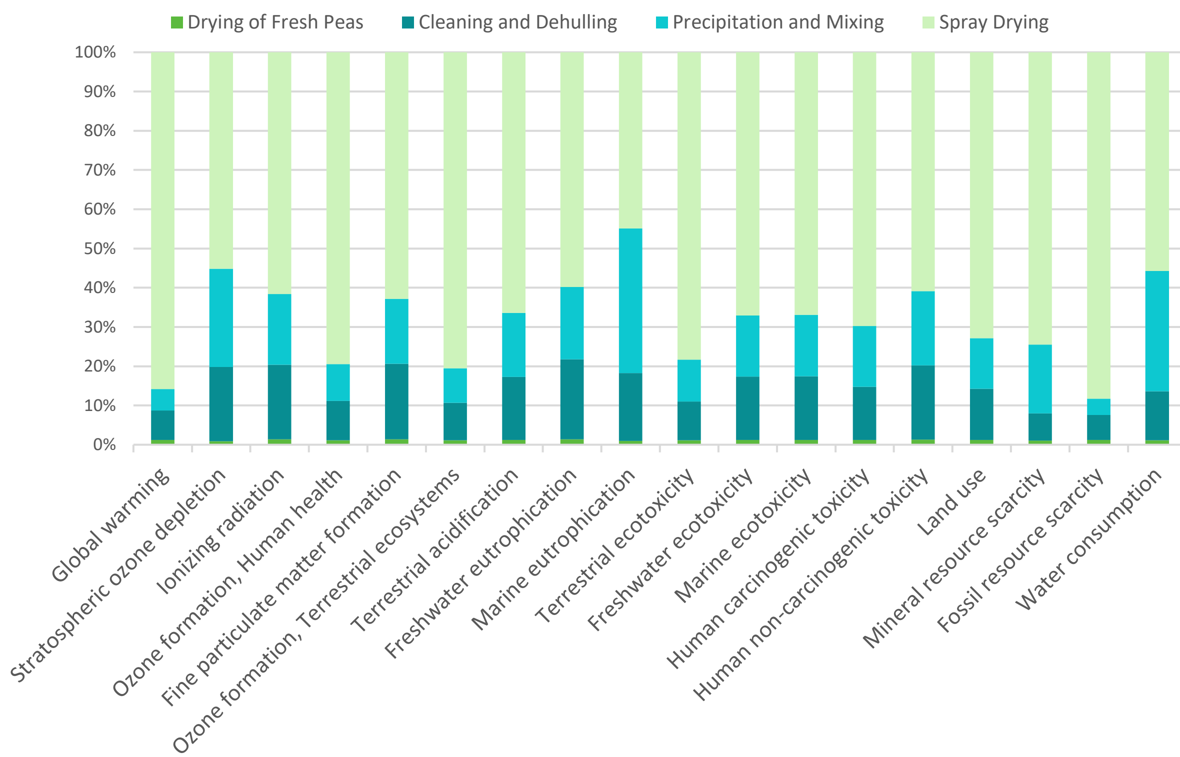

Figure 5-13. Contribution analysis for System #2, 0.190 kg of pea protein isolate, wet fractionation stage, pea-sourced, subprocesses-only. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-15. Note: To focus only on the wet fractionation utilities impacts, this graph excludes the accumulated impacts from pea agricultural cultivation and transport; the contributions shown only account for the disaggregated subprocesses.

High moisture extrusion impacts

Figure 5-14 shows the contribution analysis of the HME process. Direct electricity consumption accounts for the majority of HME impacts in all categories (range between 74 and 100%) except for water consumption (34%); direct water consumption accounts for 33% of the impacts. Wastewater treatment causes 25% of marine eutrophication impacts, and less than 3% in the rest of categories. Water consumption shows a negative contribution due to the return of water to the environment. Heat from natural gas contributes insignificantly to HME impacts (less than 2%).

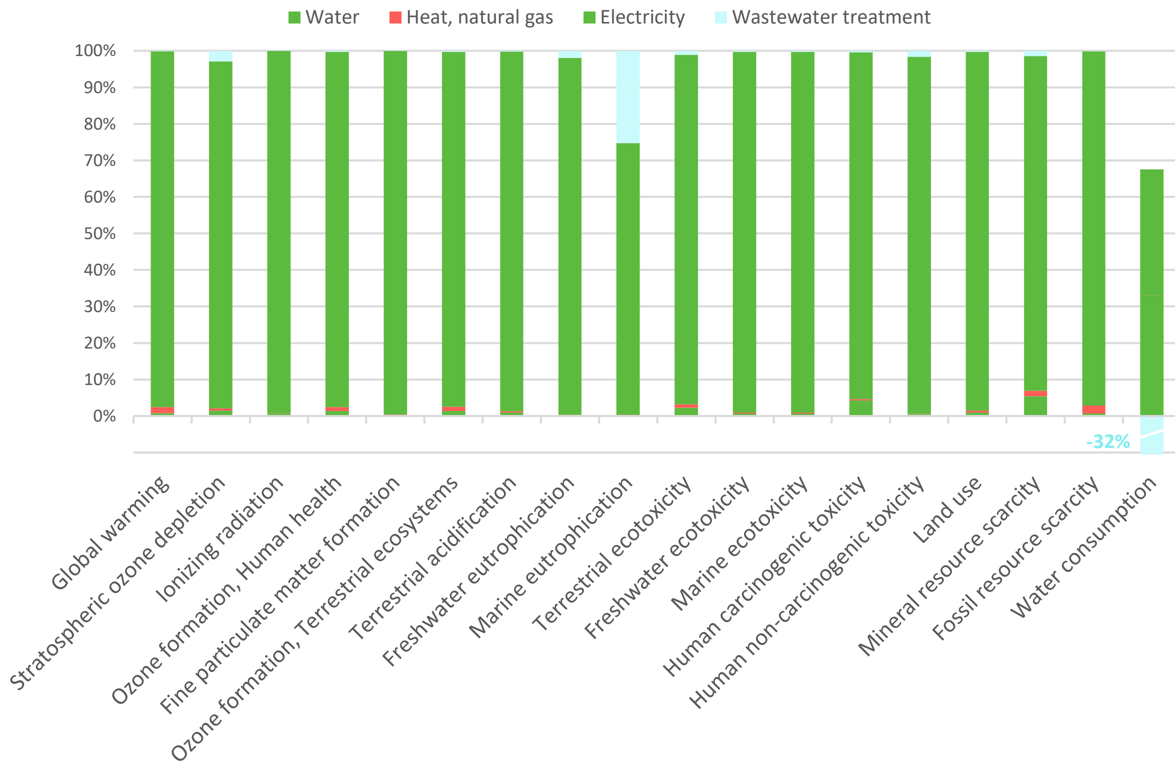

Figure 5-14. Contribution analysis for System #2, 0.441 kg of extruded meat analogue, high moisture extrusion stage, pea-sourced, utilities-only. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-16. Note: To focus only on the high moisture extrusion utilities impacts, this graph excludes the accumulated impacts from pea protein isolate wet fractionation; contributions shown only account for the disaggregated utilities.

When analyzing the extruded meat analogue from a process perspective, the extrusion step has the highest contribution to HME impacts (55–87%, most categories above 80%) (Figure 5-15). This step consumes most of the total electricity (0.35 kWh/kg) in the whole process. As in the LME from System #1, high electricity consumption is related to several impacts (e.g., emissions of CO_2, NO_x, SO_2, toxic substances) from upstream fuel production and electricity generation. The cooling process has a negative share of water consumption impacts (-18%) due to wastewater treatment for the side stream of water. The rest of the processes (preconditioning, heating, and cutting) account for the remaining 1 to 21% of environmental impacts across categories. According to the gathered data, losses across the pea HME process are less than 1%, hence they are excluded.

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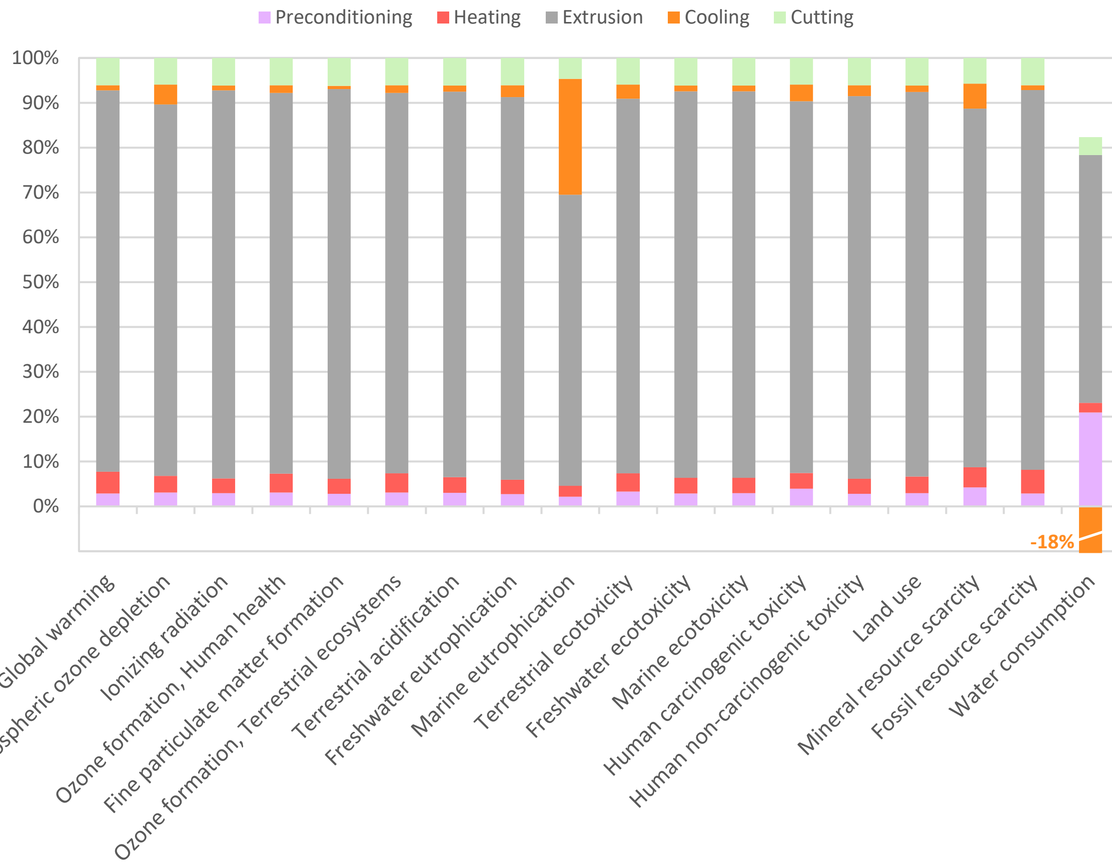

Figure 5-15. Contribution analysis for System #2, 0.441 kg of extruded meat analogue, high moisture extrusion stage, pea-sourced, subprocesses-only. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-17. Note: To focus only on the high moisture extrusion utilities impacts, this graph excludes the accumulated impacts from pea protein isolate wet fractionation; contributions shown only account for the disaggregated utilities.

5.3 System #3 (soybeans, WF, HME) results

5.3.1 Ingredient contribution analysis

Figure 5-17 shows the environmental impacts caused by the production of 1 kg of plant-based meat recipe, WF, HME, soy-sourced. Production of the plant-based meat analogue accounts for 71% of the total plant-based meat recipe impacts and 4–65% of overall impacts, with the highest contribution to ionizing radiation (65%), human carcinogenic toxicity (56%), freshwater eutrophication (56%), fossil resource scarcity (55%), fine particulate matter (41%), ozone formation—terrestrial ecosystems (44%) and human health (40%), stratospheric ozone depletion (43%), marine ecotoxicity (38%), global warming (38%), land use (37%), mineral resource scarcity (33%), and terrestrial ecotoxicity (28%).

Similar to Systems #1 and #2, other ingredients in this plant-based meat recipe have a high contribution to the overall impacts. The production of coconut oil contributes between 0 and 37%, though it accounts for only 4% of the recipe, and this process is identified as the main driver for impacts in the freshwater ecotoxicity (28%) impact category. Additionally, coconut oil notably contributes to land use (37%) and global warming (33%). For more details on the sources of impact from coconut oil production, see

Section 5.1.1. Canola oil, which represents 4% of the meat recipe, has the highest contribution to terrestrial acidification (49%), marine eutrophication (47%), and human non-carcinogenic toxicity (38%). Potato starch accounts for 2 to 52% of total impacts (52% of water consumption), while representing only 3% of the total weight of the recipe. Spices (3% of the recipe) contribute to 6 to 25% of the overall impacts (25% of impacts for terrestrial ecotoxicity). Even though it represents 10% of the meat recipe, the contribution of added water is insignificant (less than 1%). Similarly, the contribution of transport to environmental impacts is minimal (less than 1.5%).

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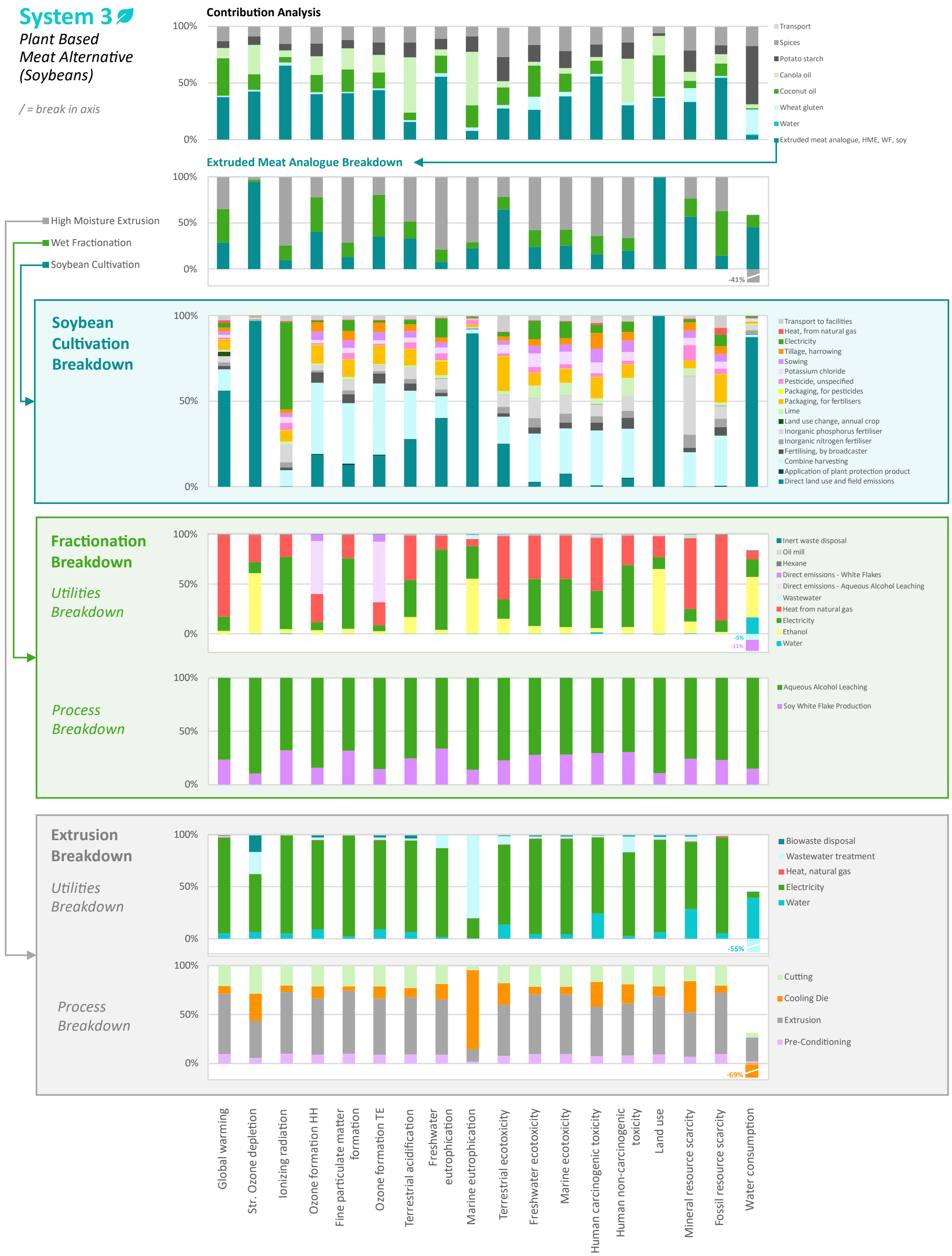

Figure 5-16. Contribution analysis dashboard for System #3, 1 kg of plant-based meat recipe, HME, WF, soybean-sourced, cradle-to-manufacturing gate. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Built based on Figure 5-17 to Figure 5-23.

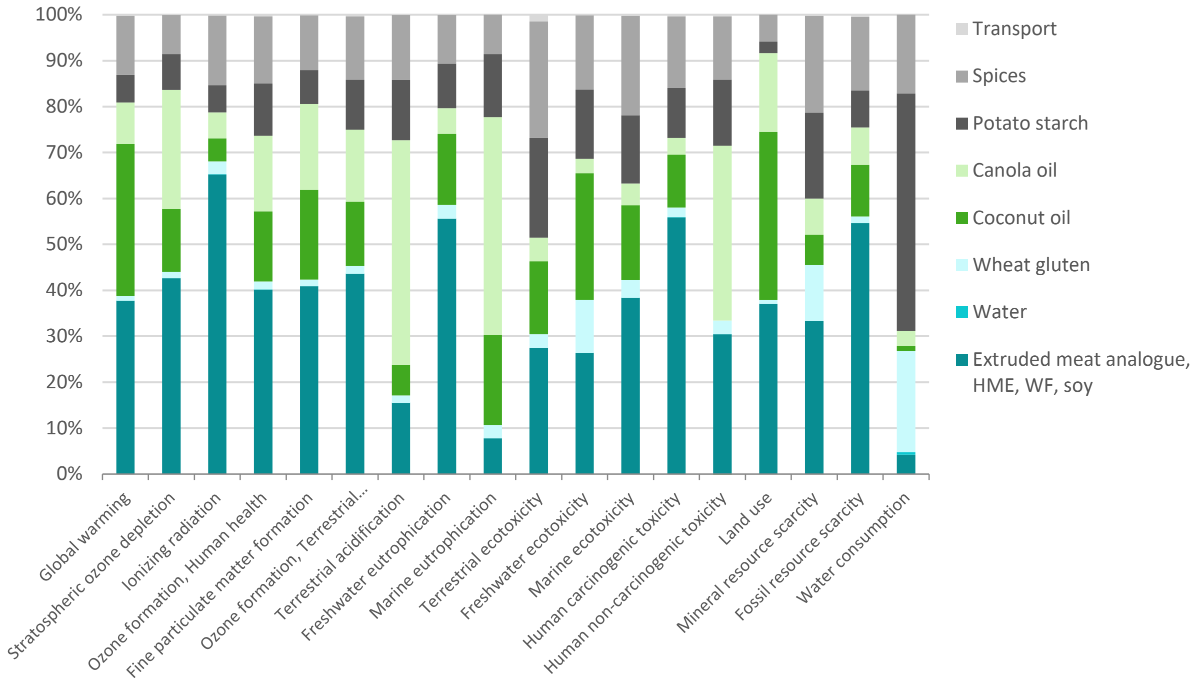

Figure 5-17. Contribution analysis for System #3, 1 kg of plant-based meat recipe, soybean, WF, HME, soy-sourced, cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-18.

5.3.2 Extruded meat analogue contribution analysis

Analysis of the extruded meat analogue contribution (Figure 5-18) shows that the HME process accounts for the highest overall contribution: freshwater eutrophication (79%), ionizing radiation (74%), marine eutrophication (71%), fine particulate matter formation (71%), human non-carcinogenic toxicity (66%), human carcinogenic toxicity (64%), marine ecotoxicity (58%), freshwater ecotoxicity (57%), and terrestrial acidification (48%). Also, this stage shows a negative contribution to water consumption (-41%) due to wastewater treatment.

The cultivation of soybeans accounts for 8 to 100% of impacts, with the highest contribution to land use (100%), stratospheric ozone depletion (94%), terrestrial ecotoxicity (65%), mineral resource scarcity (57%), water consumption (45%), and ozone formation—human health (40%). Finally, the wet fractionation process shows the highest contribution to fossil resource scarcity (48%), ozone formation—terrestrial ecosystems (45%), and global warming (36%).

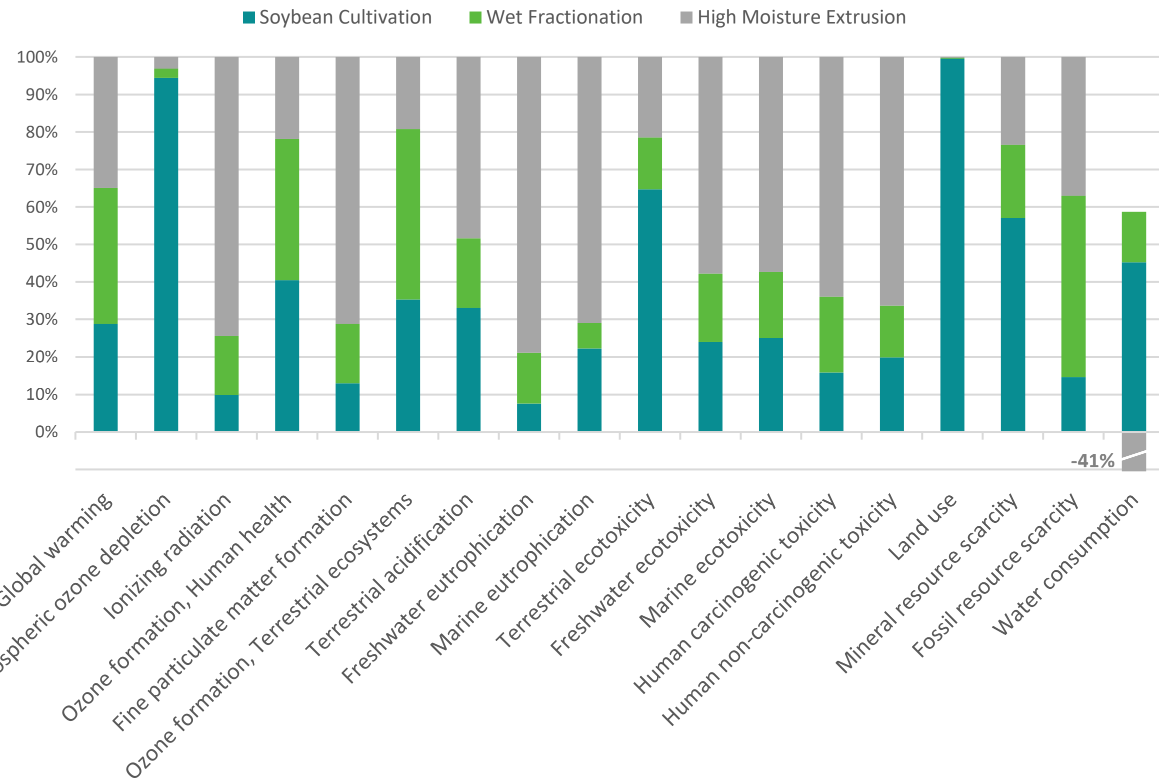

Figure 5-18. Contribution analysis for System #3, 0.714 kg of extruded meat analogue, soybean, WF, HME, soy-sourced, cradle-to-manufacturing stage. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-19.

Agricultural cultivation stage impacts

Figure 5-19 shows the contribution analysis of soybean cultivation. Direct land use for soybean cultivation (around 2.76 tons/ha) accounts for the majority of land use impacts (99%). Direct emissions related to fertilizer production cause high impacts for: stratospheric ozone depletion (98%; direct air N_2O emissions), water consumption (87%; direct water consumption from natural sources), marine eutrophication (90%; nitrate emissions to water), global warming (58%, direct air N_2O emissions), freshwater eutrophication (40%, direct phosphate and phosphorus emissions to water), terrestrial acidification (28%, air ammonia emissions from fertilizer application), and terrestrial ecotoxicity (28%, air emissions from glyphosate application).

Combine harvesting accounts for more than 25% of the total impact on ozone formation—human health and ecosystems (42% each), fine particulate matter formation (36%), human carcinogenic toxicity (34%), fossil resource scarcity (32%), human non-carcinogenic toxicity (30%), freshwater ecotoxicity (29%), terrestrial acidification (29%), and marine ecotoxicity (27%). Combine harvesting uses fossil-fuel-powered machinery, so the environmental impacts are directly related to fossil fuel consumption and direct emissions from its use (e.g., NOx, PM2.5, chromium, zinc).

The production of inorganic phosphorus fertilizer contributes to mineral resource scarcity (35%) because of upstream extraction of phosphate rock. Direct electricity consumption is the biggest contributor to ionizing radiation impacts (53%), mainly due to the presence of nuclear energy on the grid. The rest of the processes show lower contributions to soybean's overall impacts (less than 22%).

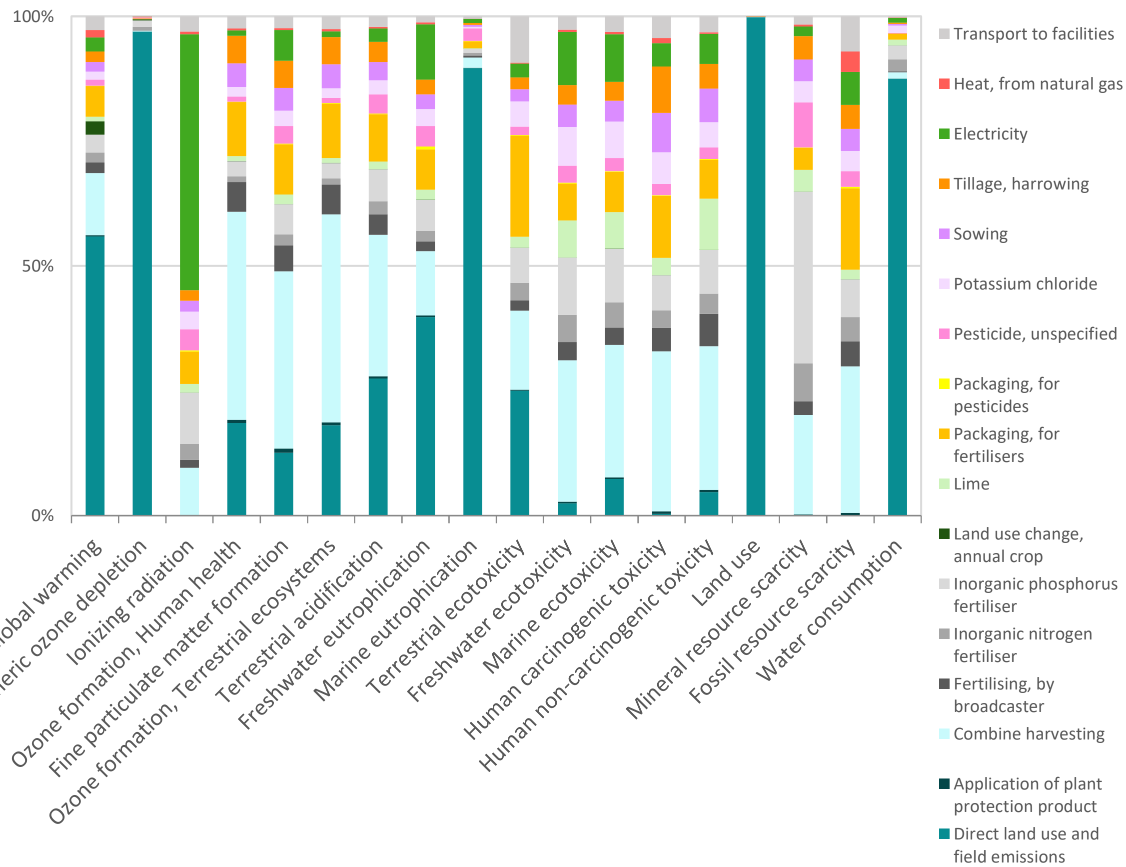

Figure 5-19. Contribution analysis for System #3, 0.213 kg of soybean cultivation, agricultural cultivation stage, soy-sourced, farm to facilities. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-20.

Wet fractionation stage impacts

Figure 5-20 shows the wet fractionation contribution analysis, which occurs in two steps: white flake production followed by aqueous alcohol leaching. The heat from natural gas shows the highest overall contribution to impacts (39% on average) as well as the highest impacts for fossil resource consumption (86%), global warming (82%), mineral resource scarcity (71%), terrestrial ecotoxicity (64%), human carcinogenic toxicity (53%), and terrestrial acidification (45%). Direct electricity consumption shows the highest contribution to freshwater eutrophication (81%), ionizing radiation (73%), fine particulate matter formation (71%), human non-carcinogenic toxicity (62%), marine ecotoxicity (48%), and freshwater ecotoxicity (47%) impact categories. The production of ethanol during the aqueous alcohol leaching process is identified as the main source of impacts for the land use (65%), stratospheric ozone depletion (61%), marine eutrophication (55%), and water consumption (41%) impact categories. These impacts are closely related to upstream maize grain cultivation (main feedstock for ethanol production), such as land occupation for maize cultivation (9.31 kg/ha), dinitrogen monoxide emissions derived from nitrogen fertilization of maize cultivation (6.38E-04 kg/kg), nitrate emissions to water from maize cultivation (5.05E-03 kg/kg), and irrigation requirements for maize cultivation (0.24 m3/kg). Finally, direct emissions from aqueous alcohol leaching (ethanol evaporation) contribute to impacts in the ozone formation—terrestrial ecosystems (61%) and human health (53%) impact categories. The wastewater and direct emissions from white flake production demonstrate negative contributions to water consumption (-8% and -16%, respectively) due to wastewater treatment.

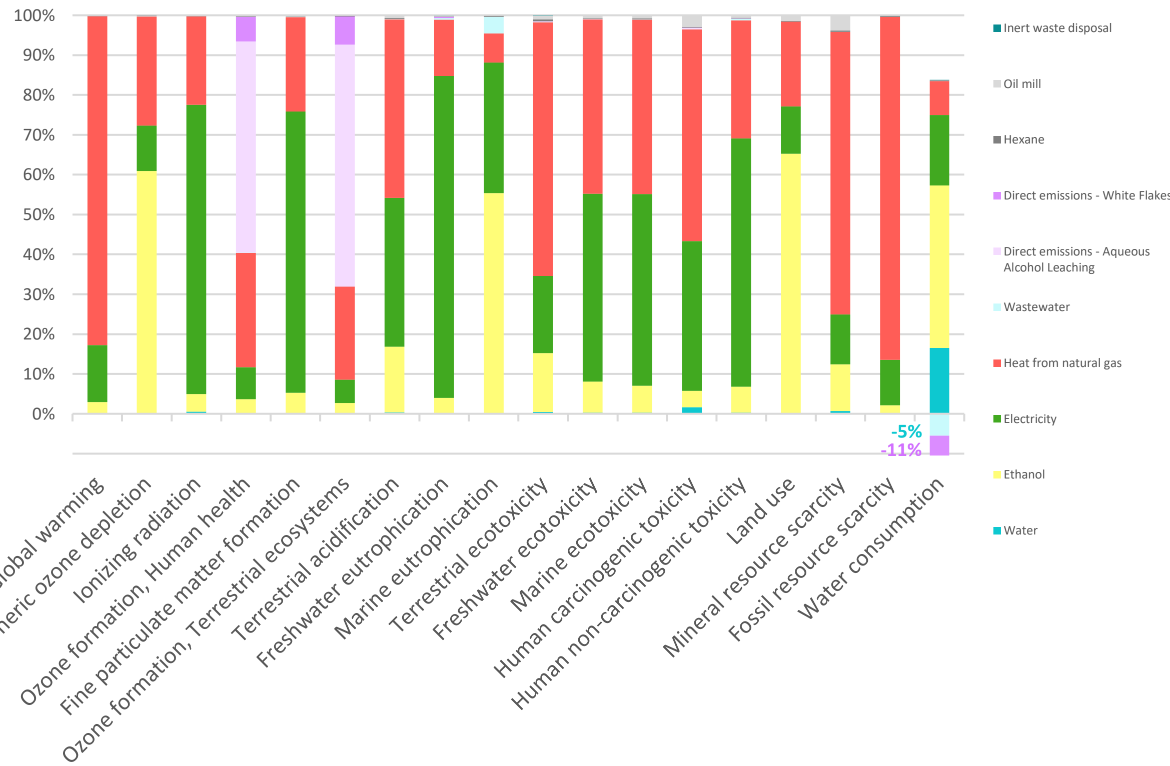

Figure 5-20. Contribution analysis for System #3, 0.215 kg of soy protein concentrate, wet fractionation stage, soy-sourced, utilities-only. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-21. Note: To focus only on the wet fractionation utilities impacts, this graph excludes the accumulated impacts from soybean agricultural cultivation and transport; contributions shown only account for the disaggregated utilities.

When analyzing the soy protein concentrate from a process perspective (Figure 5-21), the aqueous alcohol leaching process has the highest contribution to impacts (average of 77%) across all categories. Unlike Systems #1 and #2, disaggregated data for the different subprocesses of wet fractionation were not available, hence the contribution analysis is shown from an aggregate perspective. The soy white flake production (based on the soybean crushing and extraction of soybean meal) accounts for 10 to 34% of impacts.

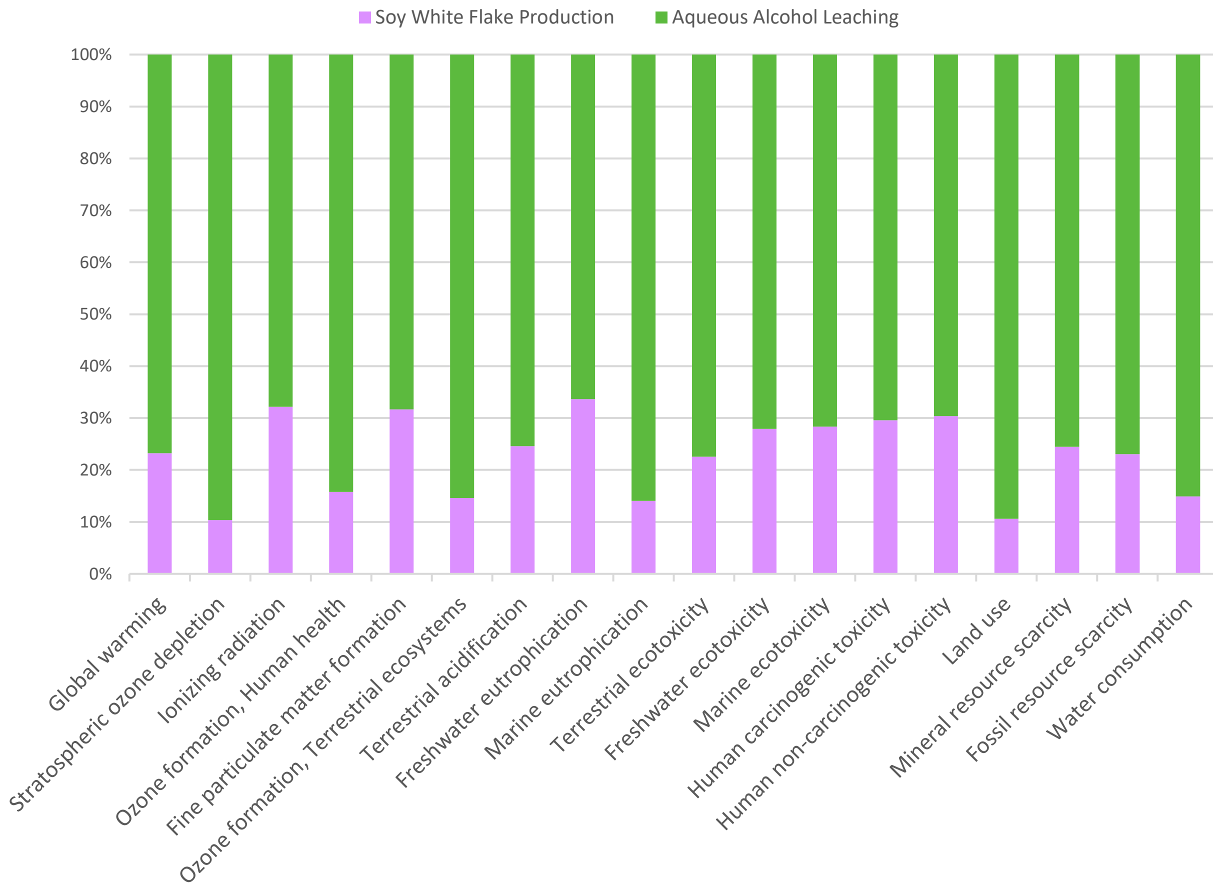

Figure 5-21. Contribution analysis for System #3, 0.215 kg of soy protein concentrate, wet fractionation stage, soy-sourced, subprocesses-only. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-22. Note: In this graph, wet fractionation refers to the aqueous alcohol leaching subprocess as shown in Figure 3-7. To focus only on the wet fractionation utilities impacts, this graph excludes the accumulated impacts from soybean agricultural cultivation and transport; contributions shown only account for the disaggregated subprocesses.

High moisture extrusion stage impacts

Figure 5-22 presents the contribution analysis for the HME process. Electricity consumption contributes the most in 16 out of 18 impact categories, with an average contribution of 76%. Direct water consumption accounts for the highest source of impact for the water consumption impact category (39%), as well as considerable impacts for the mineral resource scarcity (28%) and human carcinogenic toxicity (24%) impact categories. These impacts are closely related to upstream iron extraction and processing for the water supply infrastructure. Wastewater treatment accounts for 80% of marine eutrophication impacts (release of nitrates into water bodies), and, due to its release of side stream water into the environment, -55% of water consumption impacts.

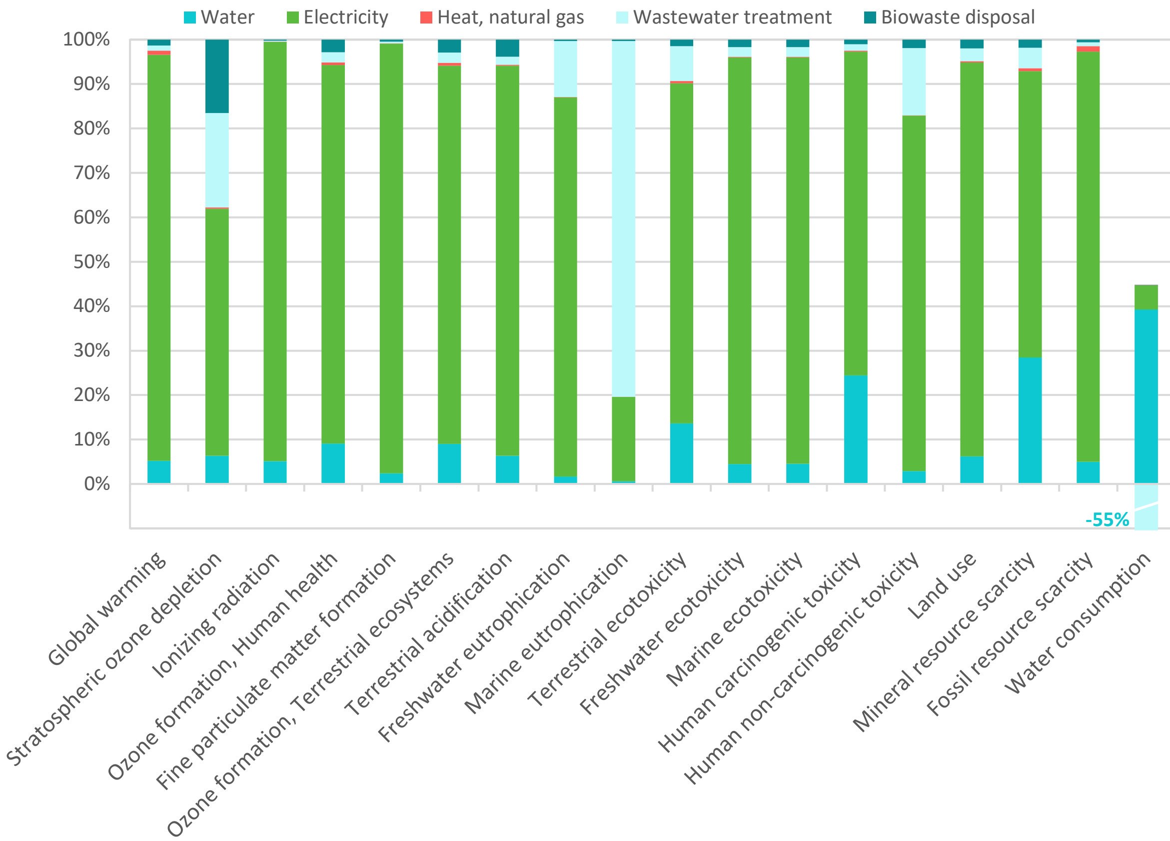

Figure 5-22. Contribution analysis for System #3, 0.714 kg of extruded meat analogue, high moisture extrusion stage, soy-sourced, utilities-only. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-23. Note: To focus only on the high moisture extrusion utilities impacts, this graph excludes the accumulated impacts from soy protein concentrate wet fractionation; contributions shown only account for the disaggregated utilities.

When analyzing the HME process from a subprocess perspective (Figure 5-23), the extrusion process shows the highest average contribution to impacts (52%), as well as the highest contribution to fine particulate matter formation (64%), ionizing radiation (63%), fossil resource scarcity (63%), global warming (62%), freshwater ecotoxicity (61%), marine ecotoxicity (61%), land use (59%), terrestrial acidification (59%), ozone formation—human health and terrestrial ecosystems (58% for both), freshwater eutrophication (57%), human non-carcinogenic toxicity (53%), human carcinogenic toxicity (50), terrestrial ecotoxicity (52%), mineral resource scarcity (46%), and stratospheric ozone depletion (38%). This subprocess involves the highest electricity consumption (0.17 kWh/kg) for extruding. The cooling die process has the highest contribution to marine eutrophication (81%), and water consumption (-70%). This process involves higher water consumption as a side stream (8.54 kg/kg), which ends up being treated as wastewater because it does not end up in the meat extrudate. The contributions of the cutting process to overall impacts does not exceed 28% (stratospheric ozone depletion) and of preconditioning does not exceed 10% across all impact categories.

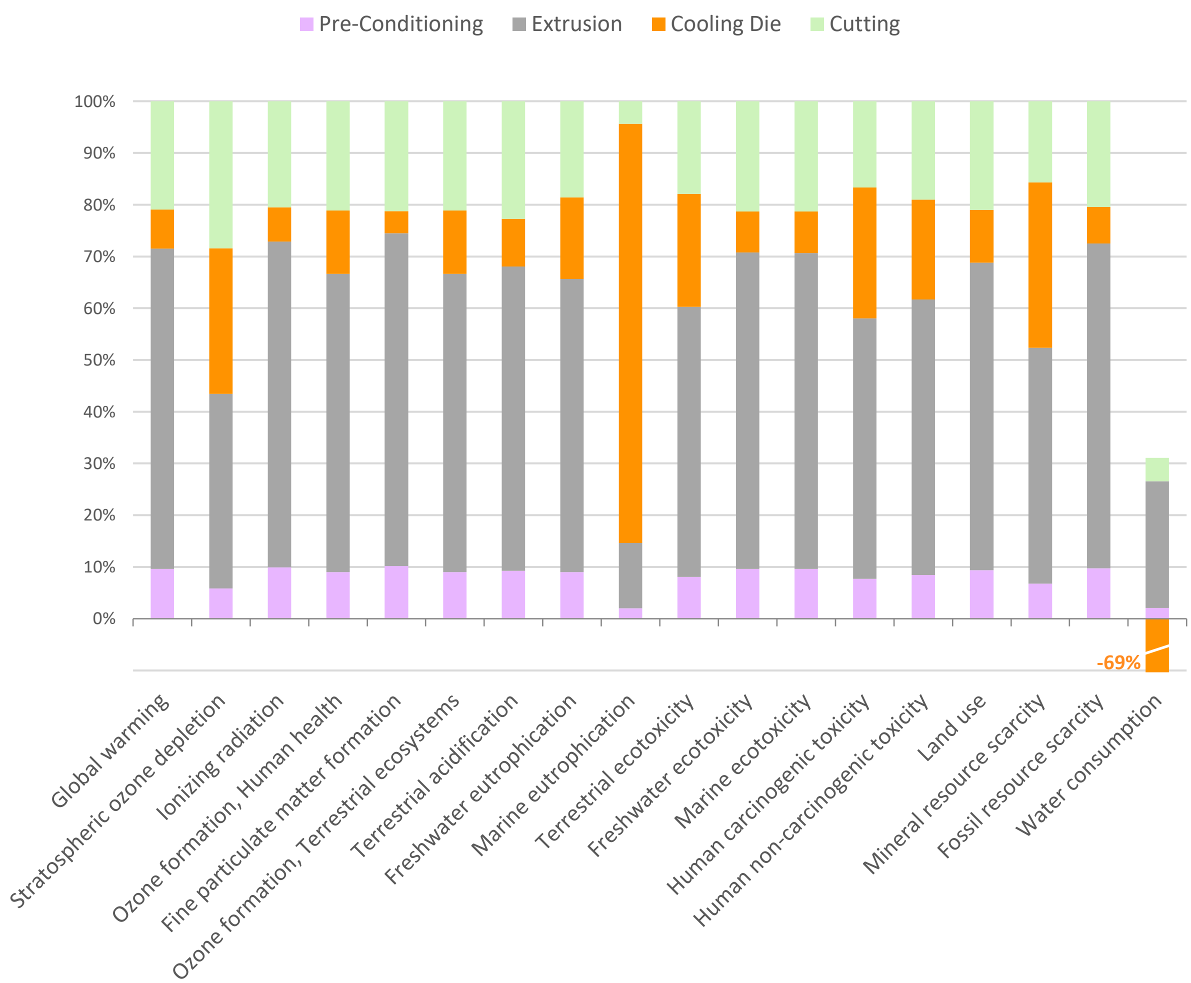

Figure 5-23. Contribution analysis for System #3, 0.714 kg of extruded meat analogue, high moisture extrusion stage, soy-sourced, subprocesses-only. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-24. Note: To focus only on the high moisture extrusion utilities impacts, this graph excludes the accumulated impacts from soy protein concentrate wet fractionation; contributions shown only account for the disaggregated utilities.

5.4 System #4 (Beef) results

5.4.1 Stage contribution to product impacts

Figure 5-24 shows the proportional contribution of each life cycle stage to the environmental impacts caused by the production of 1 kg of ground beef meat. For most impact categories, cattle husbandry contributes to the majority (>46%) of the total impact (Figure 5-25). The impact of the slaughtering stage is most pronounced in impact categories related to energy consumption: 40% of the ionizing radiation impacts; 29% of the fossil resource scarcity impacts; 17% of the human carcinogenic toxicity impacts; and 18% of the marine ecotoxicity impacts. The following sections provide a more detailed analysis of the processes that drive the impacts of these two stages. Grinding contributes 0 to 14% (ionizing radiation). This impact category is closely related to grid electricity consumption (upstream nuclear generation), which is the only input for the grinding stage. The overall environmental contribution from transport (ground mode, 200 km) is insignificant (3% of terrestrial ecotoxicity impacts, and less than 2% in most impact categories).

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System 4

Conventional Meat (Cattle)

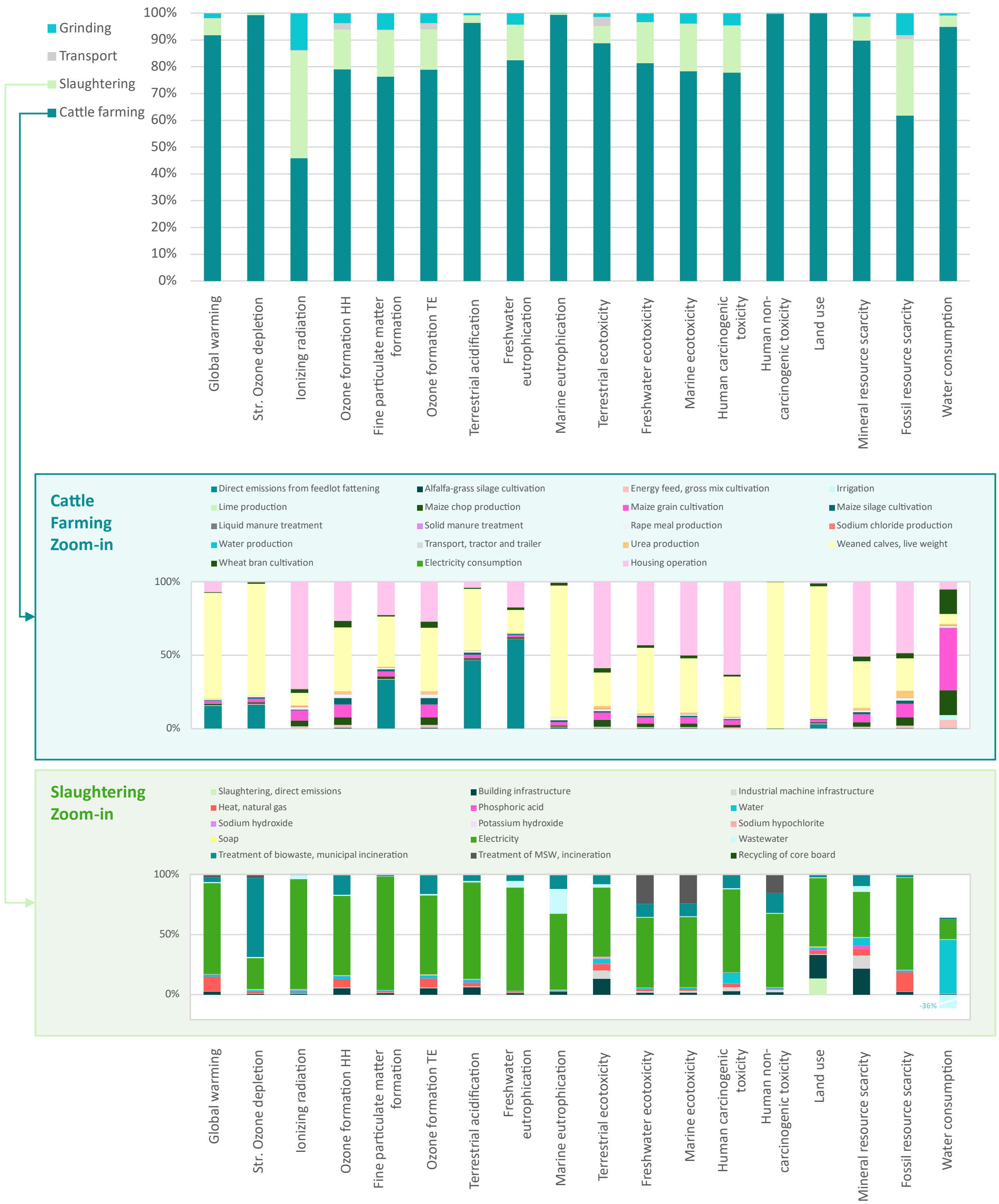

Figure 5-24. Contribution analysis dashboard for System #4, 1 kg of animal-based meat recipe, beef, cradle-to-manufacturing gate. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Built based on Figure 5-25 to Figure 5-27.

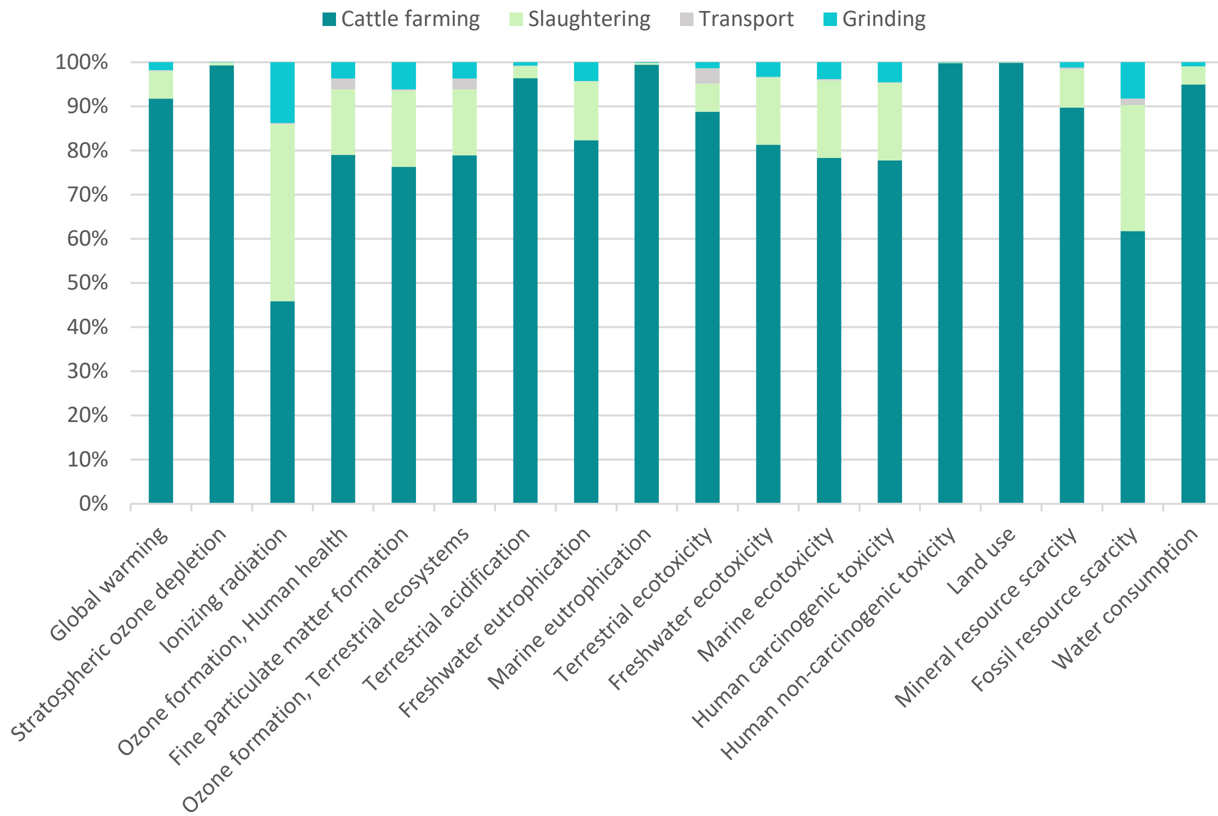

Figure 5-25. Contribution analysis for System #4, 1 kg of ground beef meat, cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-25.

Animal husbandry impacts

Figure 5-26 shows the contribution analysis for cattle farming (the main driver for System #4 environmental impacts).

The provision of weaned calves has the highest contribution to overall impacts (7 to 100% of impacts) in 9 of 18 categories. An in-depth analysis of the weaned calves subprocess is outside the scope of this analysis; however, some insights can be ascertained from the background dataset. The supply of weaned calves to the feedlot subprocess is provided by a market mix consisting of 77% intensive beef cattle production and 23% mixed and extensive production systems on pasture. These percentages are based on U.S. statistics taken from the WFLDB database (Bengoa et al. 2019). Both production systems account for a joint feed basket consumption of 0.58 kg, of which only 0.09 kg is maize and 0.02 kg is soybean meal; thus, the majority of the nutritional requirements for the calves' nursery subprocess is supplied by pastures, which are continuously fertilized (the ecoinvent dataset does not provide the exact mass consumption of grass derived from the pastures). The majority of impacts from the weaned calves' production market mix are caused by direct field emissions related to fertilizer application, enteric fermentation, and manure management.

During the feedlot subprocess, weaned calves are fattened from an average starting weight of 230 kg to an average slaughter weight of 485 kg (around 134 days). Cattle are fed with alfalfa, an energy feed mix, lime, different types of maize (grain, chop, and silage), rape meal, sodium chloride, and wheat bran. Direct field emissions contribute significantly to the impact of weaned calf provision during the animal husbandry stage. Direct field emissions from the feedlot subprocess include ammonia from nitrogen in fertilizers (2.81E-02 kg/kg), carbon dioxide from limestone and urea application (2.56E-01 kg/kg), methane from enteric emissions and manure management (3.82E-01 kg/kg), dinitrogen monoxide from nitrogen in pasture (1.66E-02 kg/kg), nitrate (5.64E-01 kg/kg) and phosphorus (3.97E-04 kg/kg) from fertilizer leachates, copper emissions to water (1.15E-06 kg/kg) and soil (1.15E-02 kg/kg) from mineral fertilizers, among others. Direct emissions from the feedlot stage are the highest contributors to freshwater eutrophication (61%) and terrestrial acidification (46%) due to phosphorus emissions to water from soil erosion (2.52E-03 kg/kg) and ammonia emissions to air from manure management. Maize grain consumption has the highest contribution to water consumption (43%) due to its high upstream irrigation requirements (0.24 m^3/kg). During the feedlot stage, 2.39 kg of feed are needed to produce 1 kg of cattle, live weight (plus a water intake of 0.296 kg/kg); 2.04 kg of cattle, live weight is required to produce 1 kg of beef meat.

Another major source of impact is the housing operation, which accounts for 0 to 73% of impacts, and is the main contributor to ionizing radiation (73%), human carcinogenic toxicity (63%), terrestrial ecotoxicity (59%), mineral resource scarcity (51%), marine ecotoxicity (50%), and fossil resource scarcity (48%). Most of these impacts are caused by upstream cast iron, chromium and reinforcing steel, and concrete production for the housing infrastructure. The high contribution to ionizing radiation is closely related to the MRO electricity requirements for housing.

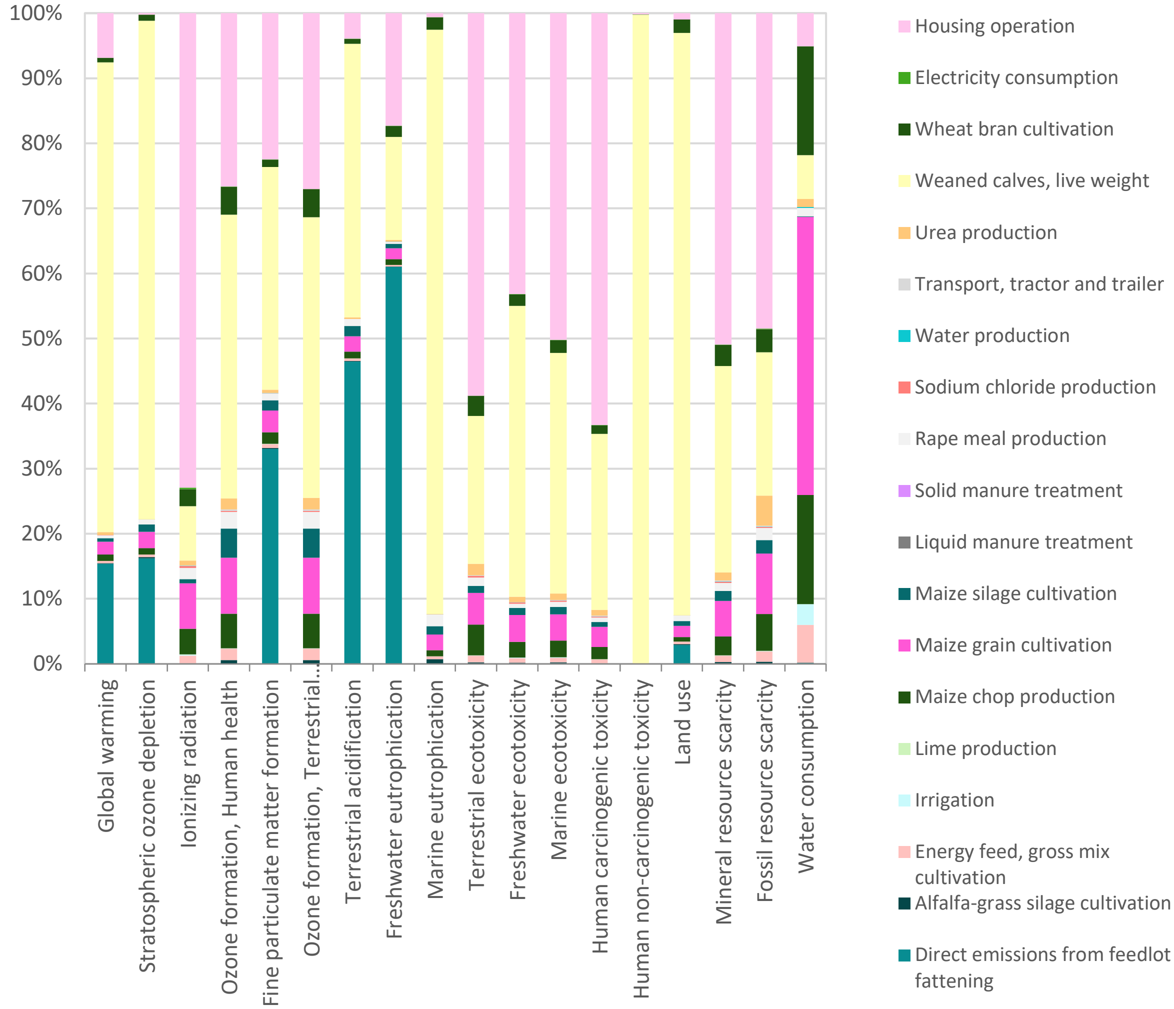

Figure 5-26. Contribution analysis for System #4, 2.04 kg of cattle, live weight, animal husbandry stage (focus on feedlot subprocess), beef. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-26.

Slaughtering stage impacts

Zooming into the slaughtering stage, Figure 5-27 shows the contribution analysis related to producing 1 kg of beef meat (slaughtering of 2.04 kg of cattle, live weight). Electricity is the main driver of the environmental impacts of slaughtering with the highest impacts in 16 of 18 categories. The MRO electricity grid relies heavily on natural gas, lignite, and nuclear, which explains the high contribution of energy to fine particulate matter formation (PM 2.5, 94%) and ionizing radiation (radon-222, 91%). As for the rest of materials and energy consumption, biowaste incineration is the highest contributor to stratospheric ozone depletion (66%, NO_x emissions), incineration of MSW has a particularly high contribution to freshwater and marine ecotoxicity (24% and 25%, respectively, caused by zinc and copper emissions from leachates), and direct water consumption accounts for the majority of the water consumption impact category (4%).

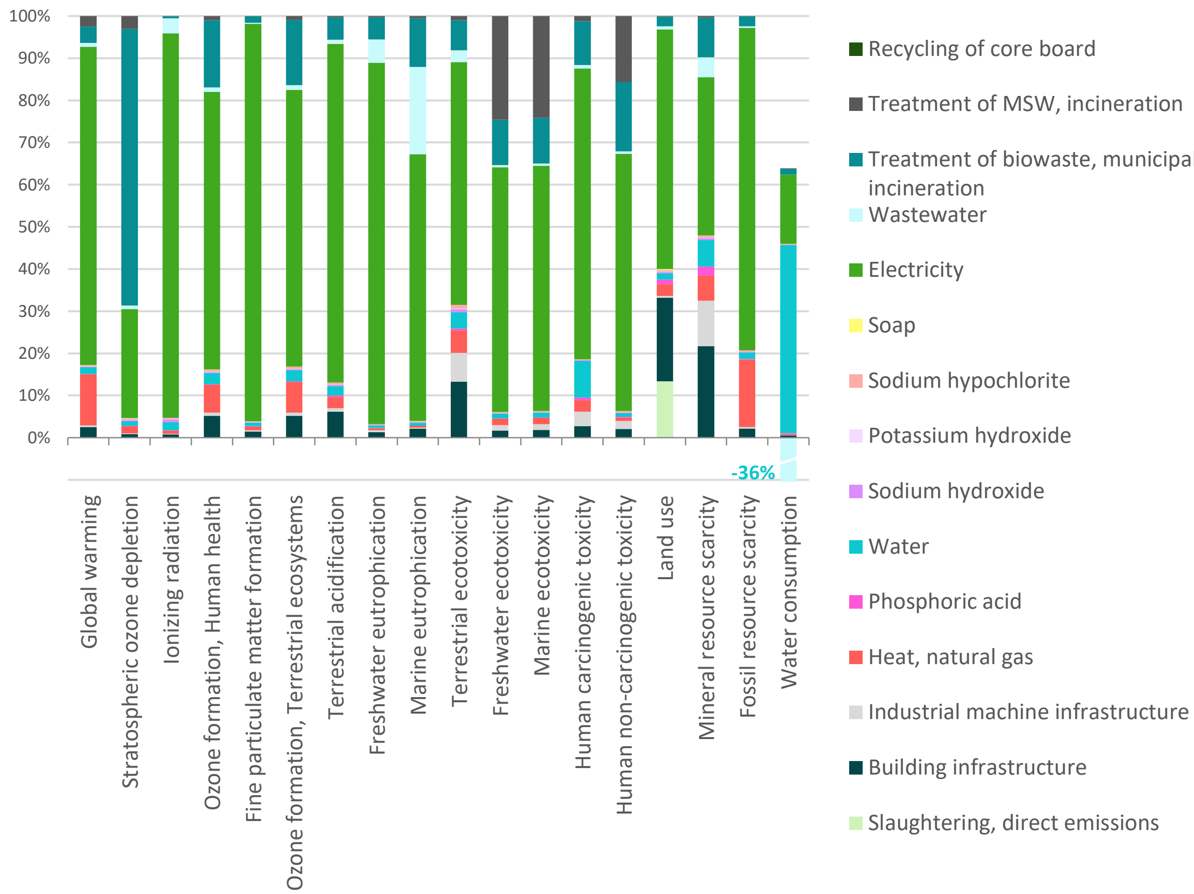

Figure 5-27. Contribution analysis for System #4, 2.04 kg of slaughtered beef meat, slaughtering stage, beef. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-27.

5.5 System (Pork) #5 results

5.5.1 Stage contribution to product impacts

Figure 5-29 shows the proportional contribution of each life cycle stage to the environmental impacts caused by the production of 1 kg of ground pork meat. As in System #4, the swine husbandry stage of producing pork meat has the highest contribution among all the impact categories (68–100%). The slaughtering process has the second highest contribution to impacts (0–17%). Grinding, for which electricity consumption is the only input, contributes to 0–14% of impacts, mainly ionizing radiation (14%), freshwater eutrophication (12%), and human non-carcinogenic toxicity (13%) impact categories. These impacts are mainly related to upstream generation of electricity. Transport contributes less than 2% to overall impacts.

System 5

Conventional Meat (Swine)

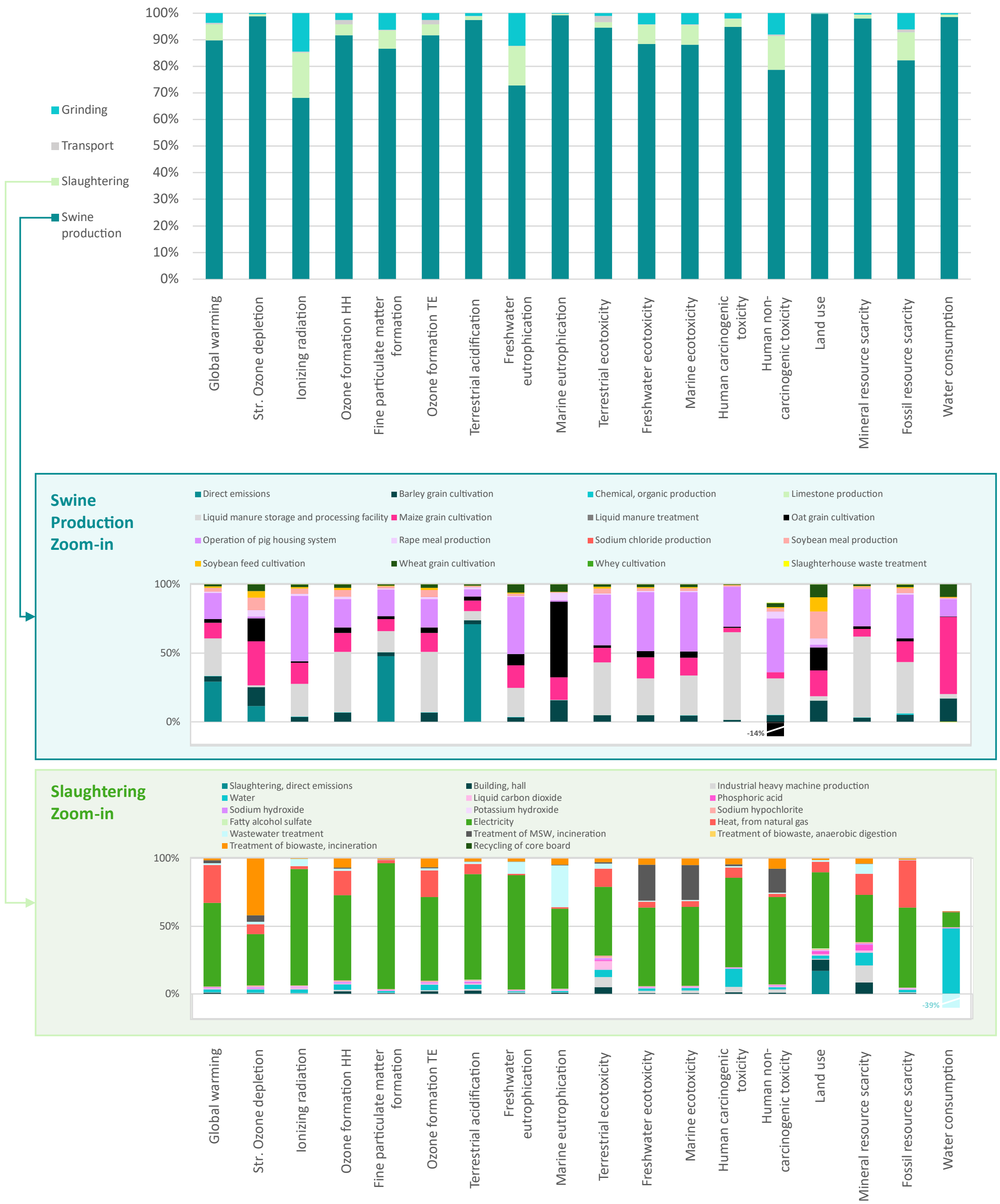

Figure 5-28. Contribution analysis dashboard for System #5, 1 kg of animal-based meat recipe, pork, cradle-to-manufacturing gate. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Built based on Figure 5-29 to Figure 5-31.

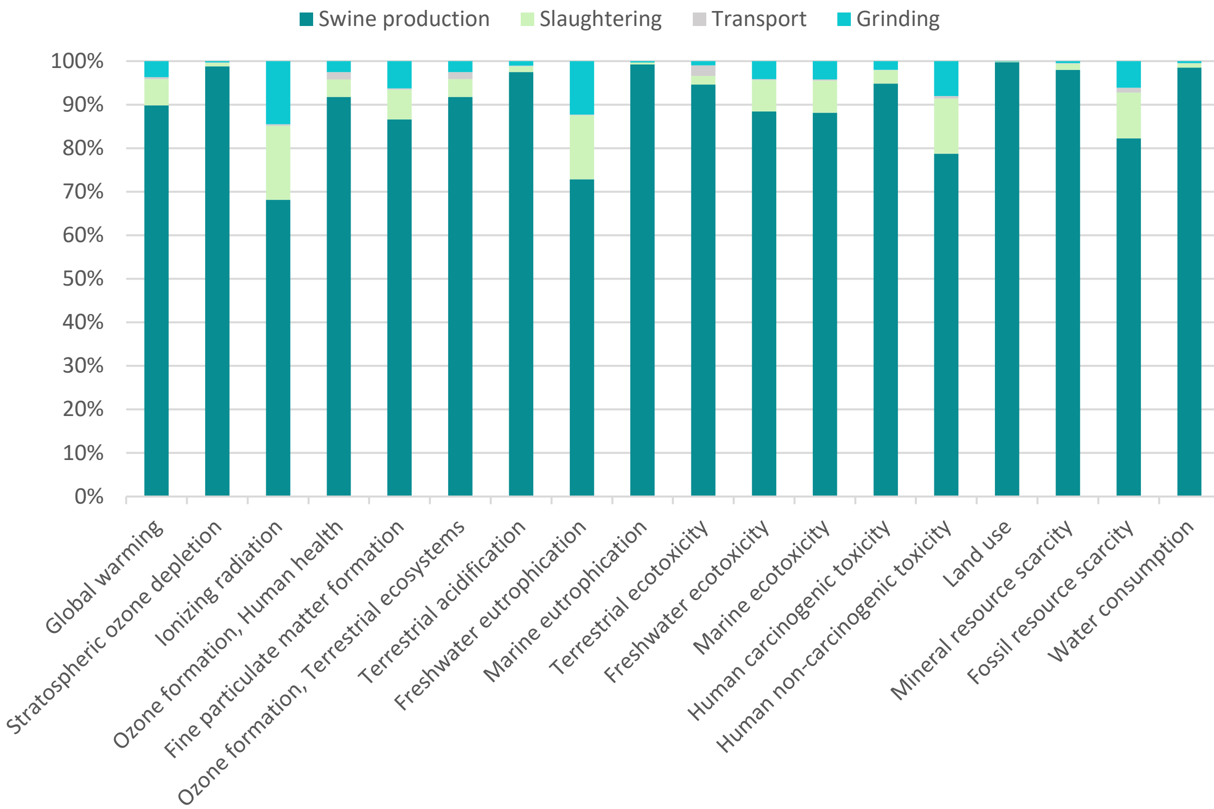

Figure 5-29. Contribution analysis for System #5, 1 kg of ground pork meat, cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-28.

Animal husbandry impacts

Figure 5-30 shows the contribution analysis from industrial swine production (the main driver for System #5 environmental impacts). Here, 1.49 kg of swine is required to produce 1 kg of pork meat. Direct emissions from swine farming are the highest contributors to terrestrial acidification (71%), fine particulate matter (48%), and global warming (29%). The emissions of ammonia (2.43E-2 kg/kg live weight), particulates (1.84E-3 kg/kg live weight), and methane (5.31E-2 kg/kg live weight) during housing and manure storage are the main contributors to these categories, respectively. A total of 2.95 kg of feed (maize grain, barley grain, oat grain, soybean meal, wheat grain, and soybean grain) is needed to produce 1 kg of swine, live weight. Maize grain impacts are focused on water consumption (56%) and stratospheric ozone depletion (32%) caused by direct irrigation requirements (0.244 m^3/kg) and upstream dinitrogen oxides emissions during the agricultural cultivation phase. The cultivation of oat grains emits nitrates in high amounts (0.22 kg/kg), which contributes heavily to overall marine eutrophication (55%) impacts. Soybean meal and feed sourced from soybeans from the U.S. mix, contribute significantly to land use (30%), in part due to the land use requirements required for soybean cultivation (the U.S. model for soybean in ecoinvent states a yield of 1,120 kg/acre). The liquid manure storage and processing facility is the highest contributor to human carcinogenic toxicity (64%), mineral resource scarcity (59%), fossil resource scarcity (37%), ozone formation—human health and terrestrial ecosystems (both 44%), and terrestrial ecotoxicity (38%). This facility requires cast iron, reinforcing steel, and chromium steel, which among other metals show high upstream impacts in their extraction and processing. Finally, the operation of the pig housing system, which involves upstream electricity and natural gas consumption, is responsible for 1 to 48% of impacts, with its higher contributions to ionizing radiation (48%), freshwater and marine ecotoxicity (43%), freshwater eutrophication (41%), and human non-carcinogenic toxicity (39%).

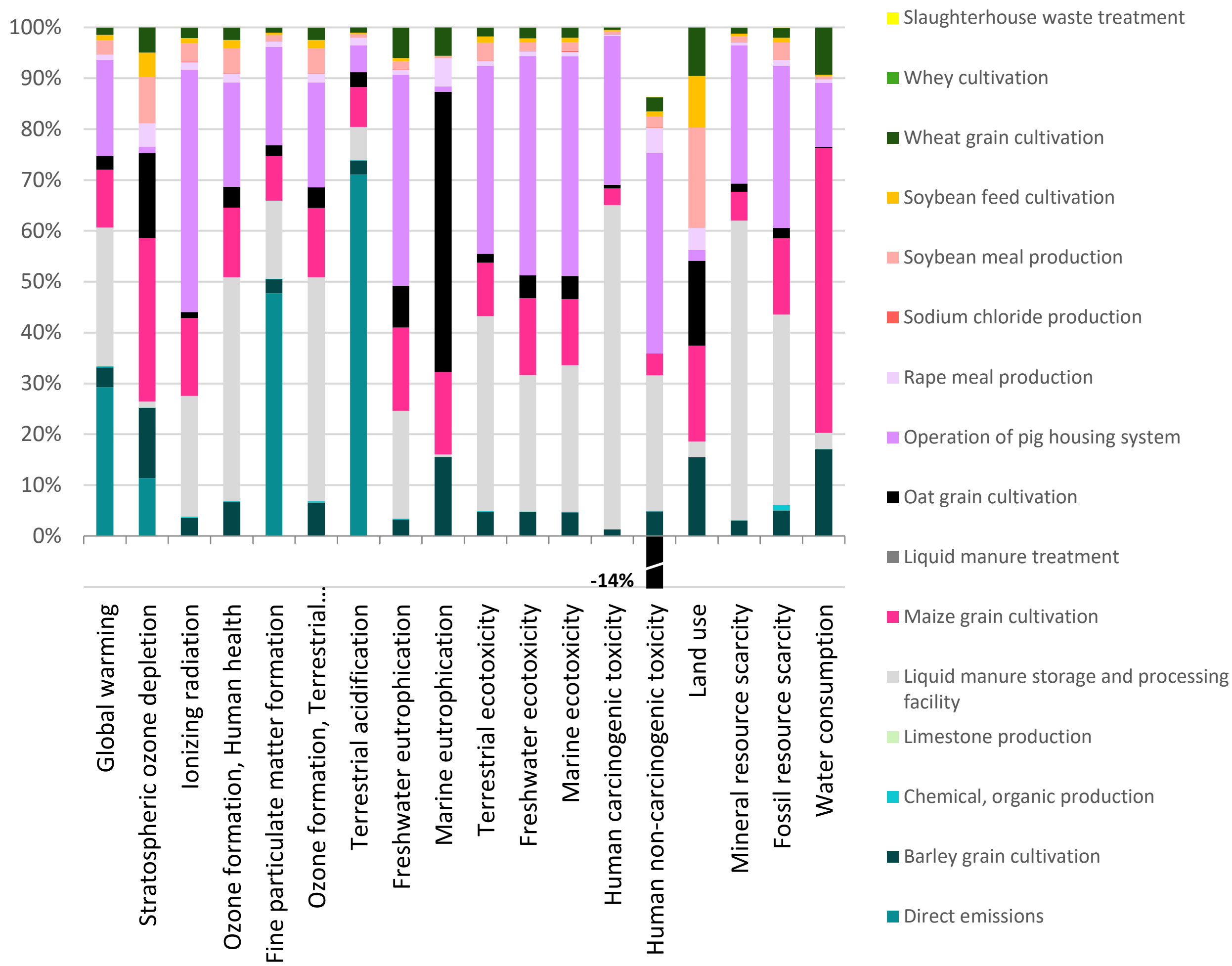

Figure 5-30. Contribution analysis for System #5, 1.49 kg of swine, live weight, animal husbandry stage, pork. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-29.

Slaughtering stage impacts

Figure 5-31 shows the contribution analysis of the slaughtering process. Here, 0.67 kg of fresh pork meat is obtained per 1 kg of swine (live weight), and 1.49 kg of swine is required to produce 1 kg of fresh pork meat. Electricity is the main driver for the environmental impacts of slaughtering, contributing 11 to 93% of the total impacts, with a focus on fine particulate matter formation (93%), ionizing radiation (86%), and freshwater eutrophication (84%) primarily from upstream emissions from electricity generation. As for the rest of the materials and energy consumption, biowaste incineration is the highest contributor to stratospheric ozone depletion (42%, NO_x emissions), incineration of MSW has a significant contribution to freshwater and marine ecotoxicity (26%, for both), caused by zinc and copper emissions from leachates), and direct water consumption accounts for most of the water consumption impact category (48%).

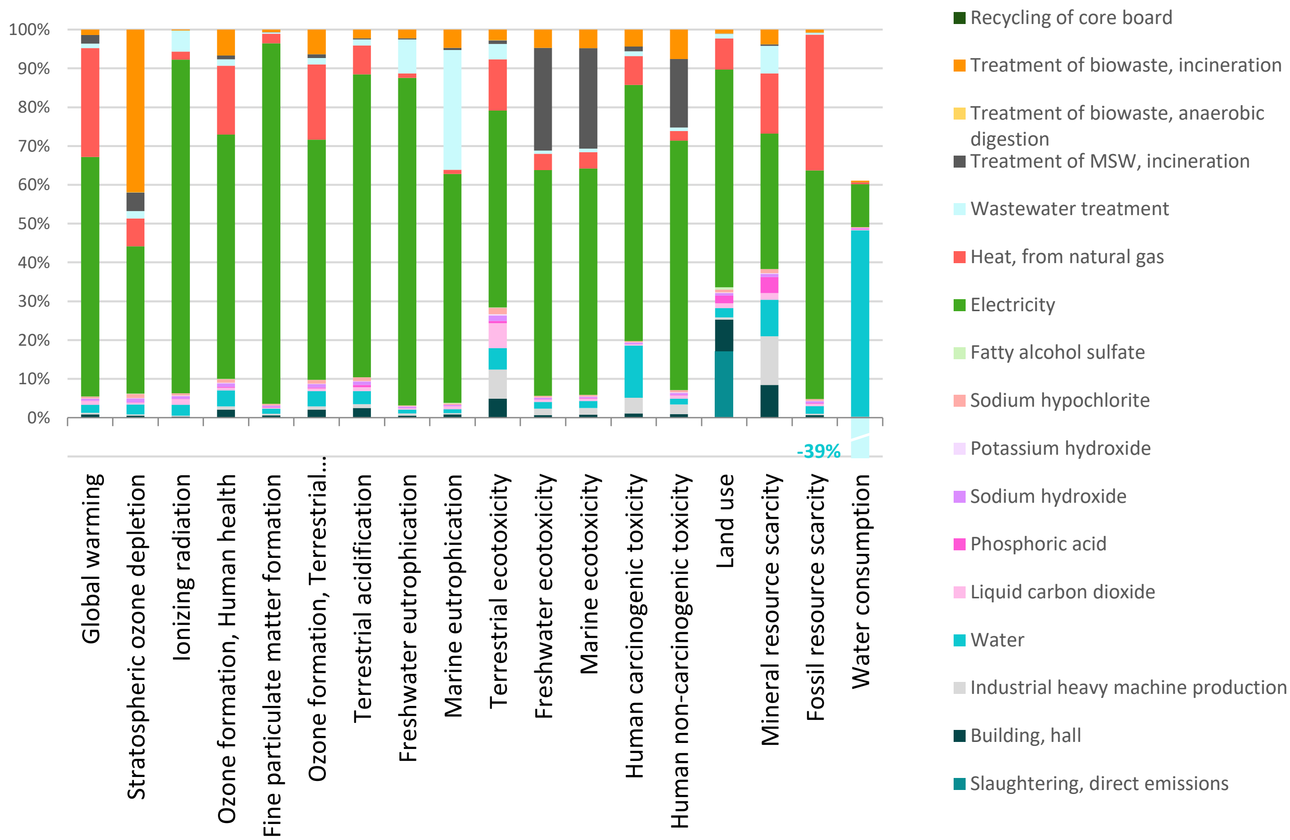

Figure 5-31. Contribution analysis for System #5, 1.49 kg of slaughtered pork meat, slaughtering stage, pork. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-30.

5.6 System #6 (Chicken) results

5.6.1 Stage contribution to product impacts

Figure 5-33 shows the proportional contribution of each life cycle stage to the environmental impacts caused by producing 1 kg of ground chicken meat. The production of chicken meat from the broiler husbandry stage has the highest contribution among all the impact categories (42–99%). The slaughtering process has a lower contribution to impacts (0–39%), but a particularly high contribution to human non-carcinogenic toxicity (39%), ionizing radiation (38%), freshwater ecotoxicity (34%), freshwater eutrophication (34%), human carcinogenic toxicity (33%), fossil resource scarcity (30%), and marine ecotoxicity (30%). Grinding contributes to 0–20% of impacts, mostly on ionizing radiation (20%) and freshwater eutrophication (18%). The overall contribution from transport (200 km) is insignificant (less than 10% in all impact categories).

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System 6

Conventional Meat (Chicken)

Figure 5-32. Contribution analysis dashboard for System #6, 1 kg of animal-based meat recipe, chicken, cradle-to-manufacturing gate. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Built based on Figure 5-33 to Figure 5-35.

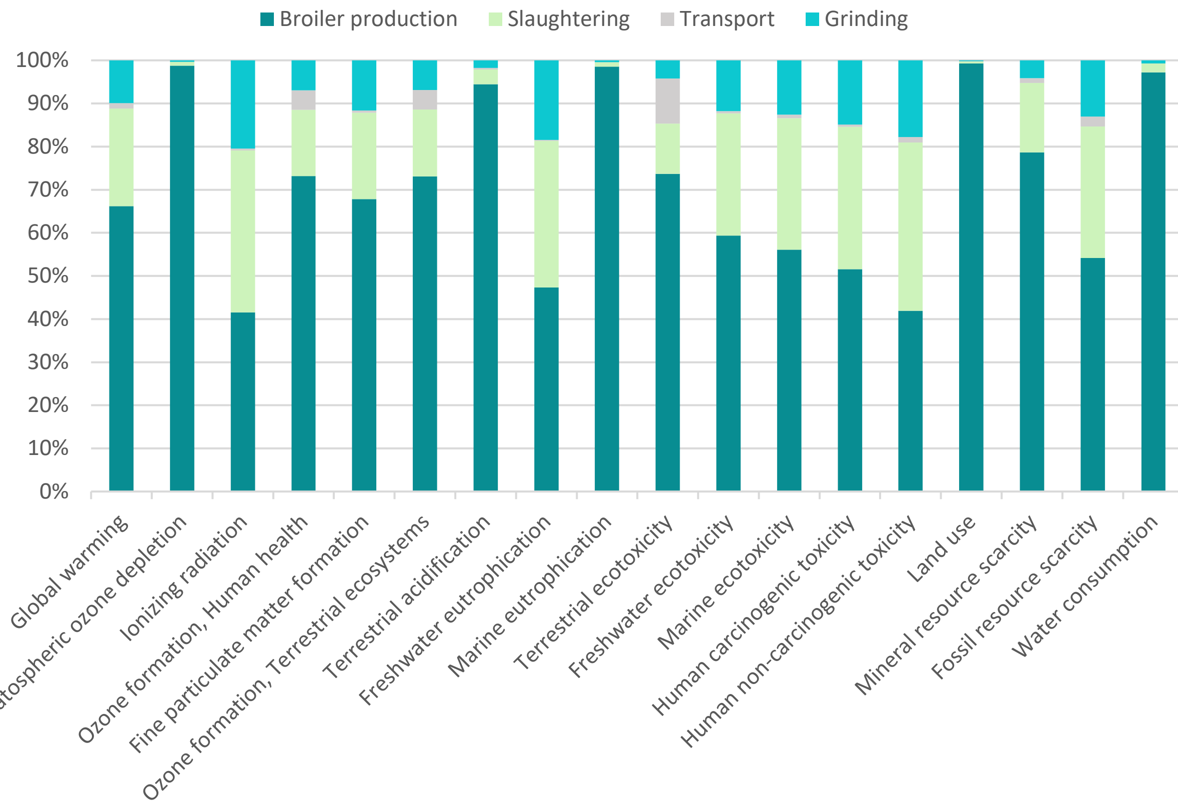

Figure 5-33. Contribution analysis for System #6, 1 kg of ground chicken meat, cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-31.

Animal husbandry impacts

Figure 5-34 shows the contribution analysis from industrial broiler production (the main driver for System #6 environmental impacts). Here, 1.52 kg of broiler is required to produce 1 kg of chicken meat. The cultivation of the energy feed has the highest average contribution to broiler husbandry (50%) and the highest contributions to 11 of 18 impact categories: water consumption (78%), mineral resource scarcity (68%), terrestrial ecotoxicity (68%), land use (67%), ozone formation—human health and terrestrial ecosystems (66%), freshwater ecotoxicity (61%), marine ecotoxicity (58%), fossil resource scarcity (53%), human carcinogenic toxicity (50%, both), and global warming (46%).

Of the 2.1 kg of total feed required to produce 1 kg of chicken meat, the energy feed represents 78% (1.64 kg), while protein feed represents the remaining 22% (0.46 kg/kg). The energy feed is composed of maize (68%), soybean meal (9%), barley (8%), and sweet sorghum (4%), among other grains (less than 2%). Maize grain has a yield of 9.31 ton/ha, requires on average 0.24 m^3 irrigated water/kg and 2.61E-02 kg of diesel/kg, demands 2.96E-03 kgP_2O_5 and 1.75E-02 kgN per kg (with upstream consumption of phosphate rock and similar minerals), emits copper from agrochemicals to soil (2.60E-07 kg/kg) and water (9.08E-06 kg/kg), emits nitrogen oxides from fertilizers (1.34E-04 kg/kg), emits chromium to water (1.37E-05 kg/kg), and emits zinc to soil (4.42E-6 kg/kg). These environmental flows along with the high concentration of maize in energy feed cause maize to be the top contributor in most of the impact categories mentioned above, with the exception of freshwater ecotoxicity, for which the upstream soybean cultivation emission of chlorpyrifos to soils (0.02 kg/kg) causes the highest impacts. The protein feed contributes to 5 to 33% of impacts across all categories.

Direct emissions from broiler production are the highest contributors to terrestrial acidification (77%), marine eutrophication (56%), fine particulate matter formation (52%), and stratospheric ozone depletion (51%). These impacts are mainly driven by emissions of ammonia to air (1.46E-02 kg/kg), nitrate to water (4.12E-02 kg/kg), and dinitrogen monoxide to air (1.08E-03 kg/kg), respectively. Electricity consumption is responsible for 0 to 53% of impacts, showing the highest contribution to ionizing radiation (53%) and freshwater eutrophication (42%) caused by upstream electricity generation.

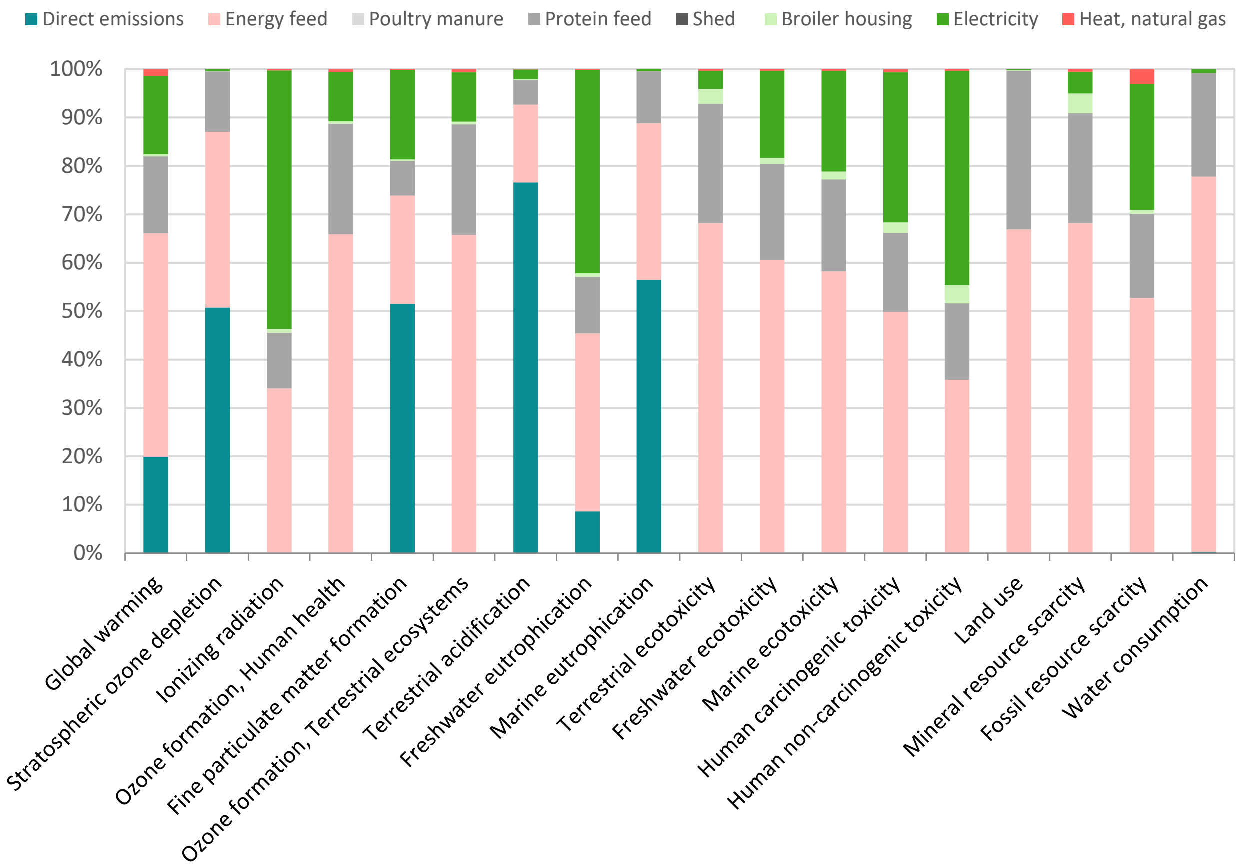

Figure 5-34. Contribution analysis for System #6, 1.52 kg of broiler, live weight, animal husbandry stage, chicken. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-32.

Slaughtering stage impacts

Zooming into the slaughtering process, Figure 5-35 shows the contribution analysis related to the slaughter of 1.52 kg of chicken, live weight. Electricity is the main driver for the environmental impacts of slaughtering, contributing 13–94% of impacts, mainly from fine particulate matter formation (94%), freshwater eutrophication (88%), and ionizing radiation (88%) due to upstream emissions of PM2.5, phosphate, and radon-222 from MRO electricity production. The incineration of MSW has a higher contribution to freshwater and marine ecotoxicity (23 and 22%, respectively), caused by zinc and copper emissions from leachates, and direct water consumption accounts for much of the water consumption impact category (47%).

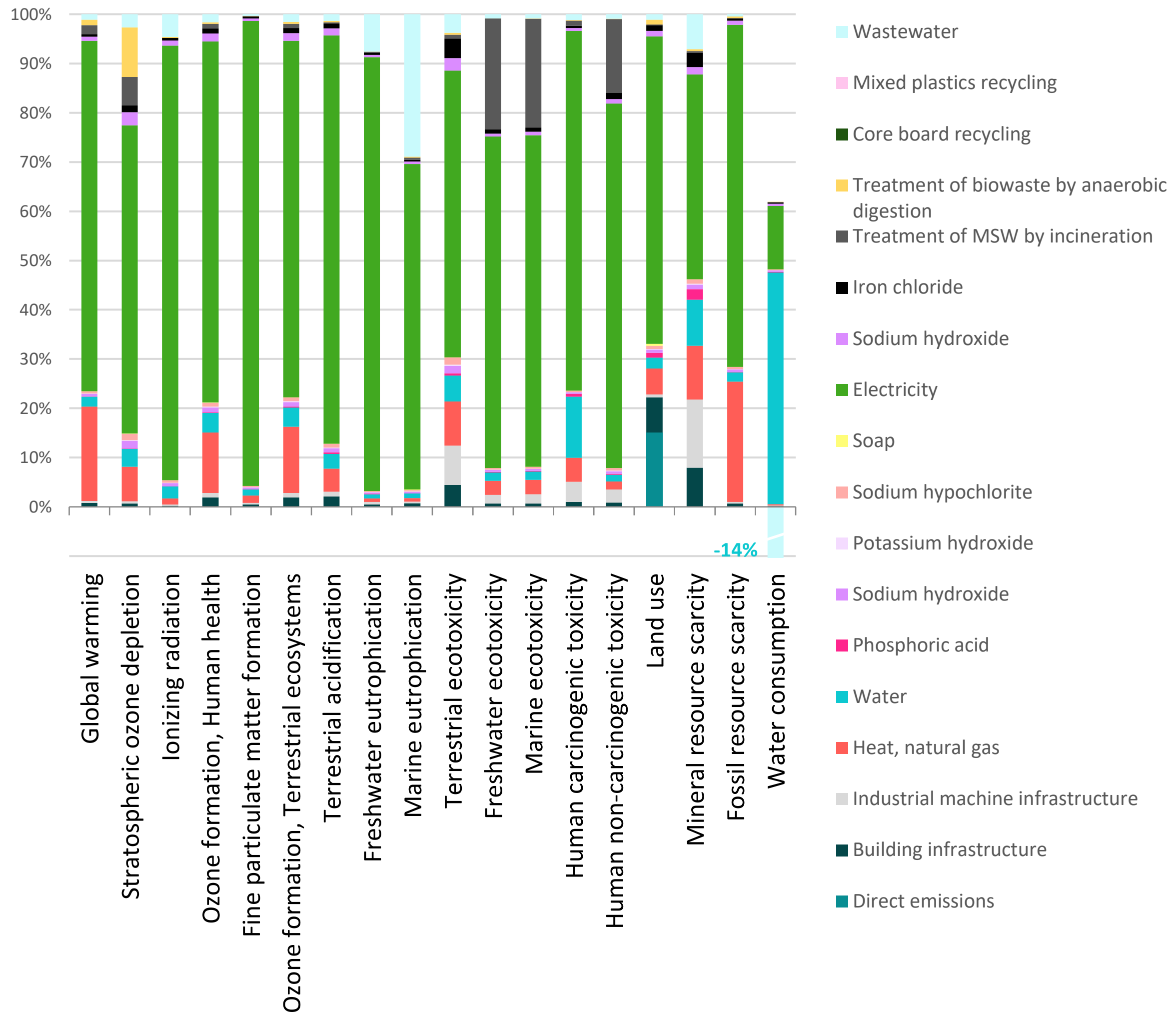

Figure 5-35. Contribution analysis for System #6, 1.52 kg of slaughtered chicken meat, slaughtering stage, chicken. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-33.

5.7 Comparisons

5.7.1 Overall comparisons

When comparing environmental impacts of all the systems (Figure 5-36), there is a wide difference between the plant-based (Systems #1–3) and the conventional meat systems (Systems #4–6). On average, across all impact categories, the environmental impacts of the three plant-based systems were 91% lower than System #4 (beef), 88% lower than System #5 (pork), and 71% lower than System #6 (chicken). Within each impact category, the conventional meat systems consistently showed 50% or greater impact compared to the maximum impact value across the plant-based systems, with the exception of System #6 (chicken meat) for the land use category (Table 5-1).

Table 5-1. Percent difference between plant-based (Systems #1–3) and animal-based (Systems #4–6) meat recipes, baseline results, per each impact category. Mass allocation, the plant-based scenario with the highest impacts, is compared to the animal-based baseline scenario, the decrease % is based on the conventional scenario. Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	Maximum Plant-Based Impacts	Maximum Plant-Based System	% Difference System #4 (Beef)	% Difference System #5 (Pork)	% Difference System #6 (Chicken)
Global warming	kg CO_2 eq	9.82E-01	System #2	93%	86%	62%
Stratospheric ozone depletion	kg CFC11 eq	4.11E-06	System #3	97%	83%	83%
Ionizing radiation	kBq Co-60 eq	3.05E-02	System #2	85%	85%	78%
Ozone formation, Human health	kg NOx eq	1.85E-03	System #3	80%	86%	63%
Fine particulate matter formation	kg PM2.5 eq	1.89E-03	System #2	90%	90%	81%
Ozone formation, Terrestrial ecosystems	kg NO_x eq	2.00E-03	System #3	79%	86%	61%
Terrestrial acidification	kg SO_2 eq	4.43E-03	System #2	95%	94%	89%
Freshwater eutrophication	kg P eq	4.44E-04	System #2	94%	84%	76%
Marine eutrophication	kg N eq	8.10E-04	System #3	96%	89%	84%
Terrestrial ecotoxicity	kg 1,4-DCB	2.06E+00	System #3	88%	91%	63%
Freshwater ecotoxicity	kg 1,4-DCB	3.75E-02	System #2	89%	87%	62%
Marine ecotoxicity	kg 1,4-DCB	3.63E-02	System #2	91%	90%	71%
Human carcinogenic toxicity	kg 1,4-DCB	3.68E-02	System #2	92%	96%	73%
Human non-carcinogenic toxicity	kg 1,4-DCB	9.28E-01	System #3	100%	80%	56%
Land use	m2a crop eq	2.20E+00	System #1	90%	58%	4%
Mineral resource scarcity	kg Cu eq	2.17E-03	System #2	89%	96%	62%
Fossil resource scarcity	kg oil eq	1.98E-01	System #2	75%	82%	61%
Water consumption	m^3	1.85E-02	System #2	92%	96%	94%

System #4 (beef) has the highest impacts in 11 of 18 impact categories:

- Global warming
- Human non-carcinogenic toxicity
- Stratospheric ozone depletion
- Land use
- Freshwater and marine eutrophication
- Terrestrial acidification
- Freshwater and marine ecotoxicity
- Ionizing radiation
- Fine particulate matter formation

The main drivers for these impact categories are: direct field emissions derived from cattle enteric metabolism; manure management; fertilizing leachates; and release of upstream toxic substances related to housing and manure storage facilities.

System #5 (pork) has the highest impacts in the remaining seven impact categories: mineral resource scarcity, human carcinogenic toxicity, water consumption, ozone formation—terrestrial ecosystems, ozone formation—human health, terrestrial ecotoxicity, and fossil resource scarcity, which are mainly caused by upstream feed basket cultivation requirements and housing and manure management infrastructure and electricity and heating requirements. In all three conventional meat systems, feed cultivation and production contribute significantly to the overall impact.

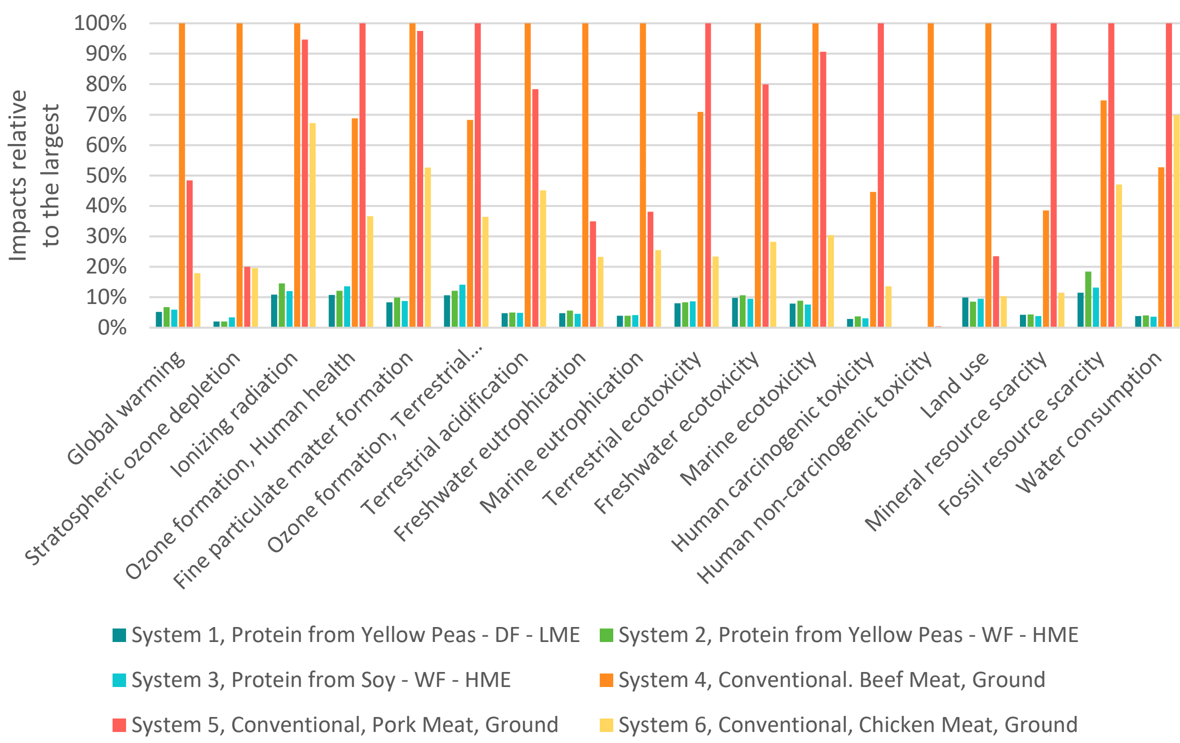

Figure 5-36. Comparison between life cycle impacts for Systems #1–6, 1 kg of ground food with meat or meat alternatives ready to be cooked, from cradle-to-manufacturing gate, before packaging or cooling. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-34.

5.7.2 Plant-based meat recipes comparisons

Figure 5-37 compares the life cycle impacts for producing 1 kg of plant-based ground meat. System #2 (pea-sourced, WF, HME, pea protein isolate) shows the highest impacts in 11 of 18 environmental categories: global warming, ionizing radiation, fine particulate matter formation, terrestrial acidification, freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, mineral resource scarcity, fossil resource scarcity, and water consumption. Direct electricity and heat consumption are the main impact drivers for these environmental categories across all plant-based systems, so System #2 has the highest overall heat consumption of natural gas (3.70 MJ), the highest biowaste generation (0.27 kg), and the second highest electricity consumption (0.60 kWh).

System #1 (pea-sourced, DF, LME, pea protein concentrate) shows the highest impacts in only one out of 18 impact categories (land use). This system requires more agricultural feedstock at the fractionation stage compared to Systems #2 and #3: 1.74 kg of fresh peas compared to 1.42 kg of fresh peas (System #2), and 0.42 kg of soybeans (System #3). This increases the required land needed for the crops.

Finally, System #3 (soy-sourced, WF, HME, soy protein concentrate) shows the highest impacts in the remaining six impact categories: stratospheric ozone depletion, ozone formation—human health and terrestrial ecosystems, marine eutrophication, terrestrial ecotoxicity, and human non-carcinogenic toxicity. These impact categories are closely related to the agricultural cultivation of soybeans. The first impact category is mostly related to direct N_2O emissions derived from fertilizer use (soybean cultivation emitted a total of 1.45E-4 kg, higher than 3.06E-6 kg from pea cultivation). The second and third categories are also caused by nitrogen-related emissions from soy cultivation (1.2E-4 kg of NO_x during combine harvesting), as well as by direct ethanol emissions from the soy protein concentrate extraction process (2.00E-3 kg). System #3 is the only system that requires ethanol.

The main source of impact for marine eutrophication is the direct nitrate emissions to water (9.18E-4 kg for System #3, three times higher than System #2's nitrate emissions). When compared on a direct 1 kg basis, soybean cultivation emits 23 times more nitrate to water than pea cultivation. System #3's high share of terrestrial ecotoxicity impacts is also caused during the agricultural phase by air emissions from glyphosate application (3.33E-5 kg). Finally, human non-carcinogenic toxicity is caused by upstream zinc and arsenic emissions to water related to lignite mining spoil involved in MRO electricity generation. This impact category accounts for the negative heavy metal emissions to agricultural soil involved in pea cultivation. Lastly, while System #2 has the highest direct water consumption (1.75 kg), System #3 has the highest overall water consumption (6.89 kg), but a great share of it ends up as treated wastewater (6.15 kg).

Ingredients like oil and starch used for plant-based systems have a high environmental contribution in all the systems. Even though the extrudate meat analogue can be considered the main ingredient in the recipe (28–71% of the recipe's mass, depending on the system), its contribution to environmental impacts varies greatly across categories (between -22% and 71%). While the meat extrudates are consistently the higher source of impact for nine impact categories (ionizing radiation, ozone formation—human health and terrestrial ecosystems, fine particulate matter, freshwater eutrophication, marine ecotoxicity, human carcinogenic toxicity, mineral and fossil resource scarcity), other ingredients have significant contributions to the rest of impact categories: global warming, freshwater ecotoxicity, and land use for coconut oil; stratospheric ozone depletion, terrestrial acidification, marine eutrophication, and human non-carcinogenic toxicity for canola oil; water consumption for potato starch; and terrestrial ecotoxicity for spices.

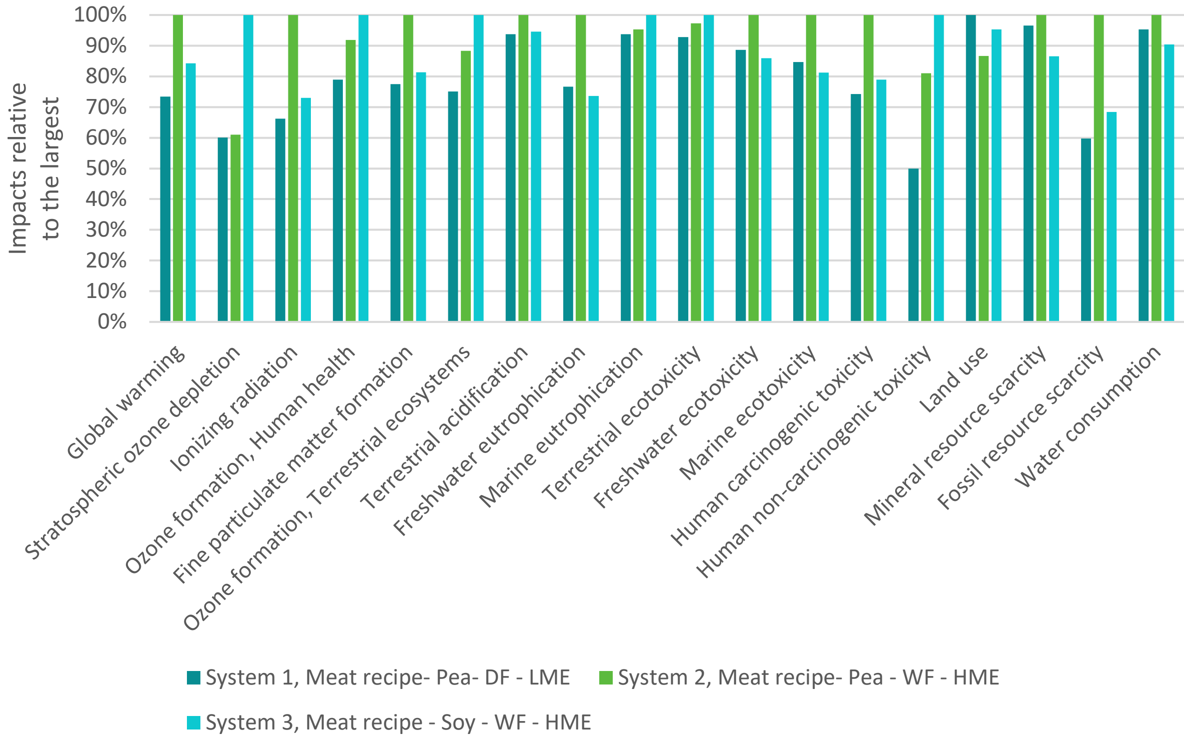

Figure 5-37. Comparison between life cycle impacts for Systems #1–3, plant-based systems, 1 kg of ground food with meat or meat alternatives ready to be cooked, from cradle-to-manufacturing gate, before packaging or cooling. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-35.

Meat extrudate comparisons

Figure 5-38 shows the comparison of high and low moisture extrusion processes. Extruded meat analogue from pea, HME (System #2), consistently shows the highest impacts in 11 of 18 categories. System #1 has the highest impact in land use, and soy-based System #3 has highest impact in stratospheric ozone depletion, ozone formation—human health and terrestrial ecosystems, marine eutrophication, human non-carcinogenic toxicity, and terrestrial ecotoxicity.

The pea-based extruded meat analogue from HME (System #2) has higher impacts than the pea-based extruded meat analogue from LME (System #1) in all impact categories but land use. Also, the pea-based extruded meat analogue from LME (System #1) has lower impacts than the soy-based extruded meat analogue from HME (System #3) in most categories, except for freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity, land use, mineral resource scarcity, and water consumption. Finally, System #1 shows a negative value for the human non-carcinogenic toxicity caused by negative heavy metal emissions to soil in the agricultural cultivation phase (explanation in Section 5.1).

To deliver the same approximate percentage of protein (dry weight) in the final meat recipe (15%) from the primary protein ingredient (pea/soy), System #3 requires the highest amount of meat extrudate (0.714 kg extrudate/kg plant-based meat) compared to System #1 (0.283 kg extrudate/kg plant-based meat) and System #2 (0.441 kg extrudate/kg plant-based meat). This is explained by the soy HME process having the lowest protein concentrate/isolate content (0.301 kg soy protein concentrate/kg extrudate compared to 0.91 kg pea protein concentrate/kg extrudate from System #1 and 0.431 kg pea protein isolate/kg extrudate from System #2), and the lowest overall protein content across meat extrudates (21%, compared to 53% and 34% protein content in the pea LME and HME meat analogues, respectively). Also, the HME process from System #3 has the highest average contribution (39%) to the meat extrudate's impacts compared to the other systems' extrusion processes. In System #3, electricity consumption and wastewater generation were identified as HME process hotspots. Any efforts to improve the environmental performance of the soy-based extruded meat analogue from HME must focus on increasing the protein content and decreasing the electricity consumption of the extrusion process.

When pea-based meat extrudates are compared directly (focusing only on the extrusion stage), the meat extrudate from System #1 (pea-based LME) has lower impacts than the meat extrudate from System #2 (pea-based HME) in all impact categories except land use. Pea-based LME has more protein concentrate in the final extrudate (91%) and a higher protein content (53%); HME's additional water requirements for the mixture result in less protein isolate in the final extrudate (43%) and a lower protein content (34%). Even though pea-based LME requires a higher amount of input than HME (0.291 kg of protein concentrate compared to 0.190 kg of protein isolate) and nearly 15 times more heat from natural gas, pea-based HME still has higher environmental impacts because it consumes 4 times more electricity and 14 times more water. Electricity consumption for the extrusion process is identified as a main hotspot for pea-based LME and HME processes.

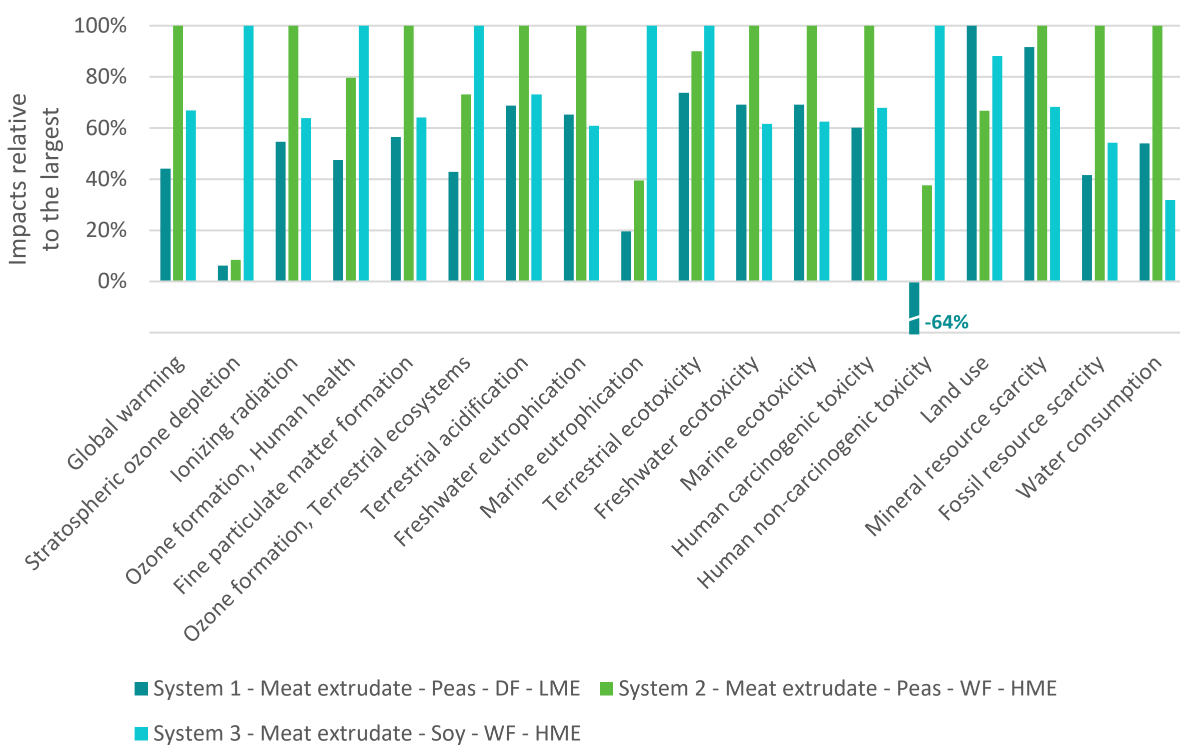

Figure 5-38. Comparison between life cycle impacts for Systems #1–3, plant-based systems, extruded meat analogues required to deliver 0.15 kg of extrudate-only protein content to final meat recipe. System #1: 0.283 kg, System #2: 0.441 kg, System #3: 0.714 kg, cradle-to-manufacturing gate, before packaging or cooling. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-36.

Protein concentrates and isolates comparisons

When the protein concentrates (System #1, pea, and System #3, soy) and isolates (System #2, pea) are compared directly (Figure 5-39), System #2 shows the highest impacts in 10 out of 18 categories (global warming, ionizing radiation, fine particulate matter, terrestrial acidification, freshwater eutrophication, freshwater and marine ecotoxicity, human carcinogenic toxicity, and mineral and fossil resource scarcity). The soy protein concentrate from System #3 has the highest impacts in the stratospheric ozone depletion, ozone formation—human health and terrestrial ecosystems, marine eutrophication, terrestrial ecotoxicity, human non-carcinogenic toxicity, and water consumption categories. Finally, the pea protein concentrate from System #1 shows the highest impacts in the land use category.

When pea-sourced proteins are compared directly, the pea protein isolate produced by wet fractionation has higher impacts in all categories than pea protein concentrate produced by dry fractionation, except for land use. Even though wet fractionation requires lower pea consumption than dry fractionation (1.42 kg versus 1.74 kg) and delivers a product with a higher protein content than dry fractionation (80% versus 58%), its overall final product to fresh feedstock yield is lower (0.13 kg pea protein isolate/kg fresh peas in System #2, compared to 0.17 kg pea protein concentrate/kg fresh peas in System #1), which affects its environmental performance. Any improvements to the yield of wet fractionation will decrease its overall impact. On a similar note, wet fractionation shows higher energy and materials requirements than dry fractionation (additional consumption of water, sodium hydroxide, and hydrochloric acid, 52% more heat, 30% more biowaste, and nearly 13 times more wastewater generation). Extracting a protein product with higher protein content will demand more energy and resources. This explains why pea protein isolate from System #2 has high impacts despite having the lowest usage across all protein concentrates/isolates in the plant-based meat recipes shown (0.190 kg pea protein isolate/kg plant-based meat compared to 0.291 kg pea protein concentrate/kg plant-based meat from System #1 and 0.215 kg soy protein concentrate/kg plant-based meat from System #3).

The comparison between the impact factors for pea and soy protein concentrates (System #1 and System #3) does not show clear trends, since each one of these protein products has the highest impacts in half of the impact categories. Pea protein concentrate from dry fractionation has higher environmental impacts in nine categories (ionizing radiation, fine particulate matter formation, terrestrial acidification, freshwater eutrophication, freshwater and marine ecotoxicity, human carcinogenic toxicity, land use, and mineral resource scarcity), the same number as for soy protein concentrate from wet fractionation (global warming, stratospheric ozone depletion, ozone formation—human health and terrestrial ecosystems, marine eutrophication, terrestrial ecotoxicity, human non-carcinogenic toxicity, fossil resource scarcity, and water consumption). This comparison helps identify trade-offs between the protein concentrate source and the type of fractionation since pea protein concentrate from dry fractionation requires 4 times more feedstock consumption and 14 times higher electricity consumption, while soy protein concentrate from wet fractionation requires ethanol consumption and nearly 100 times more water. Hexane use in System #3 is nearly a closed-loop process and, therefore, does not contribute significantly to environmental impacts.

Many of the total impacts from wet fractionation of peas in System #2, which is identified as a hotspot for the final product (0–79% of impacts), are caused by heat consumption during the spray drying process, as well as by electricity consumption for milling and cooling. On the other hand, wet fractionation of soy has a lower contribution to overall System #3 impacts (0–48%), mostly driven by lower electricity and heat consumption for spray drying. When compared directly, pea protein isolate requires around 8 times higher electricity consumption, nearly 50% higher heat consumption, and around 10 times higher water consumption than soy protein concentrate. Apart from having a lower yield (0.134 kg protein isolate/kg fresh peas compared to 0.642 kg protein concentrate/fresh soybeans), the protein isolate extraction process demands a higher overall resource consumption per input to deliver a product with higher protein content. Any efforts to improve the environmental performance of these products should focus on their energy consumption.

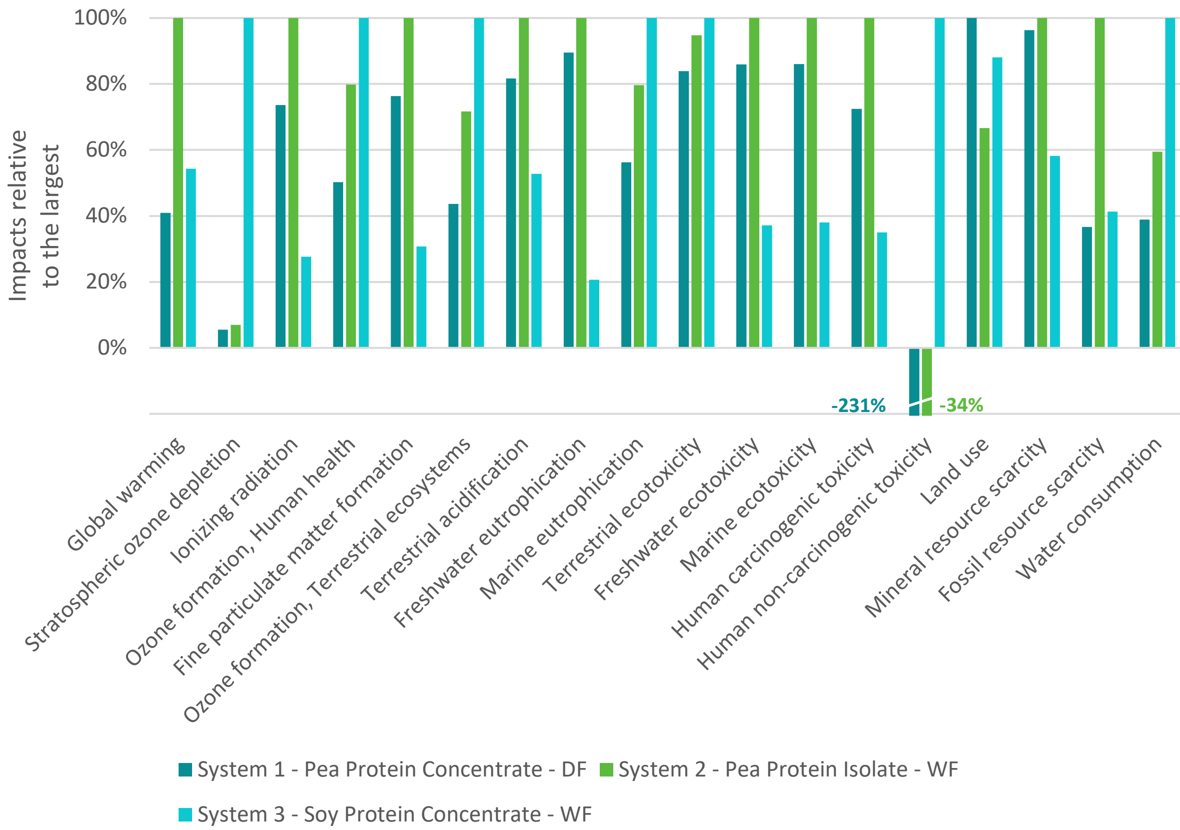

Figure 5-39. Comparison between life cycle impacts for Systems #1–3, plant-based systems, protein concentrates and isolates required to deliver 0.15 kg of extrudate-only protein content to final meat recipe. System #1: 0.291 kg of protein concentrate, System #2: 0.190 kg of protein isolate, System #3: 0.215 kg of protein concentrate, cradle-to-manufacturing gate, before packaging or cooling. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-37.

Peas and soybeans comparisons

Figure 5-40 shows a direct comparison between each plant-based system's agricultural feedstock cultivation. Contrary to the comparisons between meat extrudates and protein concentrate and isolate products, System #3 (U.S.-grown soybeans) shows higher impacts in the majority (11) of impact categories (global warming, stratospheric ozone depletion, ionizing radiation, ozone formation—human health and terrestrial ecosystems, fine particulate matter, marine eutrophication, terrestrial ecotoxicity, human non-carcinogenic toxicity, fossil resource scarcity, and water consumption). Canada-based pea cultivation from System #1 has higher impacts in the remaining categories (terrestrial acidification, freshwater eutrophication, freshwater and marine ecotoxicity, human carcinogenic toxicity, land use, and mineral resource scarcity).

System #1 has higher impacts than System #2 across all categories because of its higher consumption of fresh peas as feedstock (1.75 kg compared to 1.42 kg). This is because more pea is required (6.017 kg peas/kg of extruded meat analogue) for the DF-LME pathway on a mass basis compared to WF-HME (3.21 kg peas/kg of extruded meat analogue). Pea cultivation involves a high amount of phosphorus-derived fertilizer (1.77E-02 kg MAP/kg) and emissions to water (1.62E-04 kg P/kg, 1.38E-05 kg Zn/kg, 9.40E-06 kg Cu/kg) on a per kg basis, which drives up the impacts for the freshwater eutrophication, freshwater and marine ecotoxicity, human carcinogenic toxicity, and mineral resource scarcity categories. Also, the higher consumption of agricultural feedstock increases the terrestrial acidification and land use impacts (when compared directly per kg, pea has 30% less impacts in these two categories, but it has a 19% higher agricultural feedstock consumption for System #1 than System #2) (Table A-39). Also, since the original pea cultivation dataset shows negative values for heavy metal emissions to soil (Section 5.1), the human non-carcinogenic toxicity impacts show high negative values and contributions across Systems #1 and #2. The pea cultivation stage for both systems shows negative contributions that get cancelled out in the case of System #2 due to lower consumption of peas and feedstock, as well as heavier processing.

Soybean cultivation in the U.S. involves direct emissions to air (7.02E-04 kg N_2O /kg, 1.87E-01 kg CO_2/kg, 1.32E-02 kg NO_x /kg, 1.40E-04 kg PM2.5/kg, 3.11E-04 kg SO_2/kg, etc.), to soil (1.76E-06 kg Zn/kg), and to water (9.16E-04 kg NO_3/kg, and 1.37 E-05 kg Zn/kg), as well as high consumptions of diesel (1.24E-02 kg/kg) and upstream nuclear electricity (7.14E-03 MJ/kg). These particular emissions drive up the impacts in those 11 categories where System #3 shows the highest impacts for the agricultural phase.

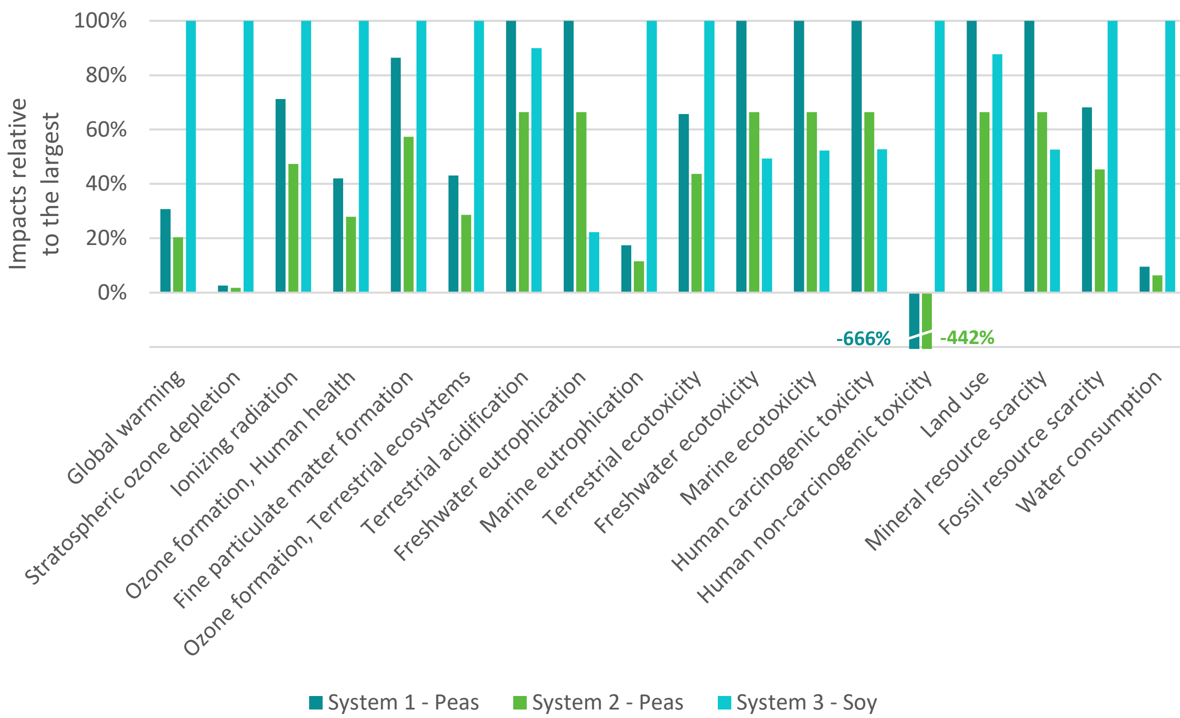

Figure 5-40. Comparison between life cycle impacts for Systems #1–3, plant-based systems, agricultural feedstocks required to deliver 0.15 kg of extrudate-only protein content to final meat recipe. System #1: 1.748 kg of Canada-MB-grown fresh peas, System #2: 1.416 kg of Canada-MB-grown peas, System #3: 0.42 kg of U.S. grown soybeans. Absolute values used for percentage calculations. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-38.

Cumulative comparisons summary

As a final summary for the plant-based meat contribution analysis, wet fractionation of peas (System #2) is the main source of impacts for the global warming, ionizing radiation, fine particulate matter formation, terrestrial acidification, freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, mineral resource scarcity, and fossil resource scarcity categories. The HME of pea protein isolate is identified as the main hotspot for water consumption. Also, System #2 has the highest impact across plant-based meat recipes in this same group of impact categories (both for WF and HME). Likewise, System #3 has the highest impacts across plant-based meat recipes for the stratospheric ozone depletion, ozone formation—human health and terrestrial ecosystems, marine eutrophication, terrestrial ecotoxicity, and human non-carcinogenic toxicity categories; soybean cultivation is identified as the main hotspot for these impacts. Finally, pea cultivation from System #1 is responsible for the highest contribution to land use impacts (placing this system as the one with the highest impact on land use).

The shift in the comparison between plant-based systems by cumulative life cycle stage is shown in Figure 5-41.

Figure 5-41. Cumulative comparison between Systems #1 to #3, plant-based meat recipes, cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03. Cumulative contribution analysis dashboard per stages for Systems #1–3, plant-based meat systems, cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03. Built based on Figure 5-38 to Figure 5-40.

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6. Interpretation

6.1 Sensitivity analysis

6.1.1 Plant-based meat processing – energy source

Across all the plant-based meat systems, electricity consumption was identified as a key driver for impacts. This study assumes that the manufacturing of plant-based protein and extrudates consumes electricity from the MRO grid, which has a high contribution from fossil fuels (52%), mostly coal and natural gas.

This sensitivity scenario assessed the effect of switching to 100% solar-sourced electricity; this source of electricity was chosen to show the effect of a shift. When changing the electricity grid, the environmental impacts of all three systems in all categories decrease (Figure 6-1), except for land use (this impact category has a direct relationship with agricultural yields and land occupation data). The analysis shows the overall environmental benefits of using renewable energy for manufacturing processes.

In Figure 6-1, System #2 shows the lowest environmental impacts because it is the system with the highest electricity consumption across the plant-based meat alternatives; any change to the electrical grid will heavily influence its environmental performance. Nine impact categories (ionizing radiation, freshwater eutrophication, fine particulate matter formation, human carcinogenic toxicity, human non-carcinogenic toxicity, freshwater ecotoxicity, marine ecotoxicity, fossil resource scarcity, and global warming) are reduced by more than 10% in every system when switching to renewable electricity. These impact categories have a closer relationship to upstream emissions derived from the high share of fossil fuels in the grid. Overall, plant-based meat produced with 100% renewable energy has on average 91% less impact than animal meat produced on the MRO grid in the baseline scenario, up from 89% less impact in the baseline scenario.

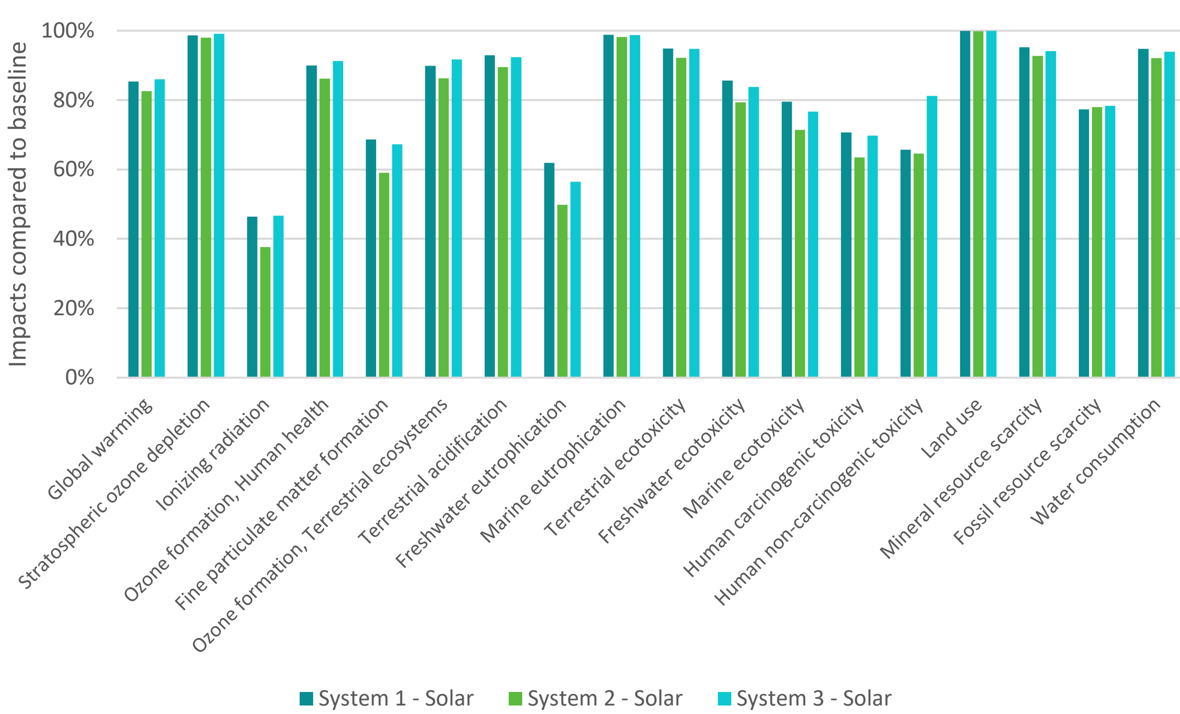

Figure 6-1. Sensitivity analysis, energy source (baseline MRO vs. solar), comparison of life cycle impacts for Systems #1–3 compared to baseline results, plant-based systems. 1 kg of ground food with meat or meat alternatives ready to be cooked, from cradle-to-manufacturing gate, before packaging or cooling. Baseline equals 100%. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-40.

Similarly, the report explored the effects on energy consumption improvements (baseline MRO grid). The effect on the environmental impacts of shifting electricity and heat consumption by -10%, -5%, +5%, and +10% for the three plant-based meat recipes (Systems #1–3) were assessed. However, the effects are negligible: there was 1% average impact reduction per each 5% reduction in energy consumption in all three systems. The data for these scenarios are shown in the Appendix (Tables A-41 through A-43).

6.1.2 Allocation approach

The baseline results for all meat recipes, both plant-based and animal-based, were modeled based on a mass allocation criterion. Following the ISO guidelines, the sensitivity of the results to allocation criteria was evaluated using economic allocation criteria (Figure 6-2). When observing the overall comparison between systems, animal-based meat continues to show higher impacts than plant-based meat. On average, plant-based meat recipes show 91% less environmental impact than animal meat.

System #4 (beef meat) continues to be the system with the highest impacts in most impact categories (11 of 18), while System #5 (pork meat) shows the highest impacts in the remaining seven impact categories; the baseline mass allocation comparison shows the same trend.

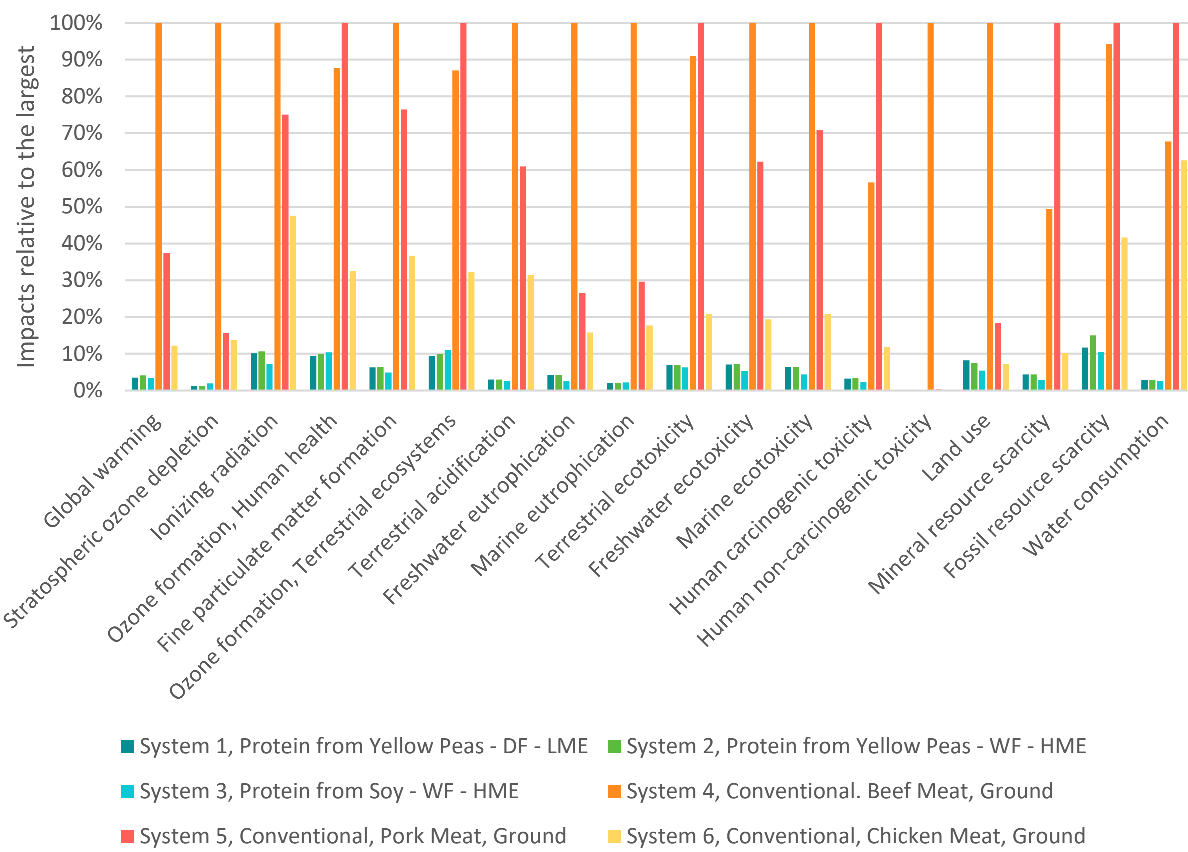

Figure 6-2. Sensitivity analysis, allocation approach (economic allocation, normalized to the highest value per impact category), comparison of life cycle impacts for Systems #1–6. 1 kg of ground food with

meat or meat alternatives ready to be cooked, from cradle-to-manufacturing gate, before packaging or cooling. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Tables A-44 and A-45.

When comparing plant-based systems only (Figure 6-3), System #2 (pea sourced, WF, protein isolate, HME) shows the highest impacts in 10 of 18 categories (the same impact categories as in the baseline comparison minus freshwater eutrophication). System #3 (soy-sourced, WF, HME, protein concentrate) continues to have the highest impacts in the same categories minus terrestrial ecotoxicity. System #1 (pea-sourced, DF, LME, protein concentrate) shows the highest impacts in the freshwater eutrophication and terrestrial ecotoxicity categories (plus land use, following the same trend as the baseline mass allocation results). These impact categories are closely related to the agricultural cultivation stage, which increases the environmental burden when applying an economic allocation criteria.

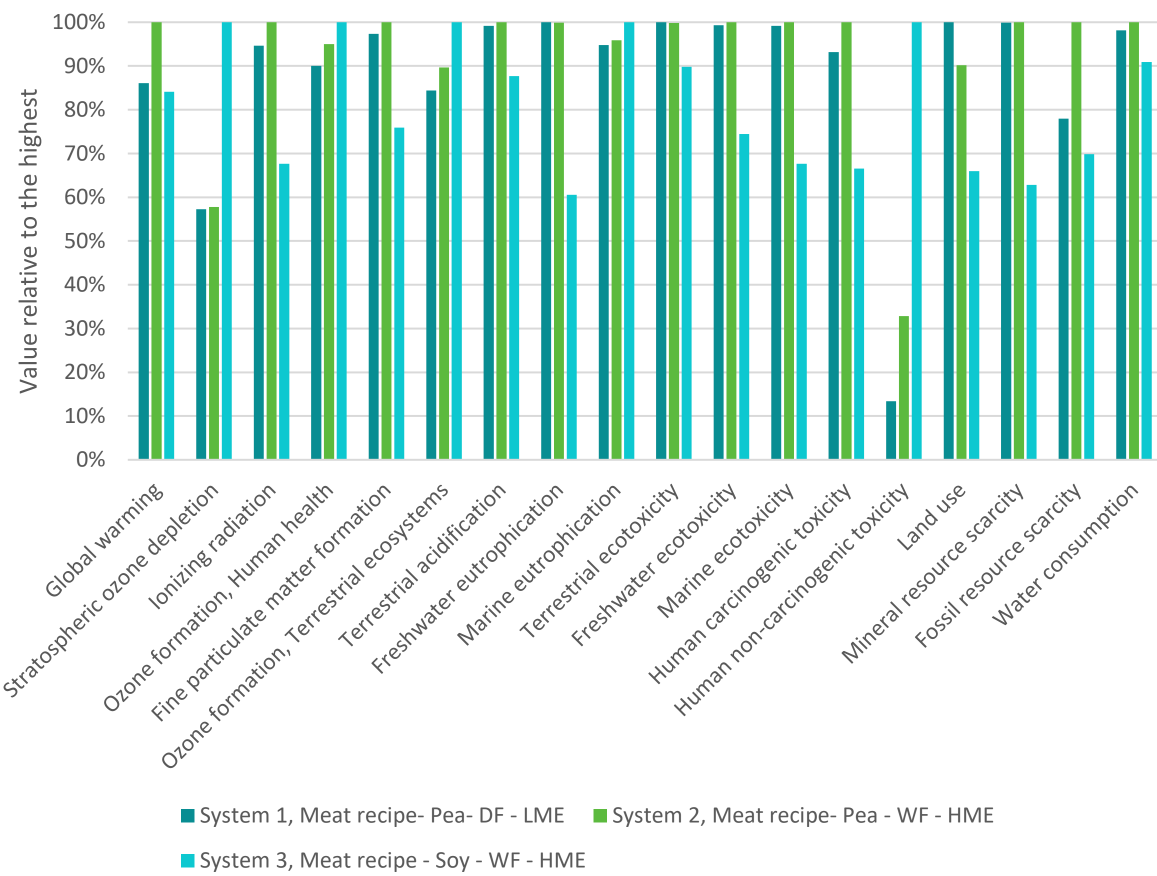

Figure 6-3. Sensitivity analysis, allocation approach (baseline mass vs. economic, economic allocation shown here), comparison of life cycle impacts for Systems #1–3, plant-based systems. 1 kg of ground food with meat or meat alternatives ready to be cooked, from cradle-to-manufacturing gate, before packaging or cooling. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Tables A-44 and A-45.

When analyzing the overall shift in impacts per impact category when switching from mass to economic allocation (Figure 6-4), System #4 (beef meat) shows the highest sensitivity (average percent difference of 87%) (Figure 6-5). A shift to economic allocation increases by 43.9% the environmental burdens from cattle husbandry and slaughtering. System #5 (pork meat) shows an average effect of 45% when pork meat increases its allocation factor due to economic allocation. Across the plant-based systems, System #1 shows the highest sensitivity to shifts in allocation (average value of 30%): dehulled peas increase their share of the dehulling and pea cultivation burden by 6% while pea protein concentrate doubles their upstream burden (23 to 53%). System #6 (chicken meat) has a similar average value of 29% for its increase by 13% of upstream broiler husbandry and slaughtering. System #2 shows an average value of 20%: dehulled peas increase by 16%, while pea protein slurry goes from 22 to 55%. Finally, System #3 shows the lowest variation in results due to shifts in allocation (average of 7%), since economic allocation only increases by 16% and 35% for the upstream environmental burden for soy white flakes and soy protein concentrate in the soy white flake and wet fractionation processes, respectively.

It is worth mentioning human non-carcinogenic toxicity for Systems #1 and #2. In both cases, the impacts actually decrease when compared to the baseline mass allocation results, which may seem counterintuitive at first. However, this pattern is directly related to the negative values from the agricultural cultivation stage (see explanation on Section 5.1.1). Since the economic allocation factor is higher than the mass factor, these scenarios allocate a higher share of the impacts of the agricultural cultivation stage (which are negative values) to the final product, hence the impacts increase in the negative axis.

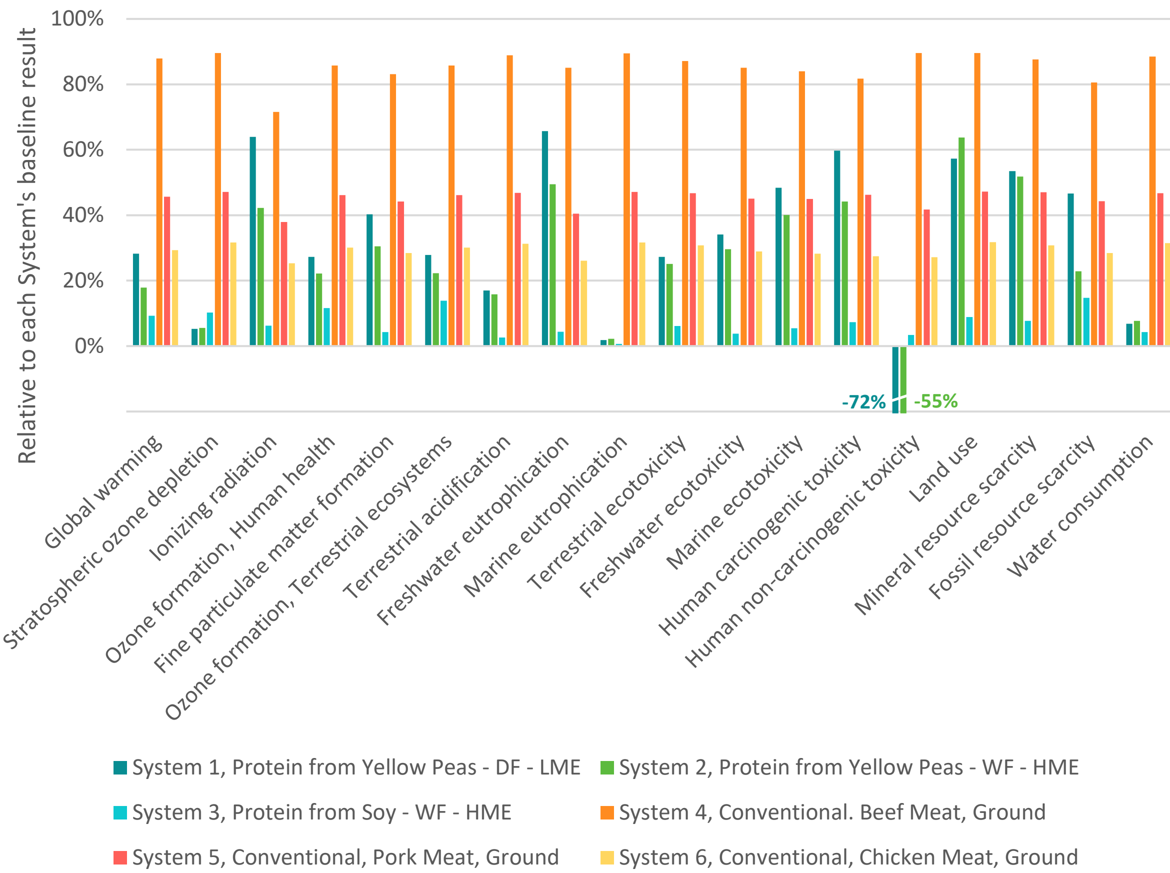

Figure 6-4. Sensitivity analysis, allocation approach (baseline mass vs. economic, comparison of relative shift per impact category), comparison of life cycle impacts for Systems #1–6. 1 kg of ground food with meat or meat alternatives ready to be cooked, from cradle-to-manufacturing gate, before packaging or cooling. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Tables A-44 and A-45.

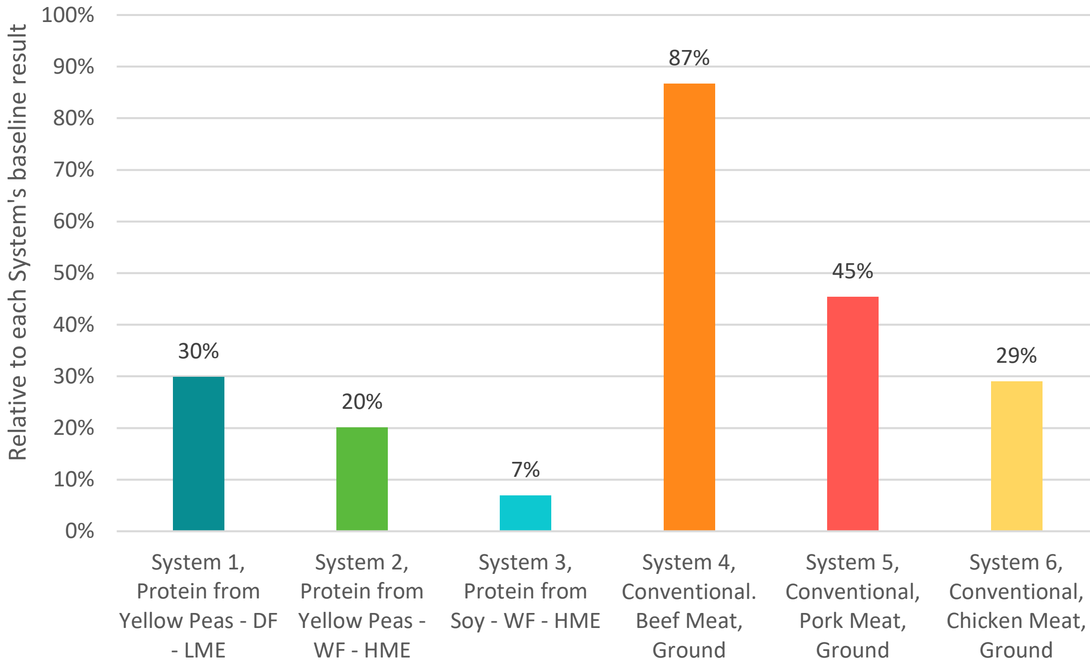

Figure 6-5. Sensitivity analysis, allocation approach (baseline mass vs. economic, comparison of average impact increase per system), comparison of life cycle impacts for Systems #1–6. 1 kg of ground food with meat or meat alternatives ready to be cooked, from cradle-to-manufacturing gate, before packaging or cooling. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Tables A-44 and A-45.

6.1.3 Crop geography

Systems #1 and #2 are pea-based. The pea is assumed to be cultivated in Canada (Manitoba). This scenario assesses the effect on final meat recipes by changing the geography. In the case of peas, Canada was compared to Germany and France, both pea-producing countries with available agricultural cultivation data on ecoinvent 3.9.1. The comparison (shown in Figure 6-6) shows numerous trade-offs when changing the country of cultivation. Canadian production systems have the highest impact only in the freshwater eutrophication category (less than 5% of variation between countries). In contrast, Canadian peas have the lowest impact in marine eutrophication and water consumption (two to three times lower impact), as well as in the stratospheric ozone depletion, terrestrial ecotoxicity, and human non-carcinogenic toxicity (around 50% less impact).

German pea cultivation shows the highest impact in global warming, ozone formation (human health and terrestrial ecosystems), fine particulate matter formation, terrestrial acidification, freshwater ecotoxicity, human carcinogenic and non-carcinogenic toxicity, mineral resource scarcity, and fossil resource scarcity impact categories. German pea cultivation has a higher yield than that of Canada (4.14 ton/ha compared to 3.87 ton/ha), and also uses a higher quantity of pesticides (5.35E-04 kg/kg compared to 2.71E-04 kg/kg). In a similar way, French pea cultivation shows the highest impact in stratospheric ozone depletion, ionizing radiation, marine eutrophication, terrestrial ecotoxicity, marine ecotoxicity, and water consumption impact categories. French pea cultivation also has higher yields (4.04 ton/ha) than Canadian but uses a more fertilizer per kg of harvested pea (5.61E-02 kg compared to 2.48E-02 kg). Canadian-cultivated peas can be regarded as a low-impact feedstock when compared to other agricultural geographies.

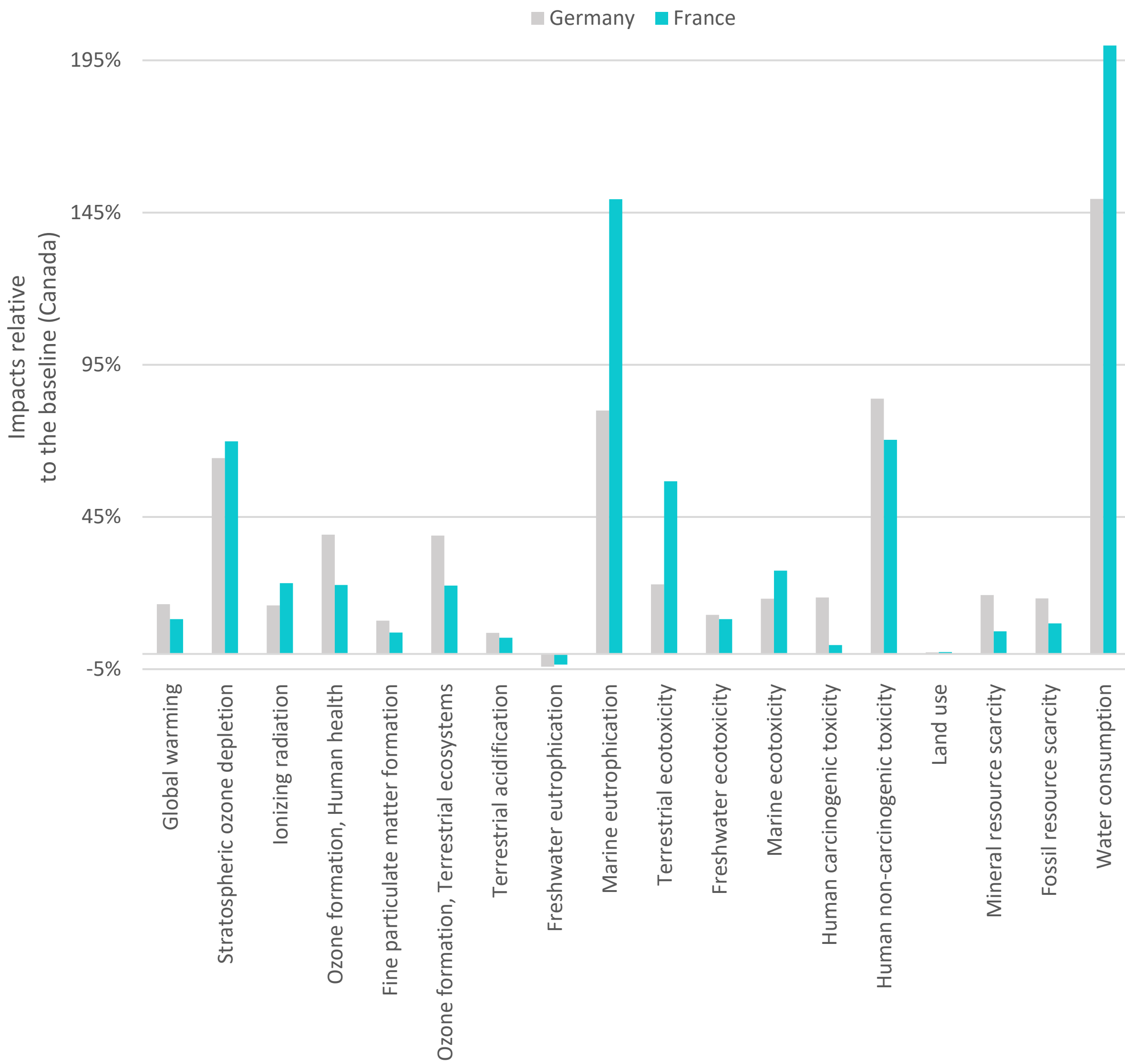

Figure 6-6. Sensitivity analysis, crop geography (comparison of relative shift per impact category), comparison of life cycle impacts for System #1. 1 kg of ground food with meat or meat alternatives ready to be cooked, from cradle-to-manufacturing gate, before packaging or cooling. Pea cultivation in Canada (baseline), Germany, and France. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-46. Note: The formula used for the plotted results is:

$$Impacts\ relative\ to\ baseline = \left(\left(\frac{Scenario_n\ impacts}{Baseline\ impacts}\right) - 1\right) \times 100\%$$

Figure 6-7 explores the same three cultivation geographies (Canada, Germany, and France) explored for System #2. This sensitivity scenario shows the same trends as for System #1, in which Canadian-cultivated peas (baseline scenario) only show as the highest impact source in freshwater eutrophication. This effect on crop geography is lower than in System #1 due to System #1 having a higher contribution from the agricultural stage (higher feedstock consumption).

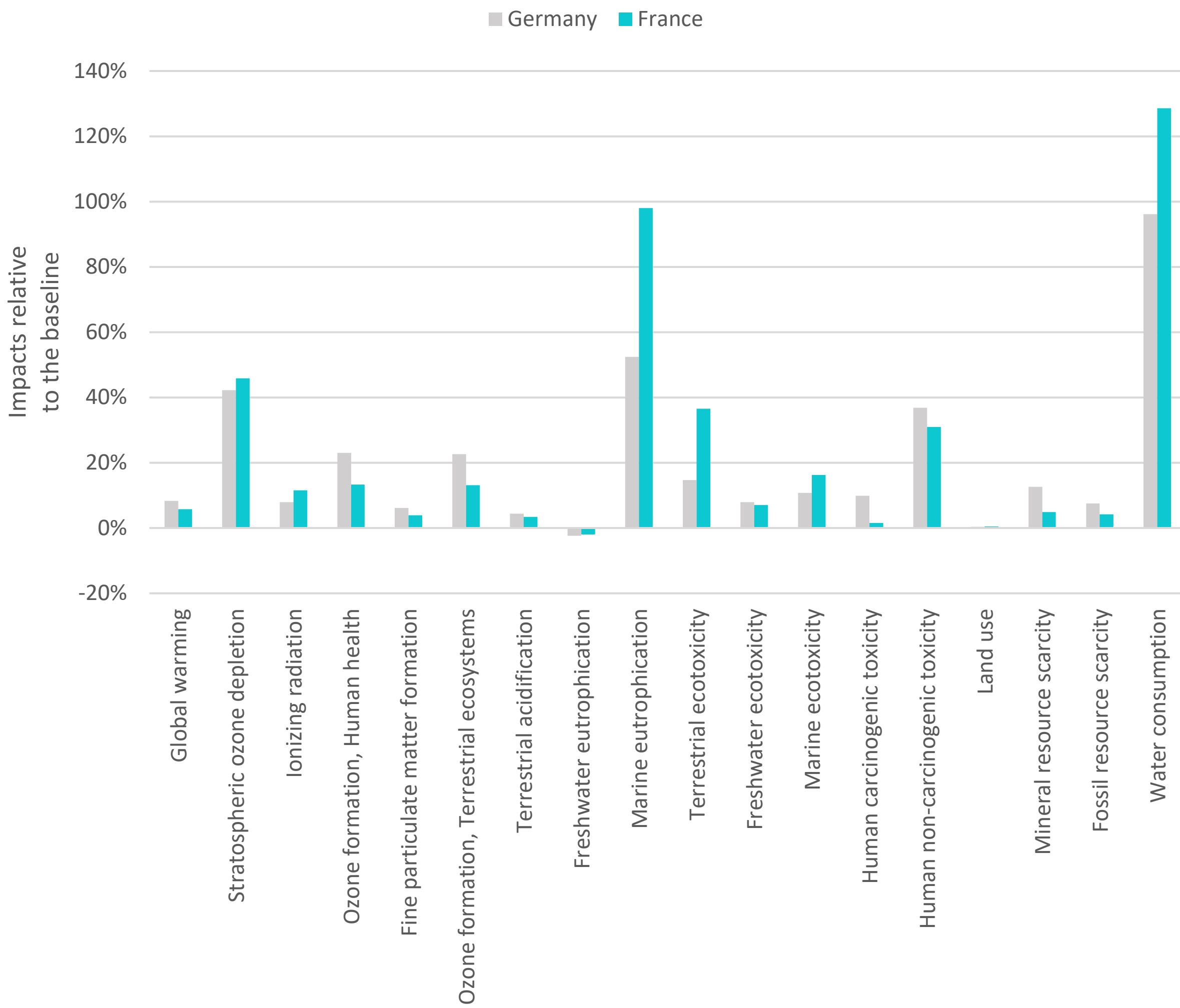

Figure 6-7. Sensitivity analysis, crop geography (comparison of relative shift per impact category), comparison of life cycle impacts for System #2. 1 kg of ground food with meat or meat alternatives ready to be cooked, from cradle-to-manufacturing gate, before packaging or cooling. Pea cultivation in Canada (baseline), Germany, and France. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-47. Note: The formula used for the plotted results is:

$$Impacts\ relative\ to\ baseline = \left(\left(\frac{Scenario_n\ impacts}{Baseline\ impacts}\right) - 1\right) \times 100\%$$

Figure 6-8 shows the effect of exploring different soybean crop geographies (the U.S., Canada, and Brazil). Canada and Brazil were chosen because of data availability in the ecoinvent 3.9.1 database. Soybeans from the U.S. have higher impacts on stratospheric ozone depletion, ionizing radiation, ozone formation—human health, land use, and fossil resource scarcity. Canadian soybeans have similar impacts to those from the U.S. (except for freshwater and marine eutrophication), and Brazilian soybeans show the highest impacts for global warming, ozone formation—human health and terrestrial ecosystems, fine particulate matter formation, terrestrial acidification, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human non-carcinogenic toxicity, mineral resource scarcity, and water consumption.

There is a considerable difference between U.S. and Brazilian soybean cultivation in terrestrial and marine ecotoxicity (two times higher impacts for the Brazilian soybeans), as well as in freshwater ecotoxicity and water consumption (10 times higher for the Brazilian soybeans). Despite showing higher agricultural yields (3.35 ton/ha compared to 3.06 ton/ha for the U.S. system and 2.93 ton/ha for the Canadian), Brazilian cultivation of soybeans involves more land use change-related CO_2 emissions, higher use of pesticides (causing direct emissions of triflumuron, glyphosate, chlorpyrifos, lambda-cyhalothrin, acephate, among others), and higher water consumption (4.13E-01 m^3/kg). Brazilian soybean cultivation uses vast amounts of water for pesticide dilution.

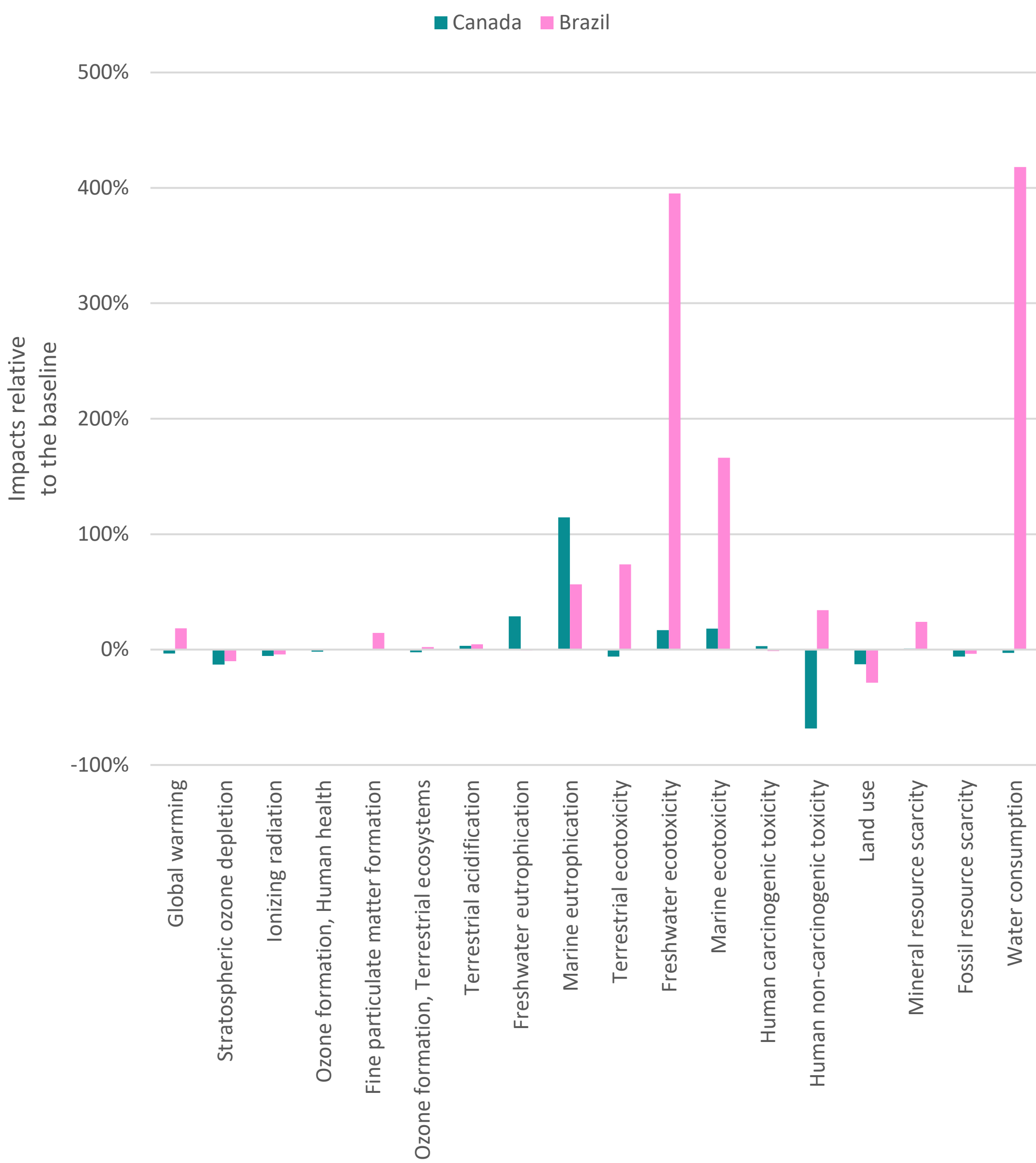

Figure 6-8. Sensitivity analysis, crop geography (comparison of relative shift per impact category), comparison of life cycle impacts for System #3. 1 kg of ground food with meat or meat alternatives ready to be cooked, from cradle-to-manufacturing gate, before packaging or cooling. Soybean cultivation in the U.S. (baseline), Canada, and Brazil. Method: ReCiPe 2016 Midpoint (H) V1.03. Data table available in Table A-48. Note: The formula used for the plotted results is:

$$Impacts\ relative\ to\ baseline = \left(\left(\frac{Scenario_n\ impacts}{Baseline\ impacts}\right) - 1\right) \times 100\%$$

6.1.4 Summary

Plant-based meat recipes consistently show lower impacts than animal-based meat recipes in all impact categories but one: freshwater ecotoxicity. On average, plant-based meat recipes cause 62% lower potential environmental impacts than animal-based meat recipes. The System #3 recipe (soybean, WF, HME) sourced from Brazilian soybeans can cause 67% more impacts in the freshwater ecotoxicity category than baseline chicken meat, the lowest impact animal-based meat product, due to the pesticide-related heavy metal emissions in the agricultural cultivation stage. It is important to note that soybeans for human food are not typically sourced from Brazil, which primarily produces soybeans for animal feed.

Baseline chicken meat (based on mass allocation criteria) is the lowest impact animal-based scenario for all impact categories, except for water consumption, the category for which baseline beef meat shows the lowest impact. In the case of plant-based meat recipes, most of the highest impact scenarios reflect changes in the crop geography (17 impact categories): switching to German peas represents the highest impacts in nine different categories (global warming, ozone formation—human health and terrestrial ecosystems, fine particulate matter formation, terrestrial acidification, human carcinogenic toxicity, land use, mineral resource scarcity, and fossil resource scarcity), while the supply of French peas is associated with the highest impacts in stratospheric ozone depletion, ionizing radiation and marine eutrophication. Switching to Brazilian soybeans shows the highest impacts in the remaining five categories: terrestrial, freshwater, and marine ecotoxicity, human non-carcinogenic toxicity, and water consumption. Finally, System #2 has the highest impact scenarios in the most categories (eight), while both Systems #1 and #3 have each the highest impact scenarios in five categories.

6.2 Uncertainty analysis

6.2.1 Monte Carlo simulation

This study performed a Monte Carlo simulation in SimaPro using 1,000 runs to test the uncertainty in each of the plant-based systems compared to the conventional systems. There are many sources of uncertainty in LCI data, including the sources and methods for collecting data, temporal and geographic representativeness, best-case estimations and assumptions when identifying gaps in data, parameter uncertainty (different input parameters, e.g., energy and material consumption, agricultural practices, material composition), and market dynamics associated with technological development.

Data quality for foreground data (i.e., primary data) was assessed using the Pedigree Matrix Approach and data quality scores were assigned to upstream inventories to generate a standard deviation for a Monte Carlo analysis. Data quality scores for background data were obtained from ecoinvent 3.9.1 and were not modified. For each of the 1,000 Monte Carlo runs, the difference between each plant-based meat system and the three animal-based meat systems was calculated for each of the 18 impact categories. Violin plots (Figure 6-8) display the resulting probability distribution of the fold-change between each of the plant-based meat systems and the three animal-meat systems. As shown in Figure 6-9, the colored center represents that, given the uncertainty of the input data, the impact result has a 50% probability of landing within this range. The outer shape represents 95% of the results.

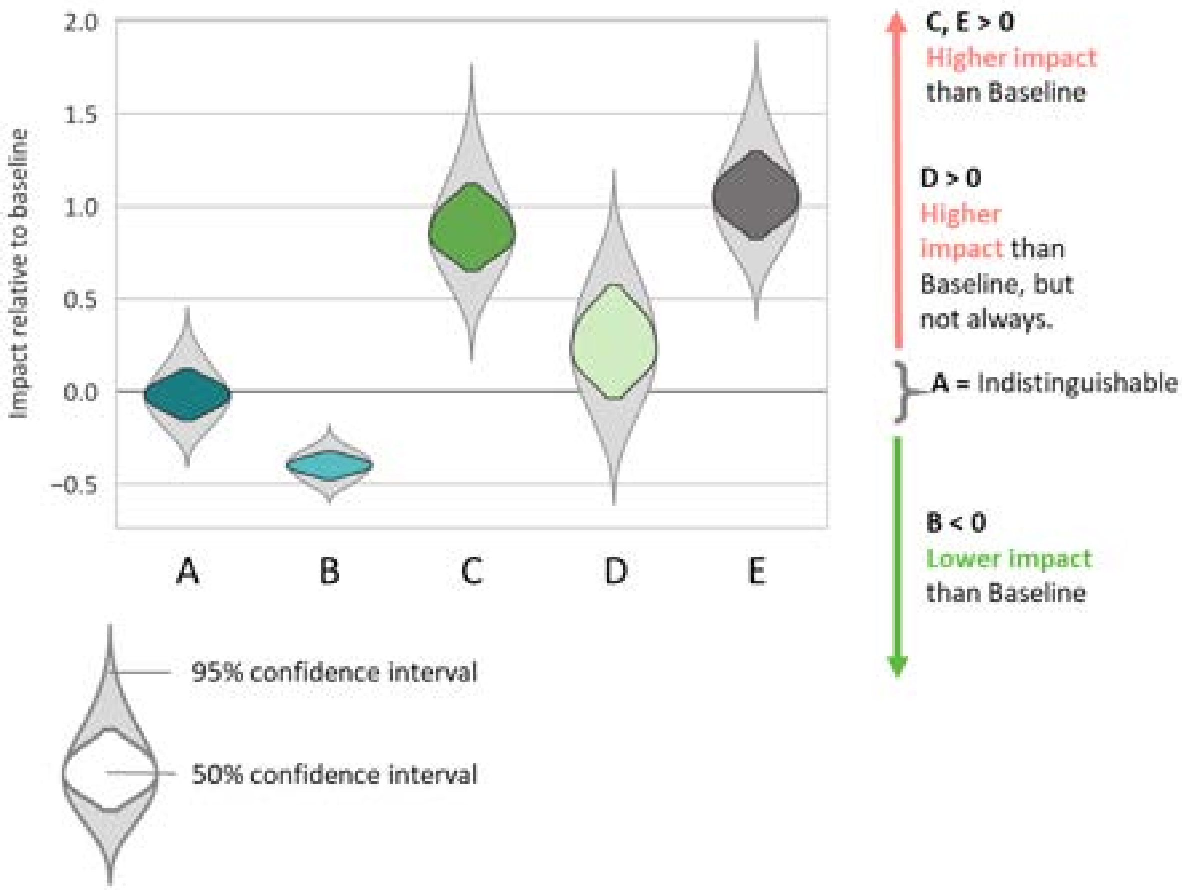

Figure 6-9. How to read these violin plots: If the plot for a given system is completely above the index line (the baseline plant-based meat product), then that animal-based meat product can be said to have higher impacts than the baseline, and the magnitude of the increased impacts can be gauged by reading the Y-axis. If the violin plot is completely below the index line, that animal-based meat product has lower impacts than the baseline. If there is significant overlap between the violin plot and the index line, then the results are too uncertain to determine that one animal-based meat product has lower or higher impacts than the comparative plant-based meat product.

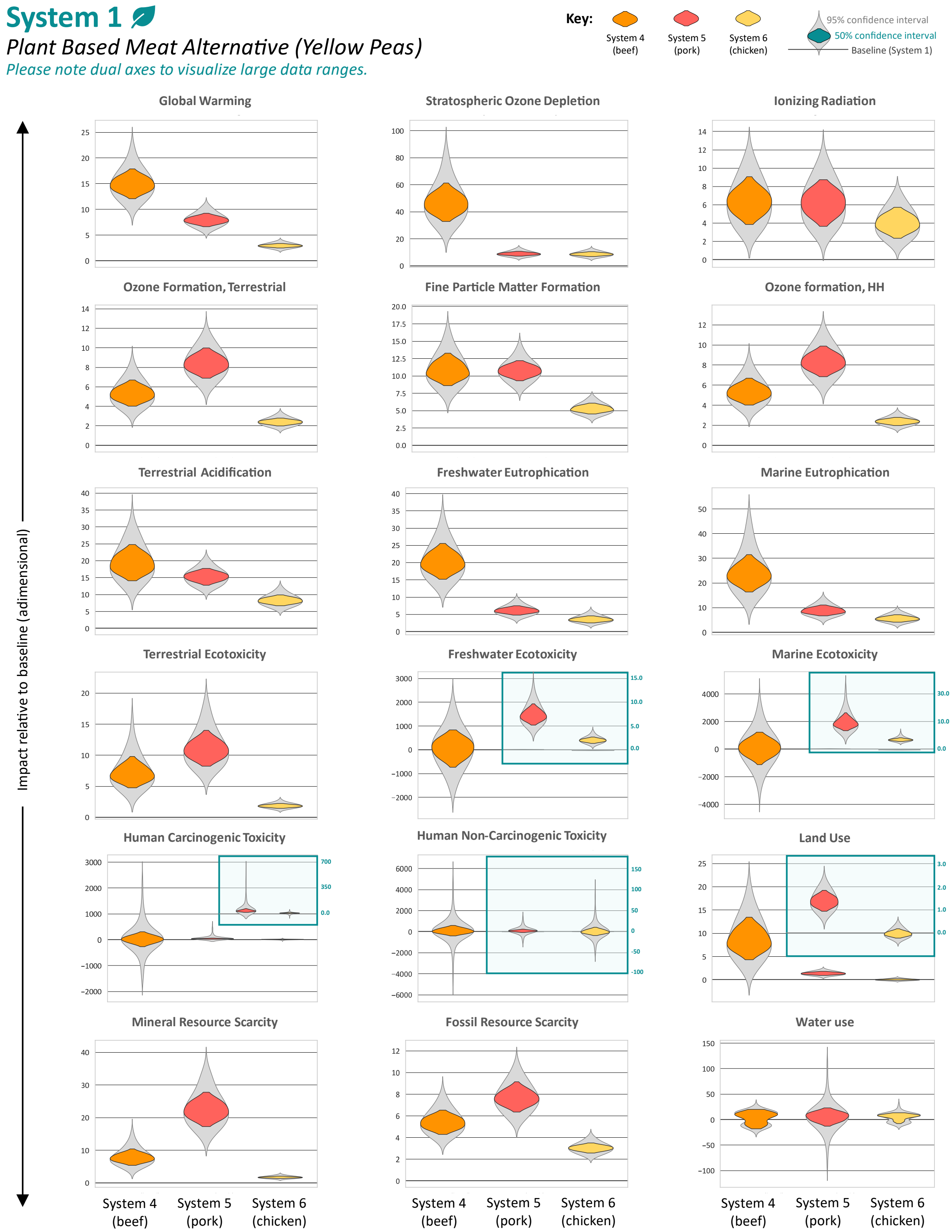

Figure 6-10. Violin plots, baseline: System #1 (peas, DF, LME). Reference: Functional Unit.

The violin plots show that the plant-based meat recipe from System #1 (pea, DF, LME) has consistently lower impacts than animal-based meat products (Systems #4–6) in global warming, stratospheric ozone depletion, ionizing radiation, ozone formation—human health and terrestrial ecosystems, fine particulate matter formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, mineral resource scarcity, and fossil resource scarcity. The human carcinogenic toxicity, human non-carcinogenic toxicity, and water consumption impact categories show a high uncertainty; therefore, for these impact categories, the violin plots show it cannot be claimed that the System #1 recipe is better or worse than the System #4, #5, or #6 recipes. Water consumption and toxicity-related impact categories usually show significant uncertainty ranges in LCA due to the high levels of uncertainty surrounding the LCI modeling of elementary flows with high contributions to these impact categories. In this study, the wide uncertainty ranges for the aforementioned categories were traced back to the initial feedstock agricultural cultivation datasets, which are taken directly from the ecoinvent 3.9.1 database. Also, the majority of elementary flows included in these impact categories show elevated uncertainty DQI within their individual Pedigree matrix.

System #4 (beef) shows high uncertainty values for the freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, and human non-carcinogenic toxicity, while System #5 (pork) shows a similar pattern in human non-carcinogenic toxicity and water consumption, and System #6 (chicken) in the case of human non-carcinogenic toxicity.

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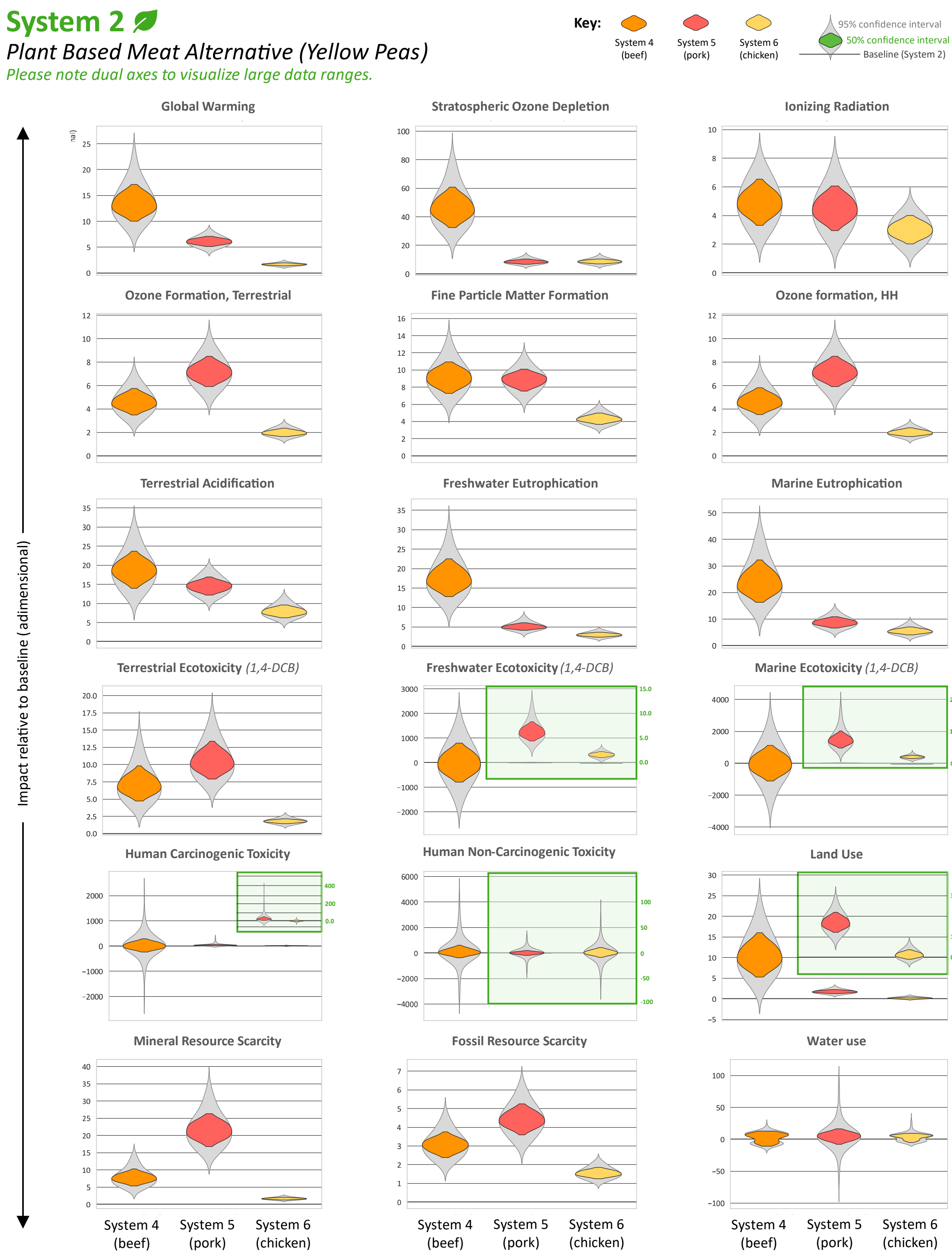

Figure 6-11. Violin plots, baseline: System #2 (peas, WF, HME). Reference: Functional Unit.

The violin plots show that the plant-based meat recipe from System #2 (pea, WF, HME) has consistently lower impacts than animal-based meat products (Systems #4–6) in global warming, stratospheric ozone depletion, ionizing radiation, ozone formation—human health and terrestrial ecosystems, fine particulate matter formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, mineral resource scarcity, and fossil resource scarcity. Similar to the violin plots for System #1, the freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, and water consumption impact categories show high ranges of uncertainty, therefore the violin plots show it cannot be claimed that the System #2 recipe is better or worse than animal-based meat products (except for the freshwater and marine ecotoxicity impact categories when compared to Systems #5 and #6 only).

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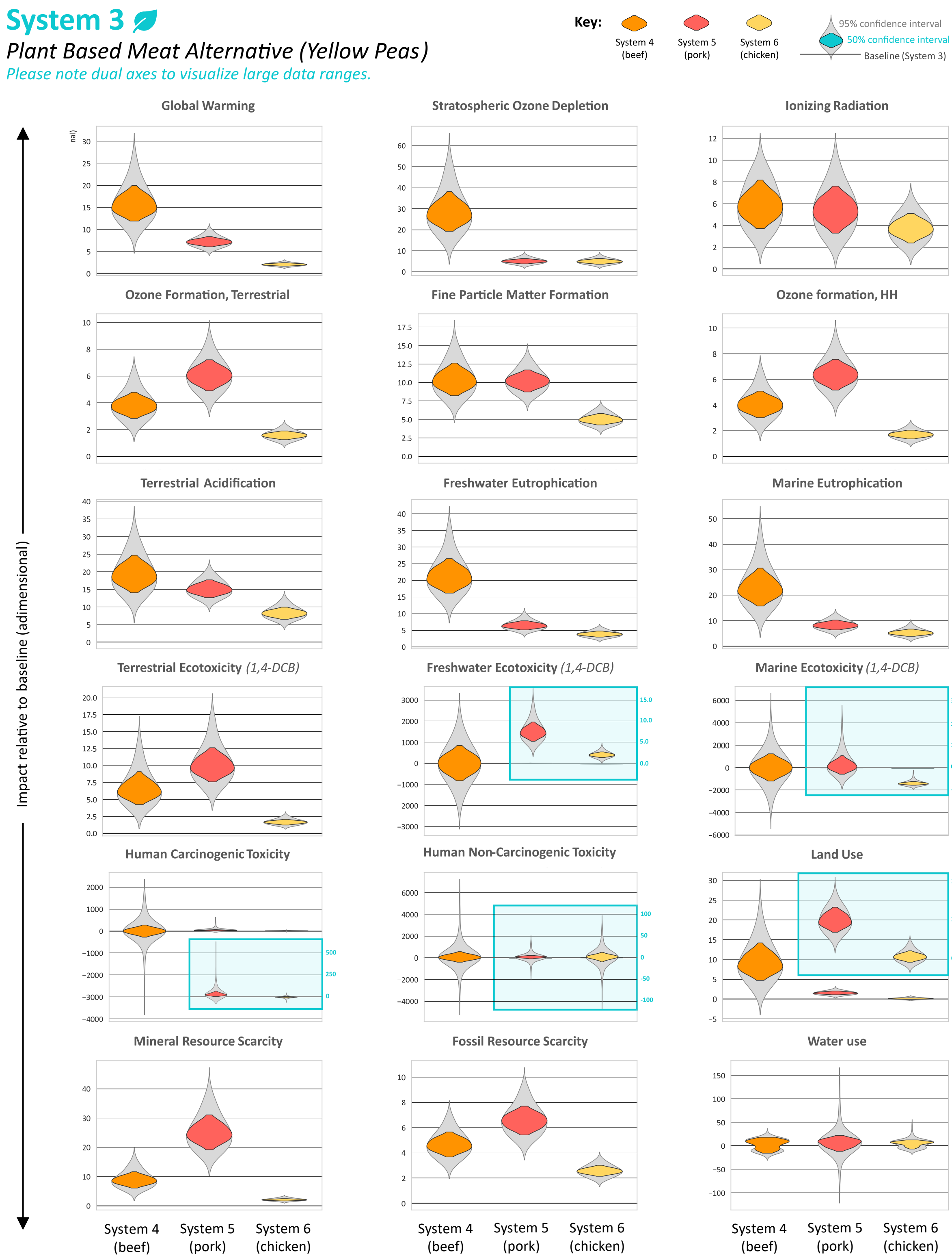

Figure 6-12. Violin plots, baseline: System #3 (soybean, WF, HME). Reference: Functional Unit.

The violin plots show that the plant-based meat recipe from System #3 (soy, WF, HME) has consistently lower impacts than animal-based meat products (Systems #4–6) in global warming, stratospheric ozone depletion, ionizing radiation, ozone formation—human health and terrestrial ecosystems, fine particulate matter formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, mineral resource scarcity, and fossil resource scarcity. The freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, and water consumption impact categories show a high uncertainty, therefore the violin plots show it cannot be claimed that the System #3 recipe is better or worse than animal-based meat products.

6.3 Limitations and quality check

6.3.1 Completeness and consistency

The inventory for raw materials production and manufacturing of all systems and processes derives from primary data and literature. Background inventory for materials, electricity, heat, and water is available in reviewed and published databases. The inventory includes all components of the product to ensure completeness and consistency.

6.3.2 Limitations

When interpreting the results of an LCA, it is important to consider the limitations of the methods and data used to provide a proper context for the study results. The ability of an LCA to consider the entire life cycle of a product makes it an attractive tool to assess potential environmental impacts. Nevertheless, like other environmental management analysis tools, an LCA has several limitations related to data quality and unavailability of potentially relevant data. Furthermore, an LCA is based on a linear extrapolation of emissions with the assumption that all the emissions contribute to an environmental effect. This is contrary to threshold-driven environmental and toxicological mechanisms. Thus, while linear extrapolation may be a reasonable approach for more global and regional impact categories such as Global Warming Potential and acidification, it may not accurately represent the human- and ecotoxicity-related impacts.

To include multiple datasets and create a recipe representative of commercially available products, the LCA results for Systems #1–3 are based on hypothetical recipes. As a result, the provided nutrient contents were calculated based on the cumulative nutrition of each recipe's individual ingredients. This is a reasonable estimation of each end product's nutritional facts, but for more accurate nutrition information, the hypothetical meat products would have to be prepared and have their nutritional profiles measured.

Even if a study has been critically reviewed, the impact assessment results are relative expressions and do not predict impacts on category midpoints (e.g., categories used through the report such as global warming, freshwater eutrophication) and endpoints (e.g., human health, wildlife species), the exceedance of thresholds, or risks.

Another limitation of the LCA framework is in the gaps of characterization factors for impact assessment and these gaps tend to be greater in toxicity-related categories. Not all elementary flows will be reflected in the midpoint results.

In this study, the main limitation lies in the representativeness of the primary data. Since these plant-based meat systems and processes have only recently been developed, a limited amount of data were available to build the LCI.

There is a lot of variation in agricultural practices (amount of pesticides and herbicides, and tillage practices) between countries, and even from farm to farm, which can affect the environmental impacts of those crops. Moreover, Poore and Nemecek (2018) pointed out that there is a huge variability on environmental impacts when it comes to cattle rearing systems. Data used for the cultivation stage of the soybean, pea, and conventional meat systems are background data available in ecoinvent and the World Food Database, which represents only a fraction of the cultivation practices and rearing systems.

7. Conclusions and recommendations

This study explores the life cycle impacts of three plant-based meat recipes (based on meat extrudates sourced from different crops and technologies) and compares them to three conventional animal-based meat products in a Midwest U.S. context. The following sections summarize the key findings for both kinds of products.

7.1 Conclusions

Plant-based meat recipes (Systems #1–3) showed consistently lower environmental impacts (89% on average) than animal-based meat recipes across most impact categories. This conclusion is supported by the findings from the uncertainty analysis, which show that plant-based meat recipes have lower global warming, stratospheric ozone depletion, ionizing radiation, ozone formation—human health and terrestrial ecosystems, fine particulate matter formation, terrestrial acidification, freshwater and marine eutrophication, terrestrial ecotoxicity, mineral, and fossil resource scarcity impacts within a 95% confidence interval. However, only certain plant-based systems have lower freshwater and marine ecotoxicity and land use impacts than animal-based systems, and no conclusion can be reached for the human carcinogenic and non-carcinogenic toxicity and water consumption impact categories. When this comparison is expanded to include all plant-based scenarios (energy source, allocation approach, and crop geography), this conclusion remains consistent, since animal-based meat recipes showed higher environmental impacts in most of the categories in all scenarios. Considering a conservative approach in which the highest impact plant-based meat recipe is compared directly to the lowest impact animal-based meat recipe, plant-based products showed an average of 49% lower impacts in all categories, except for terrestrial ecotoxicity and land use.

System #2, based on pea protein isolate obtained through wet fractionation that undergoes high moisture extrusion, is the plant-based meat recipe with the highest impacts in 11 of 18 categories. The highest contribution to overall extruded meat impacts comes from the wet fractionation process, more specifically by its high electricity and heat demands for mixing and spray drying. Also, its elevated water demand during the high moisture extrusion process is identified as the hotspot for water consumption. Meanwhile, System #3, based on soy protein concentrate obtained through wet fractionation that undergoes high moisture extrusion, shows the highest impacts in 6 of 18 categories; the soybean cultivation stage is identified as the impact hotspot for these categories. Finally, System #1, based on pea protein concentrate obtained through dry fractionation that undergoes low moisture extrusion, has the highest land use impacts caused by its high consumption of agricultural feedstock.

The contribution and sensitivity analyses show that the plant-based meat analogues' main feedstock (crop and country of cultivation) heavily influences their overall environmental performance. Also, the source of electricity consumed by the different fractionation and extrusion processes has a considerable effect on the plant-based meat environmental impacts. Since most of these technologies and processes are of recent creation (particularly for the pea-sourced systems), there is room for optimization and improvement.

Finally, the environmental impacts from the complementary ingredients (coconut oil, canola oil, potato starch, spices) of the plant-based meat recipes should be considered. Even though they represent less than half of the meat recipe weight, they show considerable impacts in certain categories (and were even identified as top contributors). Particularly, coconut oil stands as a high-impact ingredient since its upstream feedstock production increases impacts related to land use change and other related agricultural impacts. Future efforts must be invested in assessing the environmental impacts of these ingredients and their possible replacements.

7.2 Recommendations

- Explore energy consumption improvements for fractionation and extrusion processes, particularly for spray drying in the case of wet fractionated pea.
- Optimize the overall efficiency of soy extrudate production to reduce its consumption of soybeans as feedstock.
- Promote a transition in the manufacturing processes and technologies to renewable energy sources.
- Assess alternatives for complementary ingredients in the plant-based meat recipes in terms of their suitability to the recipe and their environmental performance.
- The boundaries established for this study are cradle-to-manufacturing gates. However, packaging, storage, distribution, and the associated requirements and cooking stage, can have an important contribution to the environmental impacts of the plant-based and meat systems. Future studies should expand the scope to account for those impacts and better understand the environmental impacts of the whole supply chain.

A. Appendix

A.1 LCI documentation

Table A-1. Number of sources per system, industry data.

System	Process	Number of Industry Data Sources
System 1	Dry Fractionation	2
	Low Moisture Extrusion	2
System 2	Wet Fractionation	1
	High Moisture Extrusion	2
System 3	Wet Fractionation	2
	High Moisture Extrusion	3

Table A-2. Datasets used in modeling.

Material	Dataset	Notes
Transport	Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| market for transport, freight, lorry 7.5-16 metric ton, EURO5 | Cut-off, U	
Water, for human consumption	Water {GLO}| market group for water | Cut-off, U	
Electricity, medium voltage	Electricity, medium voltage {MRO, US only}| market for electricity, medium voltage | Cut-off, U	
Heat, from natural gas	Heat, central or small-scale, natural gas {GLO}| market group for heat, central or small-scale, natural gas | Cut-off, U	
Peas	Protein pea {CA-MB}| protein pea production | Cut-off, U	
Soy white flakes	Soybean meal {US}| soybean meal and crude oil production | Cut-off, U - ESG	Modified dataset to account for production of soybean oil and soybean meal using documentation data.

		Modified dataset consumptions to account for common transport, water, electricity, and heat from natural gas
Evaporation/Moisture	Water, emission to air	Elementary flow
Impurities/Lost/Various organic wastes	Biowaste {CH}| market for biowaste | Cut-off, U	
Wastewater	Wastewater, average {CA-QC}| treatment of wastewater, average, wastewater treatment | Cut-off, U	
Steam, input	Steam, in chemical industry {RER}| steam production, in chemical industry | Cut-off, U	
Sodium hydroxide (NaOH)	Sodium hydroxide, without water, in 50% solution state {GLO}| market for sodium hydroxide, without water, in 50% solution state | Cut-off, U	
Hydrochloric acid (HCl)	Hydrochloric acid, without water, in 30% solution state {US}| zirconium and hafnium tetrachloride production, from zircon | Cut-off, U	
Ethanol, input	Ethanol, without water, in 95% solution state, from fermentation {US}| ethanol production from maize | Cut-off, U	
Ethanol, output	Ethanol, emission to air	Elementary flow
Canola oil	Rapeseed oil, at oil mill (WFLDB)/CA U	
Coconut oil	Crude coconut oil, market mix, at regional storage {US} Economic, U	
Potato starch	Potato starch {GLO}| market for potato starch | Cut-off, U	
Wheat gluten	Wheat gluten {US} ESG	

Table A-3. Spices own-created dataset.

Ingredient	Consumption	Unit	Dataset
1 kg of Spices {US} ESG			
Inputs			
Glutamic acid	0.08	kg	S-glutamic acid, at plant (WFLDB)/GLO U

Salt	0.08	kg	Salt {GLO}| market for salt | Cut-off, U
Yeast	0.28	kg	Protein feed, 100% crude {GLO}| fodder yeast to generic market for protein feed | Cut-off, U
Dried shiitake	0.28	kg	Shiitake mushroom production, fresh, at plant (WFLDB)/CN U
Citric acid	0.28	kg	Citric acid {GLO}| market for citric acid | Cut-off, U

A.2 Baseline results

Table A-4. Life cycle impacts for producing 1 kg of plant-based meat recipe from peas, DF, LME, pea-sourced, System #1. Contribution of ingredients. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	Total	Extruded meat analogue, LME, DF, pea	Water	Wheat gluten	Coconut oil	Canola oil	Potato starch	Spices	Transport
Global warming	kg CO2 eq	7.47E-01	2.13E-01	4.64E-04	8.73E-03	2.83E-01	7.77E-02	5.17E-02	1.10E-01	2.28E-03
Stratospheric ozone depletion	kg CFC11 eq	2.47E-06	1.08E-07	2.77E-10	5.71E-08	5.62E-07	1.06E-06	3.20E-07	3.52E-07	1.18E-09
Ionizing radiation	kBq Co-60 eq	2.28E-02	1.40E-02	4.97E-05	7.04E-04	1.27E-03	1.41E-03	1.50E-03	3.80E-03	4.43E-05
Ozone formation, Human health	kg NOx eq	1.46E-03	3.54E-04	1.18E-06	3.25E-05	2.83E-04	3.04E-04	2.11E-04	2.71E-04	6.54E-06
Fine particulate matter formation	kg PM2.5 eq	1.59E-03	6.02E-04	9.24E-07	2.41E-05	3.26E-04	3.12E-04	1.23E-04	1.99E-04	1.84E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.51E-03	3.74E-04	1.21E-06	3.32E-05	2.82E-04	3.14E-04	2.17E-04	2.77E-04	7.01E-06

Terrestrial acidification	kg SO2 eq	4.24E-03	6.25E-04	1.61E-06	6.73E-05	2.86E-04	2.09E-03	5.61E-04	6.05E-04	4.10E-06
Freshwater eutrophication	kg P eq	3.76E-04	2.15E-04	2.10E-07	1.08E-05	5.60E-05	2.00E-05	3.49E-05	3.84E-05	1.68E-07
Marine eutrophication	kg N eq	7.59E-04	1.24E-05	2.01E-08	2.36E-05	1.58E-04	3.84E-04	1.11E-04	6.95E-05	6.08E-08
Terrestrial ecotoxicity	kg 1,4-DCB	1.91E+00	4.17E-01	1.32E-03	6.02E-02	3.26E-01	1.07E-01	4.45E-01	5.22E-01	3.01E-02
Freshwater ecotoxicity	kg 1,4-DCB	3.47E-02	9.96E-03	1.82E-05	3.88E-03	9.25E-03	1.06E-03	5.05E-03	5.44E-03	5.03E-05
Marine ecotoxicity	kg 1,4-DCB	3.25E-02	1.33E-02	2.48E-05	1.19E-03	5.10E-03	1.49E-03	4.64E-03	6.74E-03	8.36E-05
Human carcinogenic toxicity	kg 1,4-DCB	2.94E-02	1.54E-02	2.17E-04	6.52E-04	3.59E-03	1.12E-03	3.40E-03	4.89E-03	1.08E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	4.64E-01	-1.82E-01	4.37E-04	2.81E-02	-1.27E-03	3.54E-01	1.33E-01	1.29E-01	1.60E-03
Land use	m2a crop eq	2.20E+00	8.80E-01	8.65E-06	1.76E-02	7.66E-01	3.59E-01	5.23E-02	1.23E-01	7.87E-05
Mineral resource scarcity	kg Cu eq	2.12E-03	8.50E-04	3.37E-06	2.32E-04	1.26E-04	1.50E-04	3.56E-04	4.00E-04	5.37E-06
Fossil resource scarcity	kg oil eq	1.24E-01	5.93E-02	1.13E-04	2.09E-03	1.59E-02	1.15E-02	1.13E-02	2.27E-02	7.09E-04
Water consumption	m3	1.79E-02	1.21E-03	5.09E-04	3.75E-03	1.85E-04	5.70E-04	8.78E-03	2.92E-03	4.53E-06

Table A-5. Life cycle impacts for producing 0.283 kg of extruded meat analogue from peas, DF, LME, pea-sourced, System #1. Contribution of main stages. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	Total	Pea Cultivation	Dry Fractionation	Low Moisture Extrusion
Global warming	kg CO2 eq	2.13E-01	3.20E-02	1.27E-01	5.43E-02
Stratospheric ozone depletion	kg CFC11 eq	1.08E-07	4.50E-08	4.92E-08	1.39E-08
Ionizing radiation	kBq Co-60 eq	1.40E-02	1.19E-03	9.99E-03	2.82E-03
Ozone formation, Human health	kg NOx eq	3.54E-04	1.35E-04	1.57E-04	6.15E-05
Fine particulate matter formation	kg PM2.5 eq	6.02E-04	7.74E-05	4.10E-04	1.14E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.74E-04	1.42E-04	1.66E-04	6.64E-05
Terrestrial acidification	kg SO2 eq	6.25E-04	2.46E-04	2.85E-04	9.42E-05
Freshwater eutrophication	kg P eq	2.15E-04	6.74E-05	1.16E-04	3.12E-05
Marine eutrophication	kg N eq	1.24E-05	2.54E-06	7.75E-06	2.08E-06
Terrestrial ecotoxicity	kg 1,4-DCB	4.17E-01	2.71E-01	1.01E-01	4.47E-02
Freshwater ecotoxicity	kg 1,4-DCB	9.96E-03	4.28E-03	4.41E-03	1.27E-03
Marine ecotoxicity	kg 1,4-DCB	1.33E-02	5.67E-03	5.89E-03	1.70E-03
Human carcinogenic toxicity	kg 1,4-DCB	1.54E-02	5.20E-03	7.82E-03	2.43E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	-1.82E-01	-3.59E-01	1.39E-01	3.83E-02
Land use	m2a crop eq	8.80E-01	8.77E-01	1.55E-03	5.40E-04
Mineral resource scarcity	kg Cu eq	8.50E-04	6.82E-04	1.20E-04	4.77E-05
Fossil resource scarcity	kg oil eq	5.93E-02	8.40E-03	3.49E-02	1.60E-02
Water consumption	m3	1.21E-03	1.85E-04	7.50E-04	2.78E-04

Table A-6. Life cycle impacts for producing 1.748 kg of fresh peas, pea-sourced, System #1. Contribution of agricultural cultivation and transportation to facilities stage. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03. Results directly exported from ecoinvent 3.9.1 dataset "Protein pea {CA-MB}| protein pea production | Cut-off, U"

Impact category	Unit	Total	Direct land use and field emissions	Ammonium sulfate	Application of plant protection product	Combine harvesting	Drying of protein pea	Glyphosate	Monoammonium phosphate	Pea seed, for sowing	Peat moss	Pesticide, unspecified	Potassium chloride	Sowing	Sulfur	Tillage, harrowing, by rotary harrow	Tillage, rolling	Tillage, rotary cultivator	Zinc	Transport to facilities
Global warming	kg CO2 eq	3.20E-02	1.27E-03	6.05E-05	1.40E-03	5.29E-03	1.54E-05	3.96E-04	5.38E-03	1.00E-05	2.88E-04	5.95E-04	1.11E-03	1.30E-03	2.44E-05	3.00E-03	1.09E-03	6.67E-03	9.79E-06	4.06E-03
Stratospheric ozone depletion	kg CFC11 eq	4.50E-08	3.37E-08	1.86E-11	5.27E-10	1.54E-09	1.16E-11	1.73E-10	1.28E-09	1.12E-10	4.66E-12	1.84E-09	4.52E-10	4.13E-10	7.85E-12	7.95E-10	3.17E-10	1.75E-09	5.51E-12	2.11E-09
Ionizing radiation	kBq Co-60 eq	1.19E-03	0.00E+00	4.33E-06	3.79E-06	1.75E-04	2.56E-07	3.45E-05	4.18E-04	3.13E-07	1.23E-06	3.67E-05	4.18E-05	2.65E-05	8.97E-08	1.03E-04	2.91E-05	2.33E-04	1.86E-06	7.90E-05
Ozone formation, Human health	kg NOx eq	1.35E-04	0.00E+00	2.11E-07	1.57E-05	2.95E-05	2.45E-08	9.44E-07	1.49E-05	4.77E-08	6.02E-08	1.63E-06	4.31E-06	9.94E-06	5.37E-08	1.25E-05	6.51E-06	2.70E-05	5.40E-08	1.17E-05
Fine particulate matter formation	kg PM2.5 eq	7.75E-05	1.54E-05	1.91E-07	5.68E-06	1.27E-05	2.27E-08	6.66E-07	9.16E-06	1.79E-08	2.92E-08	1.66E-06	1.98E-06	2.84E-06	7.07E-07	6.44E-06	2.37E-06	1.44E-05	2.12E-08	3.27E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.42E-04	0.00E+00	2.18E-07	1.60E-05	3.09E-05	2.54E-08	9.87E-07	1.56E-05	4.89E-08	6.18E-08	1.70E-06	4.47E-06	1.03E-05	5.73E-08	1.33E-05	6.79E-06	2.88E-05	5.48E-08	1.25E-05
Terrestrial acidification	kg SO2 eq	2.46E-04	1.26E-04	5.94E-07	6.73E-06	2.62E-05	6.12E-08	1.29E-06	2.03E-05	4.05E-08	5.25E-08	4.55E-06	4.54E-06	5.78E-06	2.42E-06	1.13E-05	4.46E-06	2.51E-05	5.99E-08	7.31E-06
Freshwater eutrophication	kg P eq	6.75E-05	5.70E-05	4.39E-08	4.60E-08	2.41E-06	5.50E-09	5.21E-07	1.76E-06	4.16E-09	5.42E-09	3.30E-07	3.86E-07	3.42E-07	1.31E-09	1.19E-06	3.54E-07	2.74E-06	1.14E-08	2.99E-07
Marine eutrophication	kg N eq	2.54E-06	1.24E-06	3.01E-08	2.73E-08	1.92E-07	2.33E-10	3.53E-08	2.44E-07	7.03E-08	4.29E-10	1.89E-07	3.39E-08	3.73E-08	5.05E-10	9.24E-08	3.19E-08	2.11E-07	6.66E-10	1.09E-07
Terrestrial ecotoxicity	kg 1,4-DCB	2.72E-01	6.49E-03	3.53E-03	2.06E-03	6.34E-02	2.77E-04	1.78E-03	3.92E-02	9.51E-05	7.05E-05	3.19E-03	1.39E-02	6.58E-03	7.57E-05	2.15E-02	6.51E-03	4.88E-02	4.05E-04	5.38E-02
Freshwater ecotoxicity	kg 1,4-DCB	4.28E-03	1.96E-03	2.74E-05	6.69E-06	7.71E-04	5.50E-06	1.92E-05	3.79E-04	6.68E-07	6.85E-07	3.86E-05	1.23E-04	7.24E-05	1.88E-07	2.20E-04	6.50E-05	5.00E-04	8.90E-06	8.97E-05
Marine ecotoxicity	kg 1,4-DCB	5.68E-03	2.59E-03	3.68E-05	1.02E-05	1.00E-03	6.83E-06	2.37E-05	4.96E-04	1.04E-06	8.98E-07	4.13E-05	1.62E-04	9.57E-05	3.07E-07	2.94E-04	8.69E-05	6.68E-04	1.23E-05	1.49E-04
Human carcinogenic toxicity	kg 1,4-DCB	5.20E-03	-4.89E-05	1.23E-05	1.70E-05	1.08E-03	1.72E-06	2.44E-05	3.92E-04	5.56E-07	7.31E-07	3.33E-05	1.30E-04	1.67E-04	4.12E-07	9.03E-04	2.46E-04	2.04E-03	4.15E-06	1.93E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	-3.59E-01	-4.18E-01	7.32E-04	2.32E-04	2.05E-02	5.13E-05	3.89E-04	6.39E-03	3.32E-06	1.27E-05	6.90E-04	2.13E-03	2.88E-03	6.89E-06	6.31E-03	1.92E-03	1.41E-02	3.44E-04	2.86E-03

Land use	m2a crop eq	8.78E-01	8.76E-01	2.33E-06	3.14E-05	3.28E-04	4.22E-07	1.36E-05	3.03E-04	6.08E-05	6.66E-05	1.36E-05	5.81E-05	1.00E-04	1.90E-07	1.94E-04	8.26E-05	5.14E-04	4.76E-07	1.40E-04
Mineral resource scarcity	kg Cu eq	6.83E-04	0.00E+00	2.95E-06	1.00E-06	9.00E-05	2.21E-07	6.01E-06	3.26E-04	7.55E-08	3.27E-08	1.74E-05	1.13E-05	1.19E-05	2.47E-08	5.82E-05	1.60E-05	1.31E-04	9.33E-07	9.58E-06
Fossil resource scarcity	kg oil eq	8.41E-03	0.00E+00	1.51E-05	4.15E-04	1.37E-03	1.54E-06	1.19E-04	1.60E-03	2.01E-06	7.78E-05	1.89E-04	3.38E-04	3.57E-04	7.10E-06	7.37E-04	2.80E-04	1.62E-03	2.60E-06	1.26E-03
Water consumption	m3	1.85E-04	0.00E+00	1.14E-06	9.70E-07	2.38E-05	4.91E-06	9.22E-06	6.42E-05	1.20E-06	1.22E-07	1.30E-06	2.04E-05	3.76E-06	9.63E-08	1.27E-05	3.79E-06	2.89E-05	3.00E-07	8.08E-06

Table A-7. Life cycle impacts for producing 0.291 kg of pea protein concentrate, peas, dry fractionation, pea-sourced, System #1. Contribution of utilities in fractionation stage. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.
Note: To focus only on the dry fractionation utilities impacts, this table excludes the accumulated impacts from pea agricultural cultivation and transport, hence the subtotal only accounts for the disaggregated utilities.

Impact category	Unit	Subtotal	Electricity	Heat, natural gas	Biowaste disposal	Wastewater treatment
Global warming	kg CO2 eq	1.27E-01	8.71E-02	3.66E-02	3.06E-03	6.42E-06
Stratospheric ozone depletion	kg CFC11 eq	4.92E-08	2.58E-08	4.53E-09	1.88E-08	5.75E-11
Ionizing radiation	kBq Co-60 eq	9.99E-03	9.71E-03	2.17E-04	5.76E-05	1.35E-07
Ozone formation, Human health	kg NOx eq	1.57E-04	1.17E-04	3.06E-05	9.63E-06	1.87E-08
Fine particulate matter formation	kg PM2.5 eq	4.10E-04	3.96E-04	9.75E-06	4.71E-06	8.39E-09
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.66E-04	1.21E-04	3.51E-05	1.01E-05	1.93E-08
Terrestrial acidification	kg SO2 eq	2.85E-04	2.38E-04	2.09E-05	2.58E-05	2.84E-08
Freshwater eutrophication	kg P eq	1.16E-04	1.14E-04	1.46E-06	9.37E-07	9.87E-08
Marine eutrophication	kg N eq	7.75E-06	7.17E-06	1.18E-07	2.82E-07	1.77E-07
Terrestrial ecotoxicity	kg 1,4-DCB	1.01E-01	7.85E-02	1.89E-02	3.78E-03	4.70E-05
Freshwater ecotoxicity	kg 1,4-DCB	4.41E-03	3.96E-03	2.68E-04	1.80E-04	5.40E-07
Marine ecotoxicity	kg 1,4-DCB	5.89E-03	5.29E-03	3.53E-04	2.43E-04	7.31E-07
Human carcinogenic toxicity	kg 1,4-DCB	7.82E-03	6.87E-03	7.11E-04	2.41E-04	7.87E-07
Human non-carcinogenic toxicity	kg 1,4-DCB	1.39E-01	1.27E-01	4.41E-03	7.31E-03	1.40E-04
Land use	m2a crop eq	1.55E-03	1.31E-03	1.71E-04	7.15E-05	2.46E-07
Mineral resource scarcity	kg Cu eq	1.20E-04	8.07E-05	3.32E-05	5.75E-06	3.33E-08
Fossil resource scarcity	kg oil eq	3.49E-02	2.23E-02	1.22E-02	3.81E-04	1.15E-06
Water consumption	m3	7.50E-04	7.50E-04	2.64E-05	1.80E-05	-4.42E-05

Table A-8. Life cycle impacts for producing 0.291 kg of pea protein concentrate, peas, dry fractionation, pea-sourced, System #1. Contribution of subprocesses in fractionation stage. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.

Note: To focus only on the dry fractionation utilities impacts, this table excludes the accumulated impacts from pea agricultural cultivation and transport, hence the subtotal only accounts for the disaggregated subprocesses.

Impact category	Unit	Subtotal	Drying	Cleaning and Dehulling	Milling	Fine Grinding and Air Classification
Global warming	kg CO2 eq	1.27E-01	6.19E-03	2.54E-02	1.90E-02	7.62E-02
Stratospheric ozone depletion	kg CFC11 eq	4.92E-08	8.93E-10	1.52E-08	9.31E-09	2.38E-08
Ionizing radiation	kBq Co-60 eq	9.99E-03	1.15E-04	1.41E-03	2.06E-03	6.40E-03
Ozone formation, Human health	kg NOx eq	1.57E-04	5.54E-06	3.10E-05	2.67E-05	9.41E-05
Fine particulate matter formation	kg PM2.5 eq	4.10E-04	4.82E-06	5.92E-05	8.44E-05	2.62E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.66E-04	6.26E-06	3.33E-05	2.76E-05	9.90E-05
Terrestrial acidification	kg SO2 eq	2.85E-04	5.13E-06	5.29E-05	5.55E-05	1.71E-04
Freshwater eutrophication	kg P eq	1.16E-04	1.19E-06	1.65E-05	2.42E-05	7.46E-05
Marine eutrophication	kg N eq	7.75E-06	7.85E-08	1.34E-06	1.57E-06	4.77E-06
Terrestrial ecotoxicity	kg 1,4-DCB	1.01E-01	3.48E-03	1.89E-02	1.73E-02	6.15E-02
Freshwater ecotoxicity	kg 1,4-DCB	4.41E-03	7.36E-05	7.21E-04	8.72E-04	2.74E-03
Marine ecotoxicity	kg 1,4-DCB	5.89E-03	9.76E-05	9.62E-04	1.17E-03	3.67E-03
Human carcinogenic toxicity	kg 1,4-DCB	7.82E-03	1.64E-04	1.29E-03	1.50E-03	4.87E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	1.39E-01	1.73E-03	2.26E-02	2.82E-02	8.60E-02
Land use	m2a crop eq	1.55E-03	3.65E-05	2.71E-04	2.90E-04	9.51E-04
Mineral resource scarcity	kg Cu eq	1.20E-04	5.63E-06	2.49E-05	1.82E-05	7.10E-05
Fossil resource scarcity	kg oil eq	3.49E-02	2.01E-03	7.21E-03	4.78E-03	2.09E-02
Water consumption	m3	7.50E-04	1.03E-05	7.54E-05	1.62E-04	5.02E-04

Table A-9. Life cycle impacts for producing 0.283 kg of extruded meat analogue, peas, dry fractionation, low moisture extrusion, pea-sourced, System #1. Contribution of utilities in extrusion stage. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.

Note: To focus only on the low moisture extrusion utilities impacts, this table excludes the accumulated impacts from pea protein concentrate dry fractionation, hence the subtotal only accounts for the disaggregated utilities.

Impact category	Unit	Subtotal	Water	Steam	Heat, natural gas	Electricity	Biowaste treatment
Global warming	kg CO2 eq	5.43E-02	5.11E-05	8.14E-03	2.32E-02	2.23E-02	5.64E-04
Stratospheric ozone depletion	kg CFC11 eq	1.39E-08	3.05E-11	9.53E-10	2.87E-09	6.61E-09	3.47E-09
Ionizing radiation	kBq Co-60 eq	2.82E-03	5.47E-06	1.79E-04	1.38E-04	2.49E-03	1.06E-05
Ozone formation, Human health	kg NOx eq	6.15E-05	1.29E-07	1.02E-05	1.94E-05	3.00E-05	1.78E-06
Fine particulate matter formation	kg PM2.5 eq	1.14E-04	1.02E-07	5.23E-06	6.18E-06	1.01E-04	8.68E-07
Ozone formation, Terrestrial ecosystems	kg NOx eq	6.64E-05	1.33E-07	1.11E-05	2.23E-05	3.10E-05	1.86E-06
Terrestrial acidification	kg SO2 eq	9.42E-05	1.78E-07	1.50E-05	1.32E-05	6.10E-05	4.76E-06
Freshwater eutrophication	kg P eq	3.12E-05	2.31E-08	9.11E-07	9.27E-07	2.92E-05	1.73E-07
Marine eutrophication	kg N eq	2.08E-06	2.21E-09	1.09E-07	7.46E-08	1.84E-06	5.20E-08
Terrestrial ecotoxicity	kg 1,4-DCB	4.47E-02	1.45E-04	1.18E-02	1.20E-02	2.01E-02	6.97E-04
Freshwater ecotoxicity	kg 1,4-DCB	1.27E-03	2.00E-06	4.66E-05	1.70E-04	1.02E-03	3.33E-05
Marine ecotoxicity	kg 1,4-DCB	1.70E-03	2.73E-06	7.00E-05	2.24E-04	1.36E-03	4.48E-05
Human carcinogenic toxicity	kg 1,4-DCB	2.43E-03	2.39E-05	1.50E-04	4.51E-04	1.76E-03	4.45E-05
Human non-carcinogenic toxicity	kg 1,4-DCB	3.83E-02	4.81E-05	1.66E-03	2.80E-03	3.25E-02	1.35E-03
Land use	m2a crop eq	5.40E-04	9.52E-07	8.25E-05	1.08E-04	3.35E-04	1.32E-05
Mineral resource scarcity	kg Cu eq	4.77E-05	3.71E-07	4.55E-06	2.11E-05	2.07E-05	1.06E-06
Fossil resource scarcity	kg oil eq	1.60E-02	1.25E-05	2.50E-03	7.75E-03	5.71E-03	7.04E-05
Water consumption	m3	2.78E-04	5.60E-05	1.01E-05	1.67E-05	1.92E-04	3.32E-06

Table A-10. Life cycle impacts for producing 0.283 kg of extruded meat analogue, peas, dry fractionation, low moisture extrusion, pea-sourced, System #1. Contribution of subprocesses in extrusion stage. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.

Note: To focus only on the low moisture extrusion subprocesses impacts, this table excludes the accumulated impacts from pea protein concentrate dry fractionation, hence the subtotal only accounts for the disaggregated subprocesses.

Impact category	Unit	Subtotal	Preconditioning	Extrusion	Conveying	Cutting	Drying	Separation	Losses disposal
Global warming	kg CO2 eq	5.43E-02	1.06E-02	9.23E-03	4.02E-03	4.02E-03	2.57E-02	1.49E-04	5.64E-04
Stratospheric ozone depletion	kg CFC11 eq	1.39E-08	1.69E-09	2.73E-09	1.19E-09	1.19E-09	3.62E-09	4.40E-11	3.47E-09
Ionizing radiation	kBq Co-60 eq	2.82E-03	4.50E-04	1.03E-03	4.48E-04	4.48E-04	4.20E-04	1.66E-05	1.06E-05
Ozone formation, Human health	kg NOx eq	6.15E-05	1.35E-05	1.24E-05	5.40E-06	5.40E-06	2.28E-05	2.00E-07	1.78E-06
Fine particulate matter formation	kg PM2.5 eq	1.14E-04	1.62E-05	4.19E-05	1.83E-05	1.83E-05	1.77E-05	6.76E-07	8.68E-07
Ozone formation, Terrestrial ecosystems	kg NOx eq	6.64E-05	1.46E-05	1.28E-05	5.58E-06	5.58E-06	2.58E-05	2.07E-07	1.86E-06
Terrestrial acidification	kg SO2 eq	9.42E-05	2.17E-05	2.52E-05	1.10E-05	1.10E-05	2.01E-05	4.07E-07	4.76E-06
Freshwater eutrophication	kg P eq	3.12E-05	4.05E-06	1.21E-05	5.25E-06	5.25E-06	4.24E-06	1.95E-07	1.73E-07
Marine eutrophication	kg N eq	2.08E-06	3.07E-07	7.60E-07	3.31E-07	3.31E-07	2.83E-07	1.23E-08	5.20E-08
Terrestrial ecotoxicity	kg 1,4-DCB	4.47E-02	1.41E-02	8.31E-03	3.62E-03	3.62E-03	1.42E-02	1.34E-04	6.97E-04
Freshwater ecotoxicity	kg 1,4-DCB	1.27E-03	1.57E-04	4.20E-04	1.83E-04	1.83E-04	2.85E-04	6.77E-06	3.33E-05
Marine ecotoxicity	kg 1,4-DCB	1.70E-03	2.17E-04	5.61E-04	2.44E-04	2.44E-04	3.78E-04	9.05E-06	4.48E-05
Human carcinogenic toxicity	kg 1,4-DCB	2.43E-03	3.62E-04	7.27E-04	3.17E-04	3.17E-04	6.50E-04	1.17E-05	4.45E-05
Human non-carcinogenic toxicity	kg 1,4-DCB	3.83E-02	5.17E-03	1.34E-02	5.85E-03	5.85E-03	6.48E-03	2.17E-04	1.35E-03
Land use	m2a crop eq	5.40E-04	1.19E-04	1.38E-04	6.03E-05	6.03E-05	1.46E-04	2.23E-06	1.32E-05
Mineral resource scarcity	kg Cu eq	4.77E-05	7.13E-06	8.55E-06	3.72E-06	3.72E-06	2.34E-05	1.38E-07	1.06E-06

Fossil resource scarcity	kg oil eq	1.60E-02	3.12E-03	2.36E-03	1.03E-03	1.03E-03	8.39E-03	3.81E-05	7.04E-05
Water consumption	m3	2.78E-04	8.66E-05	7.94E-05	3.46E-05	3.46E-05	3.85E-05	1.28E-06	3.32E-06

Table A-11. Life cycle impacts for producing 1 kg of plant-based meat recipe from peas, WF, HME, pea-sourced, System #2. Contribution of ingredients. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	Total	Extruded meat analogue, HME, WF, pea	Water	Wheat gluten	Coconut oil	Canola oil	Potato starch	Spices	Transport
Global warming	kg CO2 eq	9.82E-01	4.48E-01	3.25E-04	8.73E-03	2.83E-01	7.77E-02	5.17E-02	1.10E-01	2.28E-03
Stratospheric ozone depletion	kg CFC11 eq	2.49E-06	1.37E-07	1.94E-10	5.71E-08	5.62E-07	1.06E-06	3.20E-07	3.52E-07	1.18E-09
Ionizing radiation	kBq Co-60 eq	3.05E-02	2.17E-02	3.48E-05	7.04E-04	1.27E-03	1.41E-03	1.50E-03	3.80E-03	4.43E-05
Ozone formation, Human health	kg NOx eq	1.65E-03	5.46E-04	8.23E-07	3.25E-05	2.83E-04	3.04E-04	2.11E-04	2.71E-04	6.54E-06
Fine particulate matter formation	kg PM2.5 eq	1.89E-03	9.04E-04	6.47E-07	2.41E-05	3.26E-04	3.12E-04	1.23E-04	1.99E-04	1.84E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.72E-03	5.90E-04	8.48E-07	3.32E-05	2.82E-04	3.14E-04	2.17E-04	2.77E-04	7.01E-06
Terrestrial acidification	kg SO2 eq	4.43E-03	8.13E-04	1.13E-06	6.73E-05	2.86E-04	2.09E-03	5.61E-04	6.05E-04	4.10E-06
Freshwater eutrophication	kg P eq	4.44E-04	2.84E-04	1.47E-07	1.08E-05	5.60E-05	2.00E-05	3.49E-05	3.84E-05	1.68E-07

Marine eutrophication	kg N eq	7.69E-04	2.20E-05	1.41E-08	2.36E-05	1.58E-04	3.84E-04	1.11E-04	6.95E-05	6.08E-08
Terrestrial ecotoxicity	kg 1,4-DCB	1.97E+00	4.77E-01	9.21E-04	6.02E-02	3.26E-01	1.07E-01	4.45E-01	5.22E-01	3.01E-02
Freshwater ecotoxicity	kg 1,4-DCB	3.75E-02	1.28E-02	1.27E-05	3.88E-03	9.25E-03	1.06E-03	5.05E-03	5.44E-03	5.03E-05
Marine ecotoxicity	kg 1,4-DCB	3.63E-02	1.70E-02	1.74E-05	1.19E-03	5.10E-03	1.49E-03	4.64E-03	6.74E-03	8.36E-05
Human carcinogenic toxicity	kg 1,4-DCB	3.68E-02	2.29E-02	1.52E-04	6.52E-04	3.59E-03	1.12E-03	3.40E-03	4.89E-03	1.08E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	7.01E-01	5.52E-02	3.06E-04	2.81E-02	-1.27E-03	3.54E-01	1.33E-01	1.29E-01	1.60E-03
Land use	m2a crop eq	1.90E+00	5.87E-01	6.06E-06	1.76E-02	7.66E-01	3.59E-01	5.23E-02	1.23E-01	7.87E-05
Mineral resource scarcity	kg Cu eq	2.17E-03	8.95E-04	2.36E-06	2.32E-04	1.26E-04	1.50E-04	3.56E-04	4.00E-04	5.37E-06
Fossil resource scarcity	kg oil eq	1.98E-01	1.34E-01	7.94E-05	2.09E-03	1.59E-02	1.15E-02	1.13E-02	2.27E-02	7.09E-04
Water consumption	m3	1.85E-02	1.95E-03	3.56E-04	3.75E-03	1.85E-04	5.70E-04	8.78E-03	2.92E-03	4.53E-06

Table A-12. Life cycle impacts for producing 0.441 kg of extruded meat analogue from peas, WF, HME, pea-sourced, System #2. Contribution of main stages. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	Total	Pea Cultivation	Wet Fractionation	High Moisture Extrusion
Global warming	kg CO2 eq	4.48E-01	2.12E-02	3.31E-01	9.54E-02
Stratospheric ozone depletion	kg CFC11 eq	1.37E-07	2.99E-08	7.78E-08	2.90E-08
Ionizing radiation	kBq Co-60 eq	2.17E-02	7.89E-04	1.05E-02	1.05E-02
Ozone formation, Human health	kg NOx eq	5.46E-04	8.97E-05	3.28E-04	1.29E-04
Fine particulate matter formation	kg PM2.5 eq	9.04E-04	5.14E-05	4.28E-04	4.25E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	5.90E-04	9.41E-05	3.63E-04	1.33E-04
Terrestrial acidification	kg SO2 eq	8.13E-04	1.64E-04	3.91E-04	2.58E-04
Freshwater eutrophication	kg P eq	2.84E-04	4.48E-05	1.15E-04	1.24E-04
Marine eutrophication	kg N eq	2.20E-05	1.69E-06	9.99E-06	1.03E-05
Terrestrial ecotoxicity	kg 1,4-DCB	4.77E-01	1.80E-01	2.09E-01	8.76E-02
Freshwater ecotoxicity	kg 1,4-DCB	1.28E-02	2.84E-03	5.67E-03	4.28E-03
Marine ecotoxicity	kg 1,4-DCB	1.70E-02	3.77E-03	7.55E-03	5.72E-03
Human carcinogenic toxicity	kg 1,4-DCB	2.29E-02	3.45E-03	1.18E-02	7.72E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	5.52E-02	-2.38E-01	1.55E-01	1.38E-01
Land use	m2a crop eq	5.87E-01	5.83E-01	2.46E-03	1.42E-03

Mineral resource scarcity	kg Cu eq	8.95E-04	4.53E-04	3.48E-04	9.40E-05
Fossil resource scarcity	kg oil eq	1.34E-01	5.58E-03	1.04E-01	2.45E-02
Water consumption	m3	1.95E-03	1.23E-04	1.01E-03	8.17E-04

Table A-13. Life cycle impacts for producing 1.416 kg of fresh peas, pea-sourced, System #2. Contribution of agricultural cultivation and transportation to facilities stage. Method: ReCiPe 2016 Midpoint (H) V1.03. Results directly exported from ecoinvent 3.9.1 dataset "Protein pea {CA-MB}| protein pea production | Cut-off, U"

Impact category	Unit	Total	Direct land use and field emissions	Ammonium sulfate	Application of plant protection product	Combine harvesting	Drying of protein pea	Glyphosate	Monoammonium phosphate	Pea seed, for sowing	Peat moss	Pesticide, unspecified	Potassium chloride	Sowing	Sulfur	Tillage, harrowing, by rotary harrow	Tillage, rolling	Tillage, rotary cultivator	Zinc	Transport to facilities
Global warming	kg CO2 eq	2.12E-02	8.44E-04	4.01E-05	9.31E-04	3.51E-03	1.02E-05	2.63E-04	3.57E-03	6.66E-06	1.91E-04	3.95E-04	7.39E-04	8.63E-04	1.62E-05	1.99E-03	7.21E-04	4.43E-03	6.50E-06	2.70E-03
Stratospheric ozone depletion	kg CFC11 eq	2.99E-08	2.23E-08	1.24E-11	3.50E-10	1.02E-09	7.72E-12	1.15E-10	8.48E-10	7.46E-11	3.09E-12	1.22E-09	3.00E-10	2.74E-10	5.21E-12	5.28E-10	2.10E-10	1.16E-09	3.65E-12	1.40E-09
Ionizing radiation	kBq Co-60 eq	7.89E-04	0.00E+00	2.88E-06	2.51E-06	1.16E-04	1.70E-07	2.29E-05	2.78E-04	2.08E-07	8.13E-07	2.43E-05	2.78E-05	1.76E-05	5.95E-08	6.85E-05	1.93E-05	1.54E-04	1.23E-06	5.24E-05
Ozone formation, Human health	kg NOx eq	8.97E-05	0.00E+00	1.40E-07	1.04E-05	1.96E-05	1.62E-08	6.27E-07	9.92E-06	3.17E-08	4.00E-08	1.09E-06	2.86E-06	6.59E-06	3.56E-08	8.27E-06	4.32E-06	1.79E-05	3.58E-08	7.75E-06
Fine particulate matter formation	kg PM2.5 eq	5.14E-05	1.02E-05	1.27E-07	3.77E-06	8.40E-06	1.50E-08	4.42E-07	6.08E-06	1.19E-08	1.94E-08	1.10E-06	1.32E-06	1.88E-06	4.70E-07	4.27E-06	1.57E-06	9.53E-06	1.40E-08	2.17E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	9.41E-05	0.00E+00	1.45E-07	1.06E-05	2.05E-05	1.69E-08	6.55E-07	1.04E-05	3.25E-08	4.10E-08	1.13E-06	2.97E-06	6.82E-06	3.80E-08	8.80E-06	4.51E-06	1.91E-05	3.64E-08	8.30E-06
Terrestrial acidification	kg SO2 eq	1.64E-04	8.33E-05	3.94E-07	4.47E-06	1.74E-05	4.06E-08	8.54E-07	1.35E-05	2.69E-08	3.49E-08	3.02E-06	3.01E-06	3.84E-06	1.61E-06	7.53E-06	2.96E-06	1.67E-05	3.98E-08	4.85E-06
Freshwater eutrophication	kg P eq	4.48E-05	3.78E-05	2.91E-08	3.06E-08	1.60E-06	3.65E-09	3.46E-07	1.17E-06	2.76E-09	3.60E-09	2.19E-07	2.56E-07	2.27E-07	8.69E-10	7.90E-07	2.35E-07	1.82E-06	7.60E-09	1.98E-07
Marine eutrophication	kg N eq	1.69E-06	8.22E-07	2.00E-08	1.81E-08	1.28E-07	1.55E-10	2.34E-08	1.62E-07	4.67E-08	2.85E-10	1.25E-07	2.25E-08	2.48E-08	3.35E-10	6.13E-08	2.12E-08	1.40E-07	4.42E-10	7.21E-08
Terrestrial ecotoxicity	kg 1,4-DCB	1.80E-01	4.31E-03	2.35E-03	1.37E-03	4.21E-02	1.84E-04	1.18E-03	2.60E-02	6.31E-05	4.68E-05	2.12E-03	9.22E-03	4.37E-03	5.03E-05	1.43E-02	4.32E-03	3.24E-02	2.69E-04	3.57E-02
Freshwater ecotoxicity	kg 1,4-DCB	2.84E-03	1.30E-03	1.82E-05	4.44E-06	5.12E-04	3.65E-06	1.27E-05	2.51E-04	4.44E-07	4.55E-07	2.56E-05	8.19E-05	4.81E-05	1.24E-07	1.46E-04	4.32E-05	3.32E-04	5.91E-06	5.96E-05

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Marine ecotoxicity	kg 1,4-DCB	3.77E-03	1.72E-03	2.45E-05	6.79E-06	6.65E-04	4.54E-06	1.57E-05	3.29E-04	6.91E-07	5.96E-07	2.74E-05	1.08E-04	6.35E-05	2.04E-07	1.95E-04	5.77E-05	4.43E-04	8.19E-06	9.91E-05
Human carcinogenic toxicity	kg 1,4-DCB	3.45E-03	-3.25E-05	8.17E-06	1.13E-05	7.20E-04	1.14E-06	1.62E-05	2.60E-04	3.69E-07	4.85E-07	2.21E-05	8.62E-05	1.11E-04	2.74E-07	5.99E-04	1.63E-04	1.35E-03	2.76E-06	1.28E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	2.38E-01	-2.78E-01	4.86E-04	1.54E-04	1.36E-02	3.41E-05	2.58E-04	4.24E-03	2.21E-06	8.41E-06	4.58E-04	1.41E-03	1.91E-03	4.57E-06	4.19E-03	1.27E-03	9.39E-03	2.28E-04	1.90E-03
Land use	m2a crop eq	5.83E-01	5.81E-01	1.54E-06	2.08E-05	2.18E-04	2.80E-07	9.02E-06	2.01E-04	4.03E-05	4.42E-05	9.01E-06	3.86E-05	6.66E-05	1.26E-07	1.29E-04	5.48E-05	3.41E-04	3.16E-07	9.32E-05
Mineral resource scarcity	kg Cu eq	4.53E-04	0.00E+00	1.96E-06	6.64E-07	5.97E-05	1.46E-07	3.99E-06	2.16E-04	5.01E-08	2.17E-08	1.15E-05	7.53E-06	7.90E-06	1.64E-08	3.86E-05	1.06E-05	8.72E-05	6.19E-07	6.36E-06
Fossil resource scarcity	kg oil eq	5.58E-03	0.00E+00	1.00E-05	2.76E-04	9.12E-04	1.02E-06	7.87E-05	1.06E-03	1.33E-06	5.17E-05	1.26E-04	2.25E-04	2.37E-04	4.71E-06	4.89E-04	1.86E-04	1.08E-03	1.73E-06	8.39E-04
Water consumption	m3	1.23E-04	0.00E+00	7.54E-07	6.44E-07	1.58E-05	3.26E-06	6.12E-06	4.26E-05	7.98E-07	8.12E-08	8.60E-07	1.35E-05	2.50E-06	6.39E-08	8.43E-06	2.52E-06	1.92E-05	1.99E-07	5.36E-06

Table A-14. Life cycle impacts for producing 0.19 kg of pea protein isolate, peas, wet fractionation, pea-sourced, System #2. Contribution of utilities in fractionation stage. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.
Note: To focus only on the wet fractionation utilities impacts, this table excludes the accumulated impacts from pea agricultural cultivation and transport, hence the subtotal only accounts for the disaggregated utilities.

Impact category	Unit	Subtotal	Electricity	Heat, natural gas	Water	Wastewater treatment	Biowaste treatment	NaOH	HCl	Remaining processes
Global warming	kg CO2 eq	3.31E-01	7.75E-02	2.48E-01	6.54E-04	8.73E-05	3.58E-03	8.16E-04	3.54E-04	2.23E-05
Stratospheric ozone depletion	kg CFC11 eq	7.78E-08	2.29E-08	3.07E-08	3.90E-10	7.83E-10	2.20E-08	8.24E-10	1.71E-10	1.16E-11
Ionizing radiation	kBq Co-60 eq	1.05E-02	8.64E-03	1.47E-03	7.01E-05	1.84E-06	6.75E-05	9.09E-05	1.26E-04	4.33E-07
Ozone formation, Human health	kg NOx eq	3.28E-04	1.04E-04	2.07E-04	1.66E-06	2.54E-07	1.13E-05	2.18E-06	9.77E-07	6.40E-08
Fine particulate matter formation	kg PM2.5 eq	4.27E-04	3.52E-04	6.61E-05	1.30E-06	1.14E-07	5.51E-06	1.67E-06	7.37E-07	1.79E-08
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.63E-04	1.08E-04	2.38E-04	1.71E-06	2.63E-07	1.18E-05	2.23E-06	9.99E-07	6.85E-08
Terrestrial acidification	kg SO2 eq	3.91E-04	2.12E-04	1.41E-04	2.27E-06	3.87E-07	3.02E-05	3.00E-06	1.76E-06	4.01E-08
Freshwater eutrophication	kg P eq	1.15E-04	1.01E-04	9.91E-06	2.96E-07	1.34E-06	1.10E-06	3.81E-07	2.29E-07	1.64E-09
Marine eutrophication	kg N eq	9.98E-06	6.38E-06	7.97E-07	2.83E-08	2.40E-06	3.30E-07	3.41E-08	1.14E-08	5.95E-10
Terrestrial ecotoxicity	kg 1,4-DCB	2.09E-01	6.98E-02	1.28E-01	1.85E-03	6.39E-04	4.43E-03	3.61E-03	8.05E-04	2.95E-04

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Freshwater ecotoxicity	kg 1,4-DCB	5.67E-03	3.52E-03	1.82E-03	2.57E-05	7.35E-06	2.11E-04	4.28E-05	3.98E-05	4.92E-07
Marine ecotoxicity	kg 1,4-DCB	7.54E-03	4.71E-03	2.39E-03	3.49E-05	9.94E-06	2.84E-04	5.64E-05	5.58E-05	8.18E-07
Human carcinogenic toxicity	kg 1,4-DCB	1.18E-02	6.11E-03	4.82E-03	3.06E-04	1.07E-05	2.82E-04	5.37E-05	1.77E-04	1.06E-06
Human non-carcinogenic toxicity	kg 1,4-DCB	1.55E-01	1.13E-01	2.99E-02	6.16E-04	1.91E-03	8.56E-03	9.52E-04	4.04E-04	1.57E-05
Land use	m2a crop eq	2.46E-03	1.16E-03	1.16E-03	1.22E-05	3.35E-06	8.37E-05	1.96E-05	2.16E-05	7.70E-07
Mineral resource scarcity	kg Cu eq	3.48E-04	7.18E-05	2.25E-04	4.75E-06	4.53E-07	6.73E-06	2.84E-06	3.57E-05	5.25E-08
Fossil resource scarcity	kg oil eq	1.04E-01	1.98E-02	8.28E-02	1.60E-04	1.56E-05	4.47E-04	1.98E-04	8.78E-05	6.93E-06
Water consumption	m3	1.01E-03	6.67E-04	1.79E-04	7.17E-04	-6.01E-04	2.11E-05	1.94E-05	3.86E-06	4.43E-08

Table A-15. Life cycle impacts for producing 0.19 kg of pea protein isolate, peas, wet fractionation, pea-sourced, System #2. Contribution of subprocesses in fractionation stage. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.
Note: To focus only on the wet fractionation utilities impacts, this table excludes the accumulated impacts from pea agricultural cultivation and transport, hence the subtotal only accounts for the disaggregated subprocesses.

Impact category	Unit	Subtotal	Drying of Fresh Peas	Cleaning and Dehulling	Precipitation and Mixing	Spray Drying
Global warming	kg CO2 eq	3.31E-01	3.91E-03	2.48E-02	1.81E-02	2.84E-01
Stratospheric ozone depletion	kg CFC11 eq	7.78E-08	6.75E-10	1.48E-08	1.95E-08	4.29E-08
Ionizing radiation	kBq Co-60 eq	1.05E-02	1.41E-04	1.99E-03	1.89E-03	6.45E-03
Ozone formation, Human health	kg NOx eq	3.28E-04	3.83E-06	3.29E-05	3.07E-05	2.60E-04
Fine particulate matter formation	kg PM2.5 eq	4.27E-04	5.80E-06	8.23E-05	7.09E-05	2.68E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.63E-04	4.23E-06	3.46E-05	3.18E-05	2.92E-04
Terrestrial acidification	kg SO2 eq	3.91E-04	4.63E-06	6.28E-05	6.39E-05	2.59E-04
Freshwater eutrophication	kg P eq	1.15E-04	1.57E-06	2.33E-05	2.12E-05	6.85E-05
Marine eutrophication	kg N eq	9.98E-06	1.01E-07	1.72E-06	3.68E-06	4.48E-06
Terrestrial ecotoxicity	kg 1,4-DCB	2.09E-01	2.44E-03	2.05E-02	2.24E-02	1.64E-01
Freshwater ecotoxicity	kg 1,4-DCB	5.67E-03	7.10E-05	9.15E-04	8.80E-04	3.80E-03
Marine ecotoxicity	kg 1,4-DCB	7.54E-03	9.45E-05	1.22E-03	1.18E-03	5.05E-03
Human carcinogenic toxicity	kg 1,4-DCB	1.18E-02	1.42E-04	1.59E-03	1.82E-03	8.20E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	1.55E-01	1.95E-03	2.94E-02	2.93E-02	9.44E-02
Land use	m2a crop eq	2.46E-03	2.97E-05	3.21E-04	3.18E-04	1.79E-03
Mineral resource scarcity	kg Cu eq	3.48E-04	3.57E-06	2.43E-05	6.08E-05	2.59E-04
Fossil resource scarcity	kg oil eq	1.04E-01	1.22E-03	6.65E-03	4.33E-03	9.14E-02
Water consumption	m3	1.01E-03	1.16E-05	1.25E-04	3.09E-04	5.60E-04

Table A-16. Life cycle impacts for producing 0.441 kg of extruded meat analogue, peas, wet fractionation, high moisture extrusion, pea-sourced, System #2. Contribution of utilities in extrusion stage. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.
Note: To focus only on the high moisture extrusion utilities impacts, this table excludes the accumulated impacts from pea isolate wet fractionation, hence the subtotal only accounts for the disaggregated utilities.

Impact category	Unit	Subtotal	Water	Heat, natural gas	Electricity	Wastewater treatment
Global warming	kg CO2 eq	9.54E-02	7.00E-04	1.59E-03	9.30E-02	1.40E-04
Stratospheric ozone depletion	kg CFC11 eq	2.90E-08	4.18E-10	1.97E-10	2.75E-08	8.57E-10
Ionizing radiation	kBq Co-60 eq	1.05E-02	7.51E-05	9.45E-06	1.04E-02	3.33E-06
Ozone formation, Human health	kg NOx eq	1.29E-04	1.77E-06	1.33E-06	1.25E-04	3.90E-07
Fine particulate matter formation	kg PM2.5 eq	4.25E-04	1.39E-06	4.24E-07	4.23E-04	1.95E-07
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.33E-04	1.83E-06	1.53E-06	1.29E-04	4.05E-07
Terrestrial acidification	kg SO2 eq	2.58E-04	2.44E-06	9.08E-07	2.54E-04	5.34E-07
Freshwater eutrophication	kg P eq	1.24E-04	3.17E-07	6.36E-08	1.22E-04	2.41E-06
Marine eutrophication	kg N eq	1.03E-05	3.03E-08	5.12E-09	7.66E-06	2.61E-06
Terrestrial ecotoxicity	kg 1,4-DCB	8.76E-02	1.99E-03	8.21E-04	8.38E-02	9.77E-04
Freshwater ecotoxicity	kg 1,4-DCB	4.28E-03	2.75E-05	1.17E-05	4.23E-03	1.41E-05
Marine ecotoxicity	kg 1,4-DCB	5.72E-03	3.74E-05	1.54E-05	5.65E-03	1.92E-05
Human carcinogenic toxicity	kg 1,4-DCB	7.72E-03	3.28E-04	3.09E-05	7.33E-03	2.96E-05
Human non-carcinogenic toxicity	kg 1,4-DCB	1.38E-01	6.60E-04	1.92E-04	1.35E-01	2.23E-03
Land use	m2a crop eq	1.42E-03	1.31E-05	7.43E-06	1.39E-03	4.72E-06
Mineral resource scarcity	kg Cu eq	9.40E-05	5.08E-06	1.45E-06	8.62E-05	1.33E-06
Fossil resource scarcity	kg oil eq	2.45E-02	1.71E-04	5.32E-04	2.38E-02	2.89E-05
Water consumption	m3	8.17E-04	7.68E-04	1.15E-06	8.00E-04	-7.53E-04

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Table A-17. Life cycle impacts for producing 0.441 kg of extruded meat analogue, peas, wet fractionation, high moisture extrusion, pea-sourced, System #2. Contribution of subprocesses in extrusion stage. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.
Note: To focus only on the high moisture extrusion subprocesses impacts, this table excludes the accumulated impacts from pea protein isolate wet fractionation, hence the subtotal only accounts for the disaggregated subprocesses.

Impact category	Unit	Subtotal	Preconditioning	Heating	Extrusion	Cooling	Cutting
Global warming	kg CO2 eq	9.54E-02	2.77E-03	4.61E-03	8.12E-02	1.08E-03	5.80E-03
Stratospheric ozone depletion	kg CFC11 eq	2.90E-08	8.87E-10	1.09E-09	2.40E-08	1.28E-09	1.72E-09
Ionizing radiation	kBq Co-60 eq	1.05E-02	3.08E-04	3.46E-04	9.05E-03	1.06E-04	6.47E-04
Ozone formation, Human health	kg NOx eq	1.29E-04	3.99E-06	5.38E-06	1.09E-04	2.23E-06	7.79E-06
Fine particulate matter formation	kg PM2.5 eq	4.25E-04	1.20E-05	1.41E-05	3.69E-04	3.26E-06	2.64E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.33E-04	4.12E-06	5.71E-06	1.13E-04	2.30E-06	8.05E-06
Terrestrial acidification	kg SO2 eq	2.58E-04	7.74E-06	9.14E-06	2.22E-04	3.47E-06	1.58E-05
Freshwater eutrophication	kg P eq	1.24E-04	3.44E-06	4.01E-06	1.06E-04	3.23E-06	7.58E-06
Marine eutrophication	kg N eq	1.03E-05	2.20E-07	2.53E-07	6.69E-06	2.66E-06	4.78E-07
Terrestrial ecotoxicity	kg 1,4-DCB	8.76E-02	2.92E-03	3.54E-03	7.31E-02	2.75E-03	5.22E-03
Freshwater ecotoxicity	kg 1,4-DCB	4.28E-03	1.25E-04	1.49E-04	3.69E-03	5.40E-05	2.64E-04
Marine ecotoxicity	kg 1,4-DCB	5.72E-03	1.67E-04	1.99E-04	4.93E-03	7.30E-05	3.52E-04
Human carcinogenic toxicity	kg 1,4-DCB	7.72E-03	3.04E-04	2.69E-04	6.40E-03	2.90E-04	4.57E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	1.38E-01	3.92E-03	4.58E-03	1.18E-01	3.35E-03	8.43E-03
Land use	m2a crop eq	1.42E-03	4.24E-05	5.26E-05	1.22E-03	2.06E-05	8.69E-05
Mineral resource scarcity	kg Cu eq	9.40E-05	3.97E-06	4.24E-06	7.52E-05	5.24E-06	5.37E-06
Fossil resource scarcity	kg oil eq	2.45E-02	7.07E-04	1.30E-03	2.08E-02	2.65E-04	1.48E-03
Water consumption	m3	8.17E-04	2.64E-04	2.71E-05	6.99E-04	-2.23E-04	4.99E-05

Table A-18. Life cycle impacts for producing 1 kg of plant-based meat recipe from soybean, WF, HME, soy-sourced, System #3. Contribution of ingredients. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	Total	Extruded meat analogue, HME, WF, soy	Water	Wheat gluten	Coconut oil	Canola oil	Potato starch	Spices	Transport
Global warming	kg CO2 eq	8.57E-01	3.23E-01	8.45E-05	8.73E-03	2.83E-01	7.77E-02	5.17E-02	1.10E-01	2.28E-03
Stratospheric ozone depletion	kg CFC11 eq	4.11E-06	1.75E-06	5.04E-11	5.71E-08	5.62E-07	1.06E-06	3.20E-07	3.52E-07	1.18E-09
Ionizing radiation	kBq Co-60 eq	2.51E-02	1.64E-02	9.06E-06	7.04E-04	1.27E-03	1.41E-03	1.50E-03	3.80E-03	4.43E-05
Ozone formation, Human health	kg NOx eq	1.85E-03	7.45E-04	2.14E-07	3.25E-05	2.83E-04	3.04E-04	2.11E-04	2.71E-04	6.54E-06
Fine particulate matter formation	kg PM2.5 eq	1.67E-03	6.82E-04	1.68E-07	2.41E-05	3.26E-04	3.12E-04	1.23E-04	1.99E-04	1.84E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	2.00E-03	8.74E-04	2.21E-07	3.32E-05	2.82E-04	3.14E-04	2.17E-04	2.77E-04	7.01E-06
Terrestrial acidification	kg SO2 eq	4.28E-03	6.64E-04	2.94E-07	6.73E-05	2.86E-04	2.09E-03	5.61E-04	6.05E-04	4.10E-06
Freshwater eutrophication	kg P eq	3.61E-04	2.01E-04	3.83E-08	1.08E-05	5.60E-05	2.00E-05	3.49E-05	3.84E-05	1.68E-07
Marine eutrophication	kg N eq	8.10E-04	6.30E-05	3.66E-09	2.36E-05	1.58E-04	3.84E-04	1.11E-04	6.95E-05	6.08E-08
Terrestrial ecotoxicity	kg 1,4-DCB	2.06E+00	5.66E-01	2.40E-04	6.02E-02	3.26E-01	1.07E-01	4.45E-01	5.22E-01	3.01E-02
Freshwater ecotoxicity	kg 1,4-DCB	3.36E-02	8.88E-03	3.32E-06	3.88E-03	9.25E-03	1.06E-03	5.05E-03	5.44E-03	5.03E-05

Marine ecotoxicity	kg 1,4-DCB	3.12E-02	1.20E-02	4.52E-06	1.19E-03	5.10E-03	1.49E-03	4.64E-03	6.74E-03	8.36E-05
Human carcinogenic toxicity	kg 1,4-DCB	3.13E-02	1.75E-02	3.95E-05	6.52E-04	3.59E-03	1.12E-03	3.40E-03	4.89E-03	1.08E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	9.28E-01	2.83E-01	7.96E-05	2.81E-02	-1.27E-03	3.54E-01	1.33E-01	1.29E-01	1.60E-03
Land use	m2a crop eq	2.09E+00	7.76E-01	1.58E-06	1.76E-02	7.66E-01	3.59E-01	5.23E-02	1.23E-01	7.87E-05
Mineral resource scarcity	kg Cu eq	1.90E-03	6.33E-04	6.13E-07	2.32E-04	1.26E-04	1.50E-04	3.56E-04	4.00E-04	5.37E-06
Fossil resource scarcity	kg oil eq	1.42E-01	7.74E-02	2.06E-05	2.09E-03	1.59E-02	1.15E-02	1.13E-02	2.27E-02	7.09E-04
Water consumption	m3	1.70E-02	7.15E-04	9.27E-05	3.75E-03	1.85E-04	5.70E-04	8.78E-03	2.92E-03	4.53E-06

Table A-19. Life cycle impacts for producing 0.714 kg of extruded meat analogue from soybean, WF, HME, soy-sourced, System #3. Contribution of main stages. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	Total	Soybean Cultivation	Wet Fractionation	High Moisture Extrusion
Global warming	kg CO2 eq	3.23E-01	9.34E-02	1.17E-01	1.13E-01
Stratospheric ozone depletion	kg CFC11 eq	1.75E-06	1.65E-06	4.35E-08	5.49E-08
Ionizing radiation	kBq Co-60 eq	1.64E-02	1.61E-03	2.58E-03	1.22E-02
Ozone formation, Human health	kg NOx eq	7.45E-04	3.01E-04	2.81E-04	1.63E-04
Fine particulate matter formation	kg PM2.5 eq	6.82E-04	8.81E-05	1.08E-04	4.85E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	8.74E-04	3.09E-04	3.97E-04	1.68E-04
Terrestrial acidification	kg SO2 eq	6.64E-04	2.20E-04	1.23E-04	3.21E-04
Freshwater eutrophication	kg P eq	2.01E-04	1.52E-05	2.72E-05	1.58E-04

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Marine eutrophication	kg N eq	6.30E-05	1.41E-05	4.23E-06	4.47E-05
Terrestrial ecotoxicity	kg 1,4-DCB	5.66E-01	3.66E-01	7.82E-02	1.21E-01
Freshwater ecotoxicity	kg 1,4-DCB	8.88E-03	2.13E-03	1.62E-03	5.13E-03
Marine ecotoxicity	kg 1,4-DCB	1.20E-02	2.99E-03	2.12E-03	6.86E-03
Human carcinogenic toxicity	kg 1,4-DCB	1.75E-02	2.77E-03	3.52E-03	1.12E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	2.83E-01	5.62E-02	3.92E-02	1.88E-01
Land use	m2a crop eq	7.76E-01	7.72E-01	2.12E-03	1.75E-03
Mineral resource scarcity	kg Cu eq	6.33E-04	3.61E-04	1.24E-04	1.48E-04
Fossil resource scarcity	kg oil eq	7.74E-02	1.13E-02	3.75E-02	2.86E-02
Water consumption	m3	7.15E-04	1.85E-03	5.53E-04	-1.69E-03

Table A-20. Life cycle impacts for producing 0.42 kg of soybeans, soy-sourced, System #3. Contribution of agricultural cultivation and transportation to facilities stage. Method: ReCiPe 2016 Midpoint (H) V1.03. Results directly exported from ecoinvent 3.9.1 dataset “Soybean {US}| soybean production | Cut-off, U”.

Impact category	Unit	Total	Direct land use and field emissions	Application of plant protection product	Combine harvesting	Fertilizing, by broadcast	Inorganic nitrogen fertilizer	Inorganic phosphorus fertilizer	Land use change, annual crop	Lime	Packaging, for fertilizers	Packaging, for pesticides	Pesticide, unspecified	Potassium chloride	Sowing	Tillage, harrowing	Electricity	Heat, from natural gas	Transport to facilities
Global warming	kg CO2 eq	9.32E-02	5.21E-02	2.09E-04	1.16E-02	1.94E-03	1.87E-03	3.37E-03	2.51E-03	8.43E-04	5.71E-03	8.35E-05	1.12E-03	1.49E-03	1.82E-03	1.98E-03	2.61E-03	1.37E-03	2.55E-03
Stratospheric ozone depletion	kg CFC11 eq	1.65E-06	1.60E-06	7.22E-11	4.06E-09	6.66E-10	1.17E-08	2.14E-08	3.59E-09	2.63E-10	1.63E-09	1.88E-11	3.45E-09	6.06E-10	5.84E-10	6.46E-10	9.01E-10	1.70E-10	1.33E-09
Ionizing radiation	kBq Co-60 eq	1.61E-03	0.00E+00	2.14E-06	1.52E-04	2.58E-05	5.13E-05	1.65E-04	8.08E-08	2.70E-05	1.05E-04	3.29E-06	6.89E-05	5.60E-05	3.52E-05	3.41E-05	8.23E-04	8.13E-06	4.97E-05
Ozone formation, Human health	kg NOx eq	3.01E-04	5.57E-05	1.91E-06	1.25E-04	1.79E-05	3.56E-06	9.03E-06	1.67E-07	2.94E-06	3.24E-05	2.57E-07	3.07E-06	5.77E-06	1.43E-05	1.64E-05	3.32E-06	1.14E-06	7.34E-06

Fine particulate matter formation	kg PM2.5 eq	8.79E-05	1.11E-05	7.23E-07	3.12E-05	4.56E-06	1.94E-06	5.31E-06	3.26E-08	1.67E-06	8.87E-06	1.12E-07	3.12E-06	2.66E-06	4.00E-06	4.80E-06	5.41E-06	3.65E-07	2.06E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.08E-04	5.57E-05	1.95E-06	1.28E-04	1.83E-05	3.79E-06	9.39E-06	1.83E-07	3.03E-06	3.36E-05	2.70E-07	3.20E-06	5.99E-06	1.48E-05	1.69E-05	3.54E-06	1.32E-06	7.87E-06
Terrestrial acidification	kg SO2 eq	2.20E-04	6.04E-05	9.44E-07	6.22E-05	9.05E-06	5.84E-06	1.40E-05	6.41E-08	3.40E-06	2.08E-05	2.26E-07	8.55E-06	6.08E-06	8.09E-06	8.86E-06	5.87E-06	7.82E-07	4.60E-06
Freshwater eutrophication	kg P eq	1.51E-05	6.02E-06	5.30E-08	1.94E-06	2.90E-07	3.24E-07	9.42E-07	1.19E-08	3.01E-07	1.21E-06	8.92E-08	6.20E-07	5.17E-07	4.49E-07	4.40E-07	1.68E-06	5.47E-08	1.88E-07
Marine eutrophication	kg N eq	1.40E-05	1.26E-05	6.69E-09	2.94E-07	4.75E-08	8.16E-08	1.07E-07	1.07E-09	1.92E-08	2.00E-07	5.49E-09	3.54E-07	4.54E-08	5.18E-08	5.41E-08	1.15E-07	4.40E-09	6.83E-08
Terrestrial ecotoxicity	kg 1,4-DCB	3.65E-01	9.13E-02	8.22E-04	5.77E-02	7.50E-03	1.30E-02	2.56E-02	1.77E-05	8.07E-03	7.39E-02	4.96E-04	6.00E-03	1.86E-02	8.74E-03	8.76E-03	1.01E-02	7.07E-04	3.38E-02
Freshwater ecotoxicity	kg 1,4-DCB	2.13E-03	5.18E-05	7.63E-06	6.02E-04	7.77E-05	1.15E-04	2.44E-04	9.67E-08	1.57E-04	1.57E-04	3.83E-06	7.25E-05	1.65E-04	9.50E-05	8.36E-05	2.26E-04	1.01E-05	5.65E-05
Marine ecotoxicity	kg 1,4-DCB	2.99E-03	2.19E-04	1.01E-05	7.92E-04	1.03E-04	1.52E-04	3.20E-04	1.27E-07	2.19E-04	2.41E-04	5.44E-06	7.75E-05	2.17E-04	1.26E-04	1.12E-04	2.86E-04	1.32E-05	9.39E-05
Human carcinogenic toxicity	kg 1,4-DCB	2.76E-03	1.01E-05	1.28E-05	8.87E-04	1.28E-04	9.85E-05	1.94E-04	5.58E-07	9.59E-05	3.44E-04	3.71E-06	6.25E-05	1.74E-04	2.19E-04	2.57E-04	1.30E-04	2.66E-05	1.21E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	5.61E-02	2.63E-03	2.80E-04	1.61E-02	3.63E-03	2.26E-03	4.93E-03	1.91E-06	5.77E-03	4.35E-03	8.10E-05	1.30E-03	2.85E-03	3.77E-03	2.77E-03	3.40E-03	1.65E-04	1.80E-03
Land use	m2a crop eq	7.70E-01	7.69E-01	4.22E-05	2.95E-04	5.48E-05	4.48E-05	2.03E-04	2.14E-06	2.84E-05	2.77E-04	2.49E-06	2.55E-05	7.78E-05	1.32E-04	1.41E-04	6.03E-05	6.40E-06	8.83E-05
Mineral resource scarcity	kg Cu eq	3.60E-04	0.00E+00	9.11E-07	7.17E-05	9.85E-06	2.73E-05	1.24E-04	2.43E-08	1.57E-05	1.59E-05	1.73E-07	3.27E-05	1.52E-05	1.56E-05	1.70E-05	6.93E-06	1.24E-06	6.03E-06
Fossil resource scarcity	kg oil eq	1.13E-02	0.00E+00	5.76E-05	3.31E-03	5.60E-04	5.50E-04	8.50E-04	4.37E-06	2.18E-04	1.83E-03	3.46E-05	3.55E-04	4.54E-04	5.01E-04	5.42E-04	7.46E-04	4.58E-04	7.96E-04
Water consumption	m3	1.85E-03	1.62E-03	5.03E-07	2.37E-05	3.94E-06	4.37E-05	5.20E-05	3.70E-08	2.06E-05	2.31E-05	3.53E-07	2.43E-06	2.73E-05	5.15E-06	5.12E-06	1.73E-05	9.87E-07	5.08E-06

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Table A-21. Life cycle impacts for producing 0.215 kg of soy protein concentrate, soybean, wet fractionation, soy-sourced, System #3. Contribution of utilities in fractionation stage. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.
Note: To focus only on the wet fractionation utilities impacts, this table excludes the accumulated impacts from soybean agricultural cultivation and transport, hence the subtotal only accounts for the disaggregated utilities.

Impact category	Unit	Total	Water	Ethanol	Electricity	Heat from natural gas	Wastewater	Direct emissions - Aqueous Alcohol Leaching	Direct emissions - White Flakes	Hexane	Oil mill infrastructure	Inert waste disposal
Global warming	kg CO2 eq	1.17E-01	1.23E-04	3.27E-03	1.68E-02	9.65E-02	6.50E-06	0.00E+00	0.00E+00	1.02E-04	1.77E-04	3.47E-06
Stratospheric ozone depletion	kg CFC11 eq	4.36E-08	7.35E-11	2.65E-08	4.97E-09	1.19E-08	5.82E-11	0.00E+00	0.00E+00	2.25E-11	3.56E-11	1.06E-12
Ionizing radiation	kBq Co-60 eq	2.58E-03	1.32E-05	1.14E-04	1.87E-03	5.73E-04	1.37E-07	0.00E+00	0.00E+00	1.96E-06	4.94E-06	4.50E-08
Ozone formation, Human health	kg NOx eq	2.81E-04	3.12E-07	9.91E-06	2.26E-05	8.06E-05	1.89E-08	1.49E-04	1.75E-05	4.32E-07	5.38E-07	2.36E-08
Fine particulate matter formation	kg PM2.5 eq	1.08E-04	2.45E-07	5.50E-06	7.63E-05	2.57E-05	8.49E-09	0.00E+00	0.00E+00	1.22E-07	3.27E-07	6.02E-09
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.97E-04	3.21E-07	1.03E-05	2.33E-05	9.27E-05	1.96E-08	2.41E-04	2.82E-05	5.65E-07	5.67E-07	2.46E-08
Terrestrial acidification	kg SO2 eq	1.23E-04	4.28E-07	2.03E-05	4.59E-05	5.51E-05	2.88E-08	0.00E+00	0.00E+00	3.24E-07	8.53E-07	1.30E-08
Freshwater eutrophication	kg P eq	2.72E-05	5.58E-08	1.04E-06	2.20E-05	3.86E-06	9.99E-08	0.00E+00	9.94E-08	2.94E-08	7.16E-08	3.30E-10
Marine eutrophication	kg N eq	4.23E-06	5.33E-09	2.34E-06	1.38E-06	3.10E-07	1.79E-07	0.00E+00	0.00E+00	7.50E-09	7.37E-09	1.25E-10
Terrestrial ecotoxicity	kg 1,4-DCB	7.82E-02	3.49E-04	1.16E-02	1.51E-02	4.98E-02	4.75E-05	8.71E-05	2.85E-08	3.77E-04	8.00E-04	2.40E-05
Freshwater ecotoxicity	kg 1,4-DCB	1.62E-03	4.83E-06	1.26E-04	7.64E-04	7.08E-04	5.47E-07	1.42E-07	8.55E-12	3.71E-06	1.21E-05	6.10E-08

Marine ecotoxicity	kg 1,4-DCB	2.13E-03	6.58E-06	1.43E-04	1.02E-03	9.31E-04	7.40E-07	4.61E-07	1.42E-10	5.08E-06	1.67E-05	9.28E-08
Human carcinogenic toxicity	kg 1,4-DCB	3.52E-03	5.75E-05	1.45E-04	1.32E-03	1.87E-03	7.97E-07	1.22E-05	4.97E-08	5.54E-06	1.05E-04	1.85E-07
Human non-carcinogenic toxicity	kg 1,4-DCB	3.92E-02	1.16E-04	2.53E-03	2.44E-02	1.16E-02	1.42E-04	0.00E+00	2.27E-05	7.27E-05	2.46E-04	1.67E-06
Land use	m2a crop eq	2.12E-03	2.29E-06	1.38E-03	2.52E-04	4.51E-04	2.49E-07	0.00E+00	0.00E+00	3.25E-06	3.04E-05	-2.14E-07
Mineral resource scarcity	kg Cu eq	1.24E-04	8.93E-07	1.44E-05	1.56E-05	8.77E-05	3.37E-08	0.00E+00	0.00E+00	3.79E-07	4.74E-06	8.41E-09
Fossil resource scarcity	kg oil eq	3.75E-02	3.01E-05	7.56E-04	4.30E-03	3.22E-02	1.16E-06	0.00E+00	0.00E+00	1.09E-04	3.96E-05	1.62E-06
Water consumption	m3	5.53E-04	1.35E-04	3.34E-04	1.45E-04	6.95E-05	-4.47E-05	0.00E+00	-8.82E-05	1.18E-06	1.12E-06	6.13E-08

Table A-22. Life cycle impacts for producing 0.215 kg of soy protein concentrate, soybean, wet fractionation, soy-sourced, System #3. Contribution of subprocesses in fractionation stage. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.
Note: To focus only on the wet fractionation utilities impacts, this table excludes the accumulated impacts from soybean agricultural cultivation and transport, hence the subtotal only accounts for the disaggregated subprocesses.

Impact category	Unit	Total	Soy White Flake Production	Aqueous Alcohol Leaching
Global warming	kg CO2 eq	1.17E-01	2.72E-02	8.98E-02
Stratospheric ozone depletion	kg CFC11 eq	4.36E-08	4.50E-09	3.91E-08
Ionizing radiation	kBq Co-60 eq	2.58E-03	8.30E-04	1.75E-03
Ozone formation, Human health	kg NOx eq	2.81E-04	4.43E-05	2.37E-04
Fine particulate matter formation	kg PM2.5 eq	1.08E-04	3.43E-05	7.40E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.97E-04	5.80E-05	3.39E-04
Terrestrial acidification	kg SO2 eq	1.23E-04	3.02E-05	9.27E-05
Freshwater eutrophication	kg P eq	2.72E-05	9.16E-06	1.81E-05
Marine eutrophication	kg N eq	4.23E-06	5.95E-07	3.64E-06
Terrestrial ecotoxicity	kg 1,4-DCB	7.84E-02	1.77E-02	6.07E-02
Freshwater ecotoxicity	kg 1,4-DCB	1.62E-03	4.52E-04	1.17E-03
Marine ecotoxicity	kg 1,4-DCB	2.13E-03	6.02E-04	1.52E-03
Human carcinogenic toxicity	kg 1,4-DCB	3.53E-03	1.04E-03	2.48E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	3.92E-02	1.19E-02	2.73E-02
Land use	m2a crop eq	2.12E-03	2.24E-04	1.90E-03
Mineral resource scarcity	kg Cu eq	1.24E-04	3.03E-05	9.35E-05
Fossil resource scarcity	kg oil eq	3.75E-02	8.65E-03	2.88E-02
Water consumption	m3	5.53E-04	8.25E-05	4.70E-04

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Table A-23. Life cycle impacts for producing 0.714 kg of extruded meat analogue, soybean, wet fractionation, high moisture extrusion, soy-sourced, System #3. Contribution of utilities in extrusion stage. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.
Note: To focus only on the high moisture extrusion utilities impacts, this table excludes the accumulated impacts from soy concentrate wet fractionation, hence the subtotal only accounts for the disaggregated utilities.

Impact category	Unit	Subtotal	Water	Electricity	Heat, natural gas	Wastewater treatment	Biowaste
Global warming	kg CO2 eq	1.13E-01	5.83E-03	1.03E-01	1.09E-03	1.30E-03	1.47E-03
Stratospheric ozone depletion	kg CFC11 eq	5.49E-08	3.48E-09	3.06E-08	1.35E-10	1.17E-08	9.07E-09
Ionizing radiation	kBq Co-60 eq	1.22E-02	6.24E-04	1.15E-02	6.46E-06	2.74E-05	2.78E-05
Ozone formation, Human health	kg NOx eq	1.63E-04	1.48E-05	1.39E-04	9.09E-07	3.79E-06	4.64E-06
Fine particulate matter formation	kg PM2.5 eq	4.85E-04	1.16E-05	4.69E-04	2.90E-07	1.70E-06	2.27E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.68E-04	1.52E-05	1.43E-04	1.05E-06	3.93E-06	4.86E-06
Terrestrial acidification	kg SO2 eq	3.21E-04	2.03E-05	2.82E-04	6.21E-07	5.78E-06	1.24E-05
Freshwater eutrophication	kg P eq	1.58E-04	2.64E-06	1.35E-04	4.35E-08	2.00E-05	4.52E-07
Marine eutrophication	kg N eq	4.47E-05	2.52E-07	8.51E-06	3.50E-09	3.59E-05	1.36E-07
Terrestrial ecotoxicity	kg 1,4-DCB	1.21E-01	1.65E-02	9.30E-02	5.61E-04	9.54E-03	1.82E-03
Freshwater ecotoxicity	kg 1,4-DCB	5.13E-03	2.29E-04	4.70E-03	7.98E-06	1.10E-04	8.70E-05
Marine ecotoxicity	kg 1,4-DCB	6.86E-03	3.11E-04	6.28E-03	1.05E-05	1.48E-04	1.17E-04
Human carcinogenic toxicity	kg 1,4-DCB	1.12E-02	2.72E-03	8.14E-03	2.11E-05	1.60E-04	1.16E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	1.88E-01	5.49E-03	1.50E-01	1.31E-04	2.84E-02	3.53E-03
Land use	m2a crop eq	1.75E-03	1.09E-04	1.55E-03	5.08E-06	5.00E-05	3.45E-05
Mineral resource scarcity	kg Cu eq	1.48E-04	4.23E-05	9.57E-05	9.88E-07	6.76E-06	2.77E-06
Fossil resource scarcity	kg oil eq	2.86E-02	1.42E-03	2.64E-02	3.63E-04	2.33E-04	1.84E-04
Water consumption	m3	-1.69E-03	6.39E-03	8.89E-04	7.84E-07	-8.98E-03	8.67E-06

Table A-24. Life cycle impacts for producing 0.714 kg of extruded meat analogue, HME, WF, soy-sourced, System 3, cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.

Life cycle impacts for producing 0.714 kg of extruded meat analogue, soybean, wet fractionation, high moisture extrusion, soy-sourced, System #3. Contribution of subprocesses in extrusion stage. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.
Note: To focus only on the high moisture extrusion utilities impacts, this table excludes the accumulated impacts from soy concentrate wet fractionation, hence the subtotal only accounts for the disaggregated utilities.

Impact category	Unit	Subtotal	Pre-Conditionning	Extrusion	Cooling Die	Cutting	Subtotal
Global warming	kg CO2 eq	1.13E-01	1.09E-02	6.99E-02	8.55E-03	2.36E-02	1.13E-01
Stratospheric ozone depletion	kg CFC11 eq	5.49E-08	3.22E-09	2.06E-08	1.54E-08	1.56E-08	5.49E-08
Ionizing radiation	kBq Co-60 eq	1.22E-02	1.21E-03	7.68E-03	8.12E-04	2.50E-03	1.22E-02
Ozone formation, Human health	kg NOx eq	1.63E-04	1.46E-05	9.39E-05	1.99E-05	3.44E-05	1.63E-04
Fine particulate matter formation	kg PM2.5 eq	4.85E-04	4.95E-05	3.12E-04	2.09E-05	1.03E-04	4.85E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.68E-04	1.51E-05	9.71E-05	2.06E-05	3.56E-05	1.68E-04
Terrestrial acidification	kg SO2 eq	3.21E-04	2.97E-05	1.89E-04	2.96E-05	7.30E-05	3.21E-04
Freshwater eutrophication	kg P eq	1.58E-04	1.42E-05	8.96E-05	2.49E-05	2.94E-05	1.58E-04
Marine eutrophication	kg N eq	4.47E-05	8.97E-07	5.65E-06	3.62E-05	1.96E-06	4.47E-05
Terrestrial ecotoxicity	kg 1,4-DCB	1.21E-01	9.81E-03	6.34E-02	2.65E-02	2.18E-02	1.21E-01
Freshwater ecotoxicity	kg 1,4-DCB	5.13E-03	4.95E-04	3.13E-03	4.06E-04	1.09E-03	5.13E-03
Marine ecotoxicity	kg 1,4-DCB	6.86E-03	6.62E-04	4.19E-03	5.49E-04	1.46E-03	6.86E-03
Human carcinogenic toxicity	kg 1,4-DCB	1.12E-02	8.58E-04	5.62E-03	2.82E-03	1.86E-03	1.12E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	1.88E-01	1.58E-02	1.00E-01	3.62E-02	3.58E-02	1.88E-01
Land use	m2a crop eq	1.75E-03	1.63E-04	1.04E-03	1.78E-04	3.67E-04	1.75E-03
Mineral resource scarcity	kg Cu eq	1.48E-04	1.01E-05	6.76E-05	4.75E-05	2.33E-05	1.48E-04
Fossil resource scarcity	kg oil eq	2.86E-02	2.79E-03	1.80E-02	2.02E-03	5.86E-03	2.86E-02
Water consumption	m3	-1.69E-03	9.37E-05	1.09E-03	-3.07E-03	1.99E-04	-1.69E-03

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Table A-25. Life cycle impacts for producing 1 kg of ground beef meat, System #4. Contribution of main stages. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	Total	Cattle farming	Slaughtering	Transport	Grinding
Global warming	kg CO2 eq	1.45E+01	1.33E+01	9.06E-01	3.31E-02	2.57E-01
Stratospheric ozone depletion	kg CFC11 eq	1.21E-04	1.20E-04	7.81E-07	1.12E-08	7.61E-08
Ionizing radiation	kBq Co-60 eq	2.09E-01	9.58E-02	8.36E-02	6.43E-04	2.87E-02
Ozone formation, Human health	kg NOx eq	9.39E-03	7.42E-03	1.39E-03	2.29E-04	3.45E-04
Fine particulate matter formation	kg PM2.5 eq	1.91E-02	1.46E-02	3.30E-03	5.40E-05	1.17E-03
Ozone formation, Terrestrial ecosystems	kg NOx eq	9.66E-03	7.63E-03	1.44E-03	2.33E-04	3.57E-04
Terrestrial acidification	kg SO2 eq	8.80E-02	8.48E-02	2.33E-03	1.28E-04	7.02E-04
Freshwater eutrophication	kg P eq	7.85E-03	6.46E-03	1.04E-03	4.11E-06	3.36E-04
Marine eutrophication	kg N eq	1.95E-02	1.94E-02	8.90E-05	3.06E-07	2.12E-05
Terrestrial ecotoxicity	kg 1,4-DCB	1.67E+01	1.49E+01	1.07E+00	5.76E-01	2.32E-01
Freshwater ecotoxicity	kg 1,4-DCB	3.52E-01	2.87E-01	5.36E-02	5.22E-04	1.17E-02
Marine ecotoxicity	kg 1,4-DCB	4.08E-01	3.20E-01	7.15E-02	1.02E-03	1.56E-02
Human carcinogenic toxicity	kg 1,4-DCB	4.47E-01	3.47E-01	7.81E-02	7.24E-04	2.03E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	1.09E+03	1.09E+03	1.63E+00	2.60E-02	3.74E-01
Land use	m2a crop eq	2.21E+01	2.21E+01	1.81E-02	1.74E-03	3.85E-03
Mineral resource scarcity	kg Cu eq	1.93E-02	1.73E-02	1.69E-03	6.35E-05	2.38E-04
Fossil resource scarcity	kg oil eq	8.02E-01	4.95E-01	2.29E-01	1.17E-02	6.58E-02
Water consumption	m3	2.45E-01	2.32E-01	9.98E-03	9.26E-05	2.21E-03

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Table A-26. Life cycle impacts for producing 2.04 kg of cattle, live weight, feedlot operation, System #4. Contribution of feedlot subprocess. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.
Note: 2.04 kg of cattle, live weight, are required to produce 1 kg of fresh beef meat.

Impact category	Unit	Total	Direct emissions from feedlot fattening	Alfalfa-grass silage cultivation	Energy feed, gross mix cultivation	Irrigation	Lime production	Maize chop production	Maize grain cultivation	Maize silage cultivation	Liquid manure treatment	Solid manure treatment	Rape meal production	Sodium chloride production	Water production	Transport, tractor and trailer	Urea production	Weaned calves, live weight	Wheat bran cultivation	Electricity consumption	Housing operation
Global warming	kg CO2 eq	1.33E+01	2.04E+00	1.35E-02	4.36E-02	8.20E-04	4.11E-04	1.35E-01	2.59E-01	7.32E-02	0.00E+00	0.00E+00	5.79E-02	3.35E-03	3.76E-04	2.98E-03	5.90E-02	9.60E+00	8.75E-02	1.89E-03	9.12E-01
Stratospheric ozone depletion	kg CFC 11 eq	1.20E-04	1.95E-05	2.89E-07	4.70E-07	2.84E-10	1.07E-10	1.18E-06	2.99E-06	1.34E-06	0.00E+00	0.00E+00	9.56E-07	1.08E-09	2.50E-10	8.90E-10	1.02E-08	9.21E-05	1.09E-06	5.69E-10	2.96E-07
Ionizing radiation	kBq Co-60 eq	9.58E-02	0.00E+00	1.08E-04	1.09E-03	1.80E-04	6.07E-06	3.77E-03	6.69E-03	6.25E-04	0.00E+00	0.00E+00	1.66E-03	2.79E-04	2.69E-05	6.08E-05	7.33E-04	7.99E-03	2.51E-03	2.10E-04	6.99E-02
Ozone formation, Human health	kg NOx eq	7.42E-03	0.00E+00	4.27E-05	1.33E-04	1.78E-06	1.69E-06	3.91E-04	6.39E-04	3.33E-04	0.00E+00	0.00E+00	1.89E-04	1.07E-05	9.64E-07	1.83E-05	1.25E-04	3.23E-03	3.17E-04	2.64E-06	1.98E-03
Fine particulate matter formation	kg PM2.5 eq	1.46E-02	4.82E-03	2.15E-05	8.42E-05	1.76E-06	1.08E-06	2.59E-04	4.89E-04	2.29E-04	0.00E+00	0.00E+00	1.52E-04	7.22E-06	7.58E-07	6.66E-06	7.22E-05	5.00E-03	1.59E-04	8.73E-06	3.28E-03
Ozone formation, Terrestrial ecosystems	kg NOx eq	7.63E-03	0.00E+00	4.37E-05	1.37E-04	1.87E-06	1.76E-06	4.05E-04	6.57E-04	3.40E-04	0.00E+00	0.00E+00	1.96E-04	1.10E-05	9.92E-07	1.89E-05	1.32E-04	3.29E-03	3.28E-04	2.73E-06	2.06E-03
Terrestrial acidification	kg SO2 eq	8.48E-02	3.94E-02	1.07E-04	3.31E-04	2.52E-06	1.11E-06	8.80E-04	1.98E-03	1.36E-03	0.00E+00	0.00E+00	8.88E-04	1.55E-05	1.29E-06	1.24E-05	2.07E-04	3.56E-02	6.56E-04	5.75E-06	3.34E-03
Freshwater eutrophication	kg P eq	6.46E-03	3.94E-03	3.49E-06	1.75E-05	5.29E-07	2.45E-08	5.50E-05	1.09E-04	4.61E-05	0.00E+00	0.00E+00	1.69E-05	1.94E-06	1.44E-07	8.21E-07	1.75E-05	1.02E-03	1.09E-04	2.52E-06	1.12E-03
Marine eutrophication	kg N eq	1.94E-02	0.00E+00	1.37E-04	8.77E-05	3.45E-08	4.50E-09	1.83E-04	4.65E-04	2.50E-04	0.00E+00	0.00E+00	3.60E-04	3.13E-07	1.43E-08	8.49E-08	2.50E-06	1.75E-02	3.77E-04	1.56E-07	1.20E-04
Terrestrial ecotoxicity	kg 1,4-DCB	1.49E+01	1.57E-20	3.33E-02	1.53E-01	8.53E-03	7.92E-04	7.00E-01	7.29E-01	1.57E-01	0.00E+00	0.00E+00	1.88E-01	4.24E-02	1.02E-03	1.17E-02	2.63E-01	3.37E+00	4.58E-01	6.60E-03	8.73E+00
Freshwater ecotoxicity	kg 1,4-DCB	2.87E-01	2.60E-04	2.77E-04	1.97E-03	2.51E-04	7.57E-06	6.88E-03	1.19E-02	2.99E-03	0.00E+00	0.00E+00	1.94E-03	4.58E-04	1.36E-05	1.63E-04	2.42E-03	1.28E-01	4.99E-03	1.84E-04	1.24E-01
Marine ecotoxicity	kg 1,4-DCB	3.20E-01	3.53E-04	3.71E-04	2.23E-03	3.10E-04	1.01E-05	8.11E-03	1.30E-02	3.64E-03	0.00E+00	0.00E+00	2.49E-03	5.98E-04	1.85E-05	2.13E-04	3.22E-03	1.18E-01	6.29E-03	2.36E-04	1.60E-01

Human carcinogenic toxicity	kg 1,4-DCB	3.47E-01	9.23E-06	3.82E-04	1.93E-03	1.11E-04	2.95E-05	6.50E-03	1.08E-02	2.66E-03	0.00E+00	0.00E+00	2.37E-03	4.38E-04	1.54E-04	3.92E-04	3.10E-03	9.41E-02	4.59E-03	1.55E-04	2.20E-01
Human non-carcinogenic toxicity	kg 1,4-DCB	1.09E+03	1.58E-01	-2.29E-03	1.74E-02	1.70E-03	1.07E-04	6.32E-02	3.91E-02	2.85E-01	0.00E+00	0.00E+00	2.19E-01	8.24E-03	3.21E-04	8.60E-03	5.01E-02	1.09E+03	1.34E-01	3.56E-03	2.18E+00
Land use	m2a crop eq	2.21E+01	6.43E-01	3.27E-02	8.41E-02	1.78E-05	3.20E-05	1.50E-01	3.80E-01	1.61E-01	0.00E+00	0.00E+00	2.00E-01	1.45E-04	6.16E-06	2.22E-04	1.28E-03	1.98E+01	4.51E-01	3.05E-05	2.18E-01
Mineral resource scarcity	kg Cu eq	1.73E-02	0.00E+00	4.88E-05	1.70E-04	6.89E-06	1.23E-06	5.05E-04	9.50E-04	2.59E-04	0.00E+00	0.00E+00	2.16E-04	3.56E-05	2.44E-06	2.73E-05	2.18E-04	5.50E-03	5.62E-04	4.34E-06	8.84E-03
Fossil resource scarcity	kg oil eq	4.95E-01	0.00E+00	1.56E-03	7.96E-03	2.44E-04	1.26E-04	2.81E-02	4.59E-02	1.04E-02	0.00E+00	0.00E+00	9.22E-03	7.99E-04	9.04E-05	7.84E-04	2.28E-02	1.09E-01	1.76E-02	4.84E-04	2.40E-01
Water consumption	m3	2.32E-01	3.72E-04	4.78E-05	1.35E-02	7.41E-03	9.41E-06	3.90E-02	9.93E-02	2.18E-04	0.00E+00	0.00E+00	2.98E-03	8.43E-06	2.82E-04	1.06E-05	2.84E-03	1.57E-02	3.88E-02	1.65E-05	1.18E-02

Table A-27. Life cycle impacts for slaughtering 2.04 kg of cattle, live weight, slaughtering operation, System #4. Contribution of slaughtering subprocess. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.
Note: 2.04 kg of cattle, live weight, is required to produce 1 kg of fresh beef meat.

Impact category	Unit	Total	Slaughtering, direct emissions	Building infrastructure	Industrial machine infrastructure	Heat, natural gas	Phosphoric acid	Water	Sodium hydroxide	Potassium hydroxide	Sodium hypochlorite	Soap	Electricity	Wastewater	Treatment of biowaste, municipal incineration	Treatment of MSW, incineration	Recycling of core board
Global warming	kg CO2 eq	9.06E-01	0.00E+00	2.28E-02	3.38E-03	1.10E-01	6.53E-04	1.46E-02	1.56E-03	4.64E-04	2.73E-03	5.87E-05	6.84E-01	8.19E-03	3.52E-02	2.26E-02	0.00E+00
Stratospheric ozone depletion	kg CFC11 eq	7.81E-07	0.00E+00	6.73E-09	1.22E-09	1.36E-08	2.74E-10	8.72E-09	2.44E-09	2.00E-10	2.70E-09	1.86E-10	2.02E-07	6.43E-09	5.12E-07	2.36E-08	0.00E+00
Ionizing radiation	kBq Co-60 eq	8.36E-02	0.00E+00	6.23E-04	1.61E-04	6.52E-04	3.93E-05	1.57E-03	5.97E-04	3.98E-05	2.63E-04	8.32E-07	7.62E-02	2.99E-03	4.18E-04	4.37E-05	0.00E+00
Ozone formation, Human health	kg NOx eq	1.39E-03	0.00E+00	7.27E-05	9.97E-06	9.18E-05	2.33E-06	3.70E-05	3.53E-06	1.08E-06	6.72E-06	8.41E-08	9.19E-04	1.51E-05	2.22E-04	1.36E-05	0.00E+00
Fine particulate matter formation	kg PM2.5 eq	3.30E-03	0.00E+00	4.73E-05	1.01E-05	2.93E-05	2.94E-06	2.91E-05	3.05E-06	9.34E-07	6.30E-06	7.16E-08	3.11E-03	7.76E-06	4.91E-05	2.69E-06	0.00E+00
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.44E-03	0.00E+00	7.51E-05	1.05E-05	1.06E-04	2.37E-06	3.82E-05	3.57E-06	1.09E-06	6.79E-06	9.14E-08	9.49E-04	1.56E-05	2.23E-04	1.37E-05	0.00E+00
Terrestrial acidification	kg SO2 eq	2.33E-03	0.00E+00	1.43E-04	1.88E-05	6.27E-05	8.16E-06	5.08E-05	8.09E-06	1.78E-06	1.08E-05	1.65E-07	1.87E-03	2.32E-05	1.24E-04	7.20E-06	0.00E+00
Freshwater eutrophication	kg P eq	1.04E-03	0.00E+00	1.37E-05	4.70E-06	4.39E-06	9.04E-07	6.62E-06	1.51E-06	2.42E-07	1.60E-06	1.45E-08	8.94E-04	5.75E-05	5.46E-05	3.36E-06	0.00E+00

Marine eutrophication	kg N eq	8.90E-05	0.00E+00	1.91E-06	2.32E-07	3.53E-07	2.94E-08	6.33E-07	1.42E-07	1.54E-08	1.40E-07	7.23E-08	5.63E-05	1.84E-05	1.03E-05	4.76E-07	0.00E+00
Terrestrial ecotoxicity	kg 1,4-DCB	1.07E+00	0.00E+00	1.42E-01	7.31E-02	5.67E-02	5.46E-03	4.14E-02	6.59E-03	1.56E-03	9.96E-03	9.79E-05	6.16E-01	2.99E-02	7.65E-02	1.07E-02	0.00E+00
Freshwater ecotoxicity	kg 1,4-DCB	5.36E-02	0.00E+00	8.96E-04	6.99E-04	8.06E-04	6.35E-05	5.73E-04	8.70E-05	1.68E-05	1.07E-04	1.10E-06	3.11E-02	2.85E-04	5.80E-03	1.32E-02	0.00E+00
Marine ecotoxicity	kg 1,4-DCB	7.15E-02	0.00E+00	1.29E-03	1.00E-03	1.06E-03	9.36E-05	7.81E-04	1.22E-04	2.37E-05	1.51E-04	1.10E-06	4.16E-02	3.95E-04	7.76E-03	1.72E-02	0.00E+00
Human carcinogenic toxicity	kg 1,4-DCB	7.81E-02	0.00E+00	2.15E-03	2.64E-03	2.13E-03	4.85E-04	6.83E-03	1.09E-04	2.09E-05	1.39E-04	1.03E-06	5.39E-02	6.34E-04	8.10E-03	9.67E-04	0.00E+00
Human non-carcinogenic toxicity	kg 1,4-DCB	1.63E+00	0.00E+00	3.39E-02	3.11E-02	1.32E-02	2.56E-03	1.38E-02	3.59E-03	7.20E-04	4.57E-03	2.28E-05	9.95E-01	9.15E-03	2.69E-01	2.55E-01	0.00E+00
Land use	m2a crop eq	1.81E-02	2.41E-03	3.58E-03	8.35E-05	5.13E-04	1.84E-04	2.73E-04	6.34E-05	1.28E-05	6.37E-05	4.78E-05	1.03E-02	1.34E-04	4.22E-04	2.19E-05	0.00E+00
Mineral resource scarcity	kg Cu eq	1.69E-03	0.00E+00	3.66E-04	1.82E-04	9.98E-05	3.78E-05	1.06E-04	6.91E-06	1.52E-06	9.16E-06	9.79E-08	6.33E-04	8.04E-05	1.58E-04	6.66E-06	0.00E+00
Fossil resource scarcity	kg oil eq	2.29E-01	0.00E+00	4.94E-03	8.20E-04	3.67E-02	2.74E-04	3.57E-03	3.94E-04	1.25E-04	6.83E-04	4.23E-06	1.75E-01	8.96E-04	5.25E-03	2.59E-04	0.00E+00
Water consumption	m3	9.98E-03	0.00E+00	1.88E-04	4.43E-05	7.92E-05	7.10E-05	1.60E-02	5.70E-05	4.07E-06	6.21E-05	2.79E-06	5.88E-03	-1.30E-02	4.94E-04	5.22E-05	0.00E+00

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Table A-28. Life cycle impacts for producing 1 kg of ground pork meat, System #5. Contribution of main stages. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	Total	Swine production	Slaughtering	Transport	Grinding
Global warming	kg CO2 eq	7.01E+00	6.30E+00	4.21E-01	3.31E-02	2.57E-01
Stratospheric ozone depletion	kg CFC11 eq	2.43E-05	2.40E-05	2.03E-07	1.12E-08	7.61E-08
Ionizing radiation	kBq Co-60 eq	1.98E-01	1.35E-01	3.37E-02	6.43E-04	2.87E-02
Ozone formation, Human health	kg NOx eq	1.36E-02	1.25E-02	5.55E-04	2.29E-04	3.45E-04
Fine particulate matter formation	kg PM2.5 eq	1.86E-02	1.61E-02	1.27E-03	5.40E-05	1.17E-03
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.42E-02	1.30E-02	5.83E-04	2.33E-04	3.57E-04
Terrestrial acidification	kg SO2 eq	6.90E-02	6.72E-02	9.09E-04	1.28E-04	7.02E-04
Freshwater eutrophication	kg P eq	2.74E-03	2.00E-03	4.03E-04	4.11E-06	3.36E-04
Marine eutrophication	kg N eq	7.45E-03	7.40E-03	3.62E-05	3.06E-07	2.12E-05
Terrestrial ecotoxicity	kg 1,4-DCB	2.36E+01	2.23E+01	4.61E-01	5.76E-01	2.32E-01
Freshwater ecotoxicity	kg 1,4-DCB	2.82E-01	2.49E-01	2.03E-02	5.22E-04	1.17E-02
Marine ecotoxicity	kg 1,4-DCB	3.70E-01	3.26E-01	2.71E-02	1.02E-03	1.56E-02
Human carcinogenic toxicity	kg 1,4-DCB	1.00E+00	9.49E-01	3.10E-02	7.24E-04	2.03E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	4.65E+00	3.66E+00	5.88E-01	2.60E-02	3.74E-01
Land use	m2a crop eq	5.20E+00	5.19E+00	6.93E-03	1.74E-03	3.85E-03
Mineral resource scarcity	kg Cu eq	5.02E-02	4.92E-02	6.90E-04	6.35E-05	2.38E-04
Fossil resource scarcity	kg oil eq	1.07E+00	8.83E-01	1.13E-01	1.17E-02	6.58E-02
Water consumption	m3	4.64E-01	4.57E-01	4.50E-03	9.26E-05	2.21E-03

Table A-29. Life cycle impacts for producing 1.49 kg of swine, live weight, industrial system, System #5, cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.
Note: 1.49 kg of swine, live weight, at industrial system is required to produce 1 kg of fresh pork meat.

Impact category	Unit	Total	Direct emissions	Barley grain cultivation	Chemical, organic production	Limestone production	Liquid manure storage and processing facility	Maize grain cultivation	Liquid manure treatment	Oat grain cultivation	Operation of pig housing system	Rape meal production	Sodium chloride production	Soybean meal production	Soybean cultivation	Wheat grain cultivation	Whey cultivation	Slaughterhouse waste treatment
Global warming	kg CO2 eq	6.30E+00	1.84E+00	2.48E-01	1.42E-02	1.74E-04	1.72E+00	7.17E-01	0.00E+00	1.72E-01	1.19E+00	6.65E-02	2.75E-03	1.76E-01	6.52E-02	8.92E-02	7.83E-04	2.03E-03
Stratospheric ozone depletion	kg CFC11 eq	2.40E-05	2.72E-06	3.33E-06	2.43E-09	1.49E-10	2.78E-07	7.72E-06	0.00E+00	3.99E-06	3.26E-07	1.10E-06	8.88E-10	2.20E-06	1.12E-06	1.19E-06	4.06E-09	5.46E-10
Ionizing radiation	kBq Co-60 eq	1.35E-01	0.00E+00	4.80E-03	3.78E-04	2.36E-06	3.19E-02	2.06E-02	0.00E+00	1.64E-03	6.42E-02	1.91E-03	2.29E-04	4.93E-03	1.30E-03	2.75E-03	1.56E-05	6.65E-05
Ozone formation, Human health	kg NOx eq	1.25E-02	0.00E+00	8.31E-04	3.02E-05	1.91E-06	5.50E-03	1.72E-03	0.00E+00	5.10E-04	2.57E-03	2.17E-04	8.75E-06	6.09E-04	2.05E-04	3.05E-04	1.42E-06	3.61E-06
Fine particulate matter formation	kg PM2.5 eq	1.61E-02	7.70E-03	4.50E-04	1.65E-05	6.68E-07	2.48E-03	1.42E-03	0.00E+00	3.40E-04	3.12E-03	1.75E-04	5.93E-06	1.99E-04	6.99E-05	1.68E-04	1.12E-06	1.64E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.30E-02	0.00E+00	8.56E-04	3.30E-05	1.96E-06	5.72E-03	1.77E-03	0.00E+00	5.23E-04	2.68E-03	2.26E-04	9.00E-06	6.40E-04	2.10E-04	3.15E-04	1.47E-06	3.87E-06
Terrestrial acidification	kg SO2 eq	6.72E-02	4.78E-02	1.87E-03	3.96E-05	1.15E-06	4.38E-03	5.26E-03	0.00E+00	1.95E-03	3.57E-03	1.02E-03	1.27E-05	4.75E-04	1.59E-04	6.96E-04	4.91E-06	3.20E-06
Freshwater eutrophication	kg P eq	2.00E-03	0.00E+00	6.50E-05	3.17E-06	1.96E-08	4.24E-04	3.26E-04	0.00E+00	1.65E-04	8.28E-04	1.94E-05	1.59E-06	3.14E-05	1.35E-05	1.20E-04	1.63E-07	4.54E-07
Marine eutrophication	kg N eq	7.40E-03	0.00E+00	1.15E-03	2.49E-07	4.91E-09	3.79E-05	1.20E-03	0.00E+00	4.07E-03	7.88E-05	4.14E-04	2.57E-07	1.98E-05	9.73E-06	4.13E-04	7.09E-07	9.72E-08
Terrestrial ecotoxicity	kg 1,4-DCB	2.23E+01	0.00E+00	1.06E+00	3.25E-02	1.57E-03	8.56E+00	2.35E+00	0.00E+00	3.91E-01	8.24E+00	2.15E-01	3.47E-02	7.81E-01	2.69E-01	3.91E-01	2.65E-03	6.49E-03
Freshwater ecotoxicity	kg 1,4-DCB	2.49E-01	0.00E+00	1.17E-02	3.48E-04	3.88E-06	6.68E-02	3.77E-02	0.00E+00	1.11E-02	1.07E-01	2.23E-03	3.76E-04	4.05E-03	2.01E-03	5.26E-03	3.50E-05	6.15E-05
Marine ecotoxicity	kg 1,4-DCB	3.26E-01	0.00E+00	1.51E-02	4.62E-04	5.78E-06	9.39E-02	4.24E-02	0.00E+00	1.49E-02	1.41E-01	2.85E-03	4.90E-04	5.74E-03	2.74E-03	6.55E-03	3.37E-05	8.05E-05
Human carcinogenic toxicity	kg 1,4-DCB	9.49E-01	0.00E+00	1.20E-02	5.33E-04	9.95E-06	6.05E-01	3.14E-02	0.00E+00	6.06E-03	2.78E-01	2.72E-03	3.59E-04	6.10E-03	2.08E-03	4.59E-03	2.74E-05	6.79E-05
Human non-carcinogenic toxicity	kg 1,4-DCB	3.66E+00	0.00E+00	2.44E-01	7.60E-03	1.02E-04	1.34E+00	2.17E-01	0.00E+00	-6.92E-01	1.99E+00	2.51E-01	6.76E-03	1.11E-01	4.68E-02	1.41E-01	4.16E-04	1.10E-03

Land use	m2a crop eq	5.19E+00	0.00E+00	8.03E-01	1.56E-04	2.55E-05	1.62E-01	9.80E-01	0.00E+00	8.65E-01	1.09E-01	2.30E-01	1.19E-04	1.02E+00	5.25E-01	4.94E-01	3.22E-03	2.92E-05
Mineral resource scarcity	kg Cu eq	4.92E-02	0.00E+00	1.50E-03	2.70E-05	4.83E-07	2.90E-02	2.77E-03	0.00E+00	8.02E-04	1.34E-02	2.48E-04	2.92E-05	5.75E-04	2.70E-04	5.90E-04	2.35E-06	3.87E-06
Fossil resource scarcity	kg oil eq	8.83E-01	0.00E+00	4.46E-02	8.84E-03	5.10E-05	3.31E-01	1.32E-01	0.00E+00	1.83E-02	2.81E-01	1.06E-02	6.55E-04	2.99E-02	8.10E-03	1.72E-02	9.69E-05	6.57E-04
Water consumption	m3	4.57E-01	0.00E+00	7.78E-02	2.19E-04	2.62E-06	1.44E-02	2.56E-01	0.00E+00	6.07E-04	5.76E-02	3.42E-03	6.92E-06	2.59E-03	1.28E-03	4.25E-02	2.42E-05	-2.16E-05

Table A-30. Life cycle impacts for slaughtering 1.49 kg of swine, live weight, slaughtering operation, System #5. Contribution of slaughtering subprocess. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.
Note: 1.49 kg of swine, live weight, is required to produce 1 kg of fresh pork meat.

Impact category	Unit	Total	Slaughtering, direct emissions	Building infrastructure	Industrial machine infrastructure	Water	Carbon dioxide, liquid	Phosphoric acid	Sodium hydroxide	Potassium hydroxide	Sodium hypochlorite	Fatty alcohol sulfate	Electricity	Heat, natural gas	Wastewater	Treatment of MSW, incineration	Treatment of biowaste, anaerobic digestion	Treatment of biowaste, incineration	Recycling of core board
Global warming	kg CO2 eq	4.21E-01	0.00E+00	3.62E-03	1.61E-03	8.89E-03	4.00E-03	3.34E-04	1.98E-03	3.70E-04	2.17E-03	3.23E-05	2.60E-01	1.18E-01	4.99E-03	9.20E-03	8.78E-05	5.84E-03	0.00E+00
Stratospheric ozone depletion	kg CFC11 eq	2.03E-07	0.00E+00	1.07E-09	5.79E-10	5.31E-09	9.05E-10	1.57E-10	2.13E-09	1.59E-10	2.15E-09	1.19E-10	7.69E-08	1.46E-08	3.91E-09	9.63E-09	2.82E-10	8.49E-08	0.00E+00
Ionizing radiation	kBq Co-60 eq	3.37E-02	0.00E+00	9.88E-05	7.66E-05	9.53E-04	5.00E-04	2.42E-05	2.27E-04	3.16E-05	2.09E-04	1.51E-06	2.90E-02	7.00E-04	1.82E-03	1.78E-05	1.14E-06	6.92E-05	0.00E+00
Ozone formation, Human health	kg NOx eq	5.55E-04	0.00E+00	1.15E-05	4.74E-06	2.25E-05	3.78E-06	1.36E-06	5.00E-06	8.59E-07	5.34E-06	8.60E-08	3.49E-04	9.85E-05	9.19E-06	5.56E-06	4.07E-08	3.68E-05	0.00E+00
Fine particulate matter formation	kg PM2.5 eq	1.27E-03	0.00E+00	7.50E-06	4.82E-06	1.77E-05	3.07E-06	1.98E-06	4.58E-06	7.43E-07	5.01E-06	6.76E-08	1.18E-03	3.14E-05	4.72E-06	1.10E-06	2.09E-08	8.13E-06	0.00E+00
Ozone formation, Terrestrial ecosystems	kg NOx eq	5.83E-04	0.00E+00	1.19E-05	5.00E-06	2.32E-05	3.86E-06	1.39E-06	5.05E-06	8.71E-07	5.40E-06	9.32E-08	3.61E-04	1.13E-04	9.47E-06	5.59E-06	4.24E-08	3.70E-05	0.00E+00
Terrestrial acidification	kg SO2 eq	9.09E-04	0.00E+00	2.27E-05	8.94E-06	3.09E-05	8.59E-06	5.55E-06	7.89E-06	1.42E-06	8.58E-06	2.05E-07	7.10E-04	6.73E-05	1.41E-05	2.94E-06	5.02E-08	2.05E-05	0.00E+00
Freshwater eutrophication	kg P eq	4.03E-04	0.00E+00	2.18E-06	2.24E-06	4.03E-06	1.52E-06	1.99E-07	1.18E-06	1.93E-07	1.27E-06	1.97E-08	3.40E-04	4.71E-06	3.50E-05	1.37E-06	2.91E-09	9.05E-06	0.00E+00
Marine eutrophication	kg N eq	3.62E-05	0.00E+00	3.03E-07	1.10E-07	3.85E-07	2.70E-07	1.84E-08	1.07E-07	1.23E-08	1.11E-07	5.94E-08	2.14E-05	3.79E-07	1.12E-05	1.94E-07	1.38E-09	1.71E-06	0.00E+00

Terrestrial ecotoxicity	kg 1,4-DCB	4.61E-01	0.00E+00	2.25E-02	3.48E-02	2.52E-02	2.96E-02	2.91E-03	6.51E-03	1.24E-03	7.92E-03	1.11E-04	2.34E-01	6.08E-02	1.82E-02	4.37E-03	3.18E-05	1.27E-02	0.00E+00
Freshwater ecotoxicity	kg 1,4-DCB	2.03E-02	0.00E+00	1.42E-04	3.33E-04	3.49E-04	1.24E-04	1.89E-05	7.19E-05	1.34E-05	8.54E-05	2.75E-06	1.18E-02	8.65E-04	1.73E-04	5.37E-03	2.24E-07	9.61E-04	0.00E+00
Marine ecotoxicity	kg 1,4-DCB	2.71E-02	0.00E+00	2.05E-04	4.77E-04	4.75E-04	1.72E-04	2.90E-05	1.01E-04	1.89E-05	1.20E-04	2.26E-06	1.58E-02	1.14E-03	2.40E-04	7.02E-03	3.29E-07	1.29E-03	0.00E+00
Human carcinogenic toxicity	kg 1,4-DCB	3.10E-02	0.00E+00	3.40E-04	1.26E-03	4.16E-03	1.26E-04	1.56E-05	9.92E-05	1.66E-05	1.11E-04	1.56E-06	2.05E-02	2.29E-03	3.86E-04	3.94E-04	9.04E-07	1.34E-03	0.00E+00
Human non-carcinogenic toxicity	kg 1,4-DCB	5.88E-01	0.00E+00	5.38E-03	1.48E-02	8.38E-03	5.19E-03	9.17E-04	3.00E-03	5.73E-04	3.63E-03	6.27E-05	3.78E-01	1.42E-02	5.56E-03	1.04E-01	9.81E-06	4.46E-02	0.00E+00
Land use	m2a crop eq	6.93E-03	1.18E-03	5.67E-04	3.97E-05	1.66E-04	8.93E-05	1.37E-04	4.46E-05	1.02E-05	5.07E-05	3.97E-05	3.90E-03	5.51E-04	8.15E-05	8.92E-06	1.45E-06	6.99E-05	0.00E+00
Mineral resource scarcity	kg Cu eq	6.90E-04	0.00E+00	5.81E-05	8.67E-05	6.45E-05	1.24E-05	2.81E-05	5.60E-06	1.21E-06	7.28E-06	1.58E-07	2.41E-04	1.07E-04	4.89E-05	2.72E-06	5.55E-08	2.62E-05	0.00E+00
Fossil resource scarcity	kg oil eq	1.13E-01	0.00E+00	7.83E-04	3.90E-04	2.17E-03	7.16E-04	1.74E-04	4.98E-04	9.94E-05	5.43E-04	7.50E-06	6.65E-02	3.94E-02	5.45E-04	1.06E-04	6.59E-06	8.69E-04	0.00E+00
Water consumption	m3	4.50E-03	0.00E+00	2.98E-05	2.11E-05	9.75E-03	2.80E-05	3.65E-05	5.01E-05	3.24E-06	4.94E-05	5.17E-06	2.24E-03	8.49E-05	-7.90E-03	2.13E-05	9.51E-08	8.18E-05	0.00E+00

Table A-31. Life cycle impacts for producing 1 kg of ground chicken meat, System #6. Contribution of main stages. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	Total	Broiler production	Slaughtering	Transport	Grinding
Global warming	kg CO2 eq	2.59E+00	1.72E+00	5.87E-01	3.31E-02	2.57E-01
Stratospheric ozone depletion	kg CFC11 eq	2.38E-05	2.35E-05	1.98E-07	1.12E-08	7.61E-08
Ionizing radiation	kBq Co-60 eq	1.40E-01	5.83E-02	5.28E-02	6.43E-04	2.87E-02
Ozone formation, Human health	kg NOx eq	5.00E-03	3.66E-03	7.66E-04	2.29E-04	3.45E-04
Fine particulate matter formation	kg PM2.5 eq	1.01E-02	6.82E-03	2.01E-03	5.40E-05	1.17E-03
Ozone formation, Terrestrial ecosystems	kg NOx eq	5.16E-03	3.77E-03	8.01E-04	2.33E-04	3.57E-04
Terrestrial acidification	kg SO2 eq	3.97E-02	3.75E-02	1.38E-03	1.28E-04	7.02E-04
Freshwater eutrophication	kg P eq	1.83E-03	8.64E-04	6.20E-04	4.11E-06	3.36E-04
Marine eutrophication	kg N eq	4.98E-03	4.91E-03	5.20E-05	3.06E-07	2.12E-05
Terrestrial ecotoxicity	kg 1,4-DCB	5.52E+00	4.06E+00	6.46E-01	5.76E-01	2.32E-01
Freshwater ecotoxicity	kg 1,4-DCB	9.95E-02	5.91E-02	2.82E-02	5.22E-04	1.17E-02
Marine ecotoxicity	kg 1,4-DCB	1.24E-01	6.95E-02	3.77E-02	1.02E-03	1.56E-02
Human carcinogenic toxicity	kg 1,4-DCB	1.36E-01	7.03E-02	4.51E-02	7.24E-04	2.03E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	2.10E+00	8.81E-01	8.21E-01	2.60E-02	3.74E-01
Land use	m2a crop eq	2.30E+00	2.28E+00	1.00E-02	1.74E-03	3.85E-03
Mineral resource scarcity	kg Cu eq	5.77E-03	4.54E-03	9.31E-04	6.35E-05	2.38E-04
Fossil resource scarcity	kg oil eq	5.05E-01	2.74E-01	1.54E-01	1.17E-02	6.58E-02
Water consumption	m3	3.24E-01	3.15E-01	6.63E-03	9.26E-05	2.21E-03

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Table A-32. Life cycle impacts for producing 1.52 kg of broiler, live weight, industrial system, System #6, cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.
Note: 1.52 kg of broiler, live weight, at industrial system is required to produce 1 kg of fresh chicken meat.

Impact category	Unit	Total	Direct emissions	Energy feed	Poultry manure	Protein feed	Shed	Broiler housing	Electricity	Heat, natural gas
Global warming	kg CO2 eq	1.72E+00	3.42E-01	7.92E-01	0.00E+00	2.73E-01	1.25E-05	7.82E-03	2.77E-01	2.47E-02
Stratospheric ozone depletion	kg CFC11 eq	2.35E-05	1.19E-05	8.52E-06	0.00E+00	2.95E-06	3.25E-12	1.53E-08	8.20E-08	3.06E-09
Ionizing radiation	kBq Co-60 eq	5.83E-02	0.00E+00	1.98E-02	0.00E+00	6.71E-03	2.77E-07	4.46E-04	3.11E-02	1.47E-04
Ozone formation, Human health	kg NOx eq	3.66E-03	0.00E+00	2.41E-03	0.00E+00	8.33E-04	4.03E-08	2.14E-05	3.72E-04	2.07E-05
Fine particulate matter formation	kg PM2.5 eq	6.82E-03	3.51E-03	1.53E-03	0.00E+00	4.88E-04	2.30E-08	2.18E-05	1.27E-03	6.59E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.77E-03	0.00E+00	2.48E-03	0.00E+00	8.62E-04	4.18E-08	2.24E-05	3.84E-04	2.38E-05
Terrestrial acidification	kg SO2 eq	3.75E-02	2.87E-02	6.01E-03	0.00E+00	1.90E-03	4.39E-08	9.21E-05	7.49E-04	1.41E-05
Freshwater eutrophication	kg P eq	8.64E-04	7.46E-05	3.18E-04	0.00E+00	1.01E-04	1.52E-08	5.88E-06	3.64E-04	9.88E-07
Marine eutrophication	kg N eq	4.91E-03	2.77E-03	1.59E-03	0.00E+00	5.23E-04	1.15E-09	9.39E-07	2.30E-05	7.95E-08
Terrestrial ecotoxicity	kg 1,4-DCB	4.06E+00	0.00E+00	2.77E+00	0.00E+00	9.99E-01	1.51E-04	1.29E-01	1.53E-01	1.28E-02
Freshwater ecotoxicity	kg 1,4-DCB	5.91E-02	0.00E+00	3.58E-02	0.00E+00	1.17E-02	1.62E-06	7.68E-04	1.06E-02	1.81E-04
Marine ecotoxicity	kg 1,4-DCB	6.95E-02	0.00E+00	4.05E-02	0.00E+00	1.32E-02	2.10E-06	1.12E-03	1.45E-02	2.39E-04
Human carcinogenic toxicity	kg 1,4-DCB	7.03E-02	0.00E+00	3.50E-02	0.00E+00	1.15E-02	2.04E-06	1.54E-03	2.18E-02	4.80E-04

Human non-carcinogenic toxicity	kg 1,4-DCB	8.81E-01	0.00E+00	3.16E-01	0.00E+00	1.39E-01	2.72E-05	3.32E-02	3.90E-01	2.98E-03
Land use	m2a crop eq	2.28E+00	0.00E+00	1.53E+00	0.00E+00	7.49E-01	1.58E-05	2.91E-03	4.13E-03	1.15E-04
Mineral resource scarcity	kg Cu eq	4.54E-03	0.00E+00	3.09E-03	0.00E+00	1.03E-03	1.44E-07	1.87E-04	2.05E-04	2.25E-05
Fossil resource scarcity	kg oil eq	2.74E-01	0.00E+00	1.44E-01	0.00E+00	4.76E-02	2.22E-06	2.12E-03	7.13E-02	8.26E-03
Water consumption	m3	3.15E-01	7.77E-04	2.44E-01	0.00E+00	6.74E-02	1.05E-07	1.23E-04	2.39E-03	1.78E-05

Table A-33. Life cycle impacts for slaughtering 1.52 kg of broiler, live weight, slaughtering operation, System #6. Contribution of slaughtering subprocess. Cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.
Note: 1.52 kg of broiler, live weight, is required to produce 1 kg of fresh chicken meat.

Impact category	Unit	Total	Direct emissions	Building infrastructure	Industrial machine infrastructure	Heat, natural gas	Water	Phosphoric acid	Sodium hydroxide	Potassium hydroxide	Sodium hypochlorite	Soap	Electricity	Sodium hydroxide	Iron chloride	Treatment of MSW by incineration	Treatment of biowaste by anaerobic digestion	Core board recycling	Mixed plastics recycling	Wastewater
Global warming	kg CO2 eq	5.87E-01	0.00E+00	4.60E-03	2.39E-03	1.12E-01	1.20E-02	3.44E-04	2.92E-03	5.44E-04	2.57E-03	5.50E-05	4.18E-01	4.97E-03	2.95E-03	1.09E-02	6.21E-03	0.00E+00	0.00E+00	6.71E-03
Stratospheric ozone depletion	kg CFC11 eq	1.98E-07	0.00E+00	1.36E-09	8.61E-10	1.39E-08	7.15E-09	1.44E-10	3.13E-09	2.35E-10	2.55E-09	1.74E-10	1.24E-07	5.33E-09	2.70E-09	1.14E-08	1.99E-08	0.00E+00	0.00E+00	5.27E-09
Ionizing radiation	kBq Co-60 eq	5.28E-02	0.00E+00	1.26E-04	1.14E-04	6.67E-04	1.28E-03	2.07E-05	3.34E-04	4.66E-05	2.48E-04	7.80E-07	4.66E-02	5.69E-04	2.53E-04	2.11E-05	8.04E-05	0.00E+00	0.00E+00	2.45E-03
Ozone formation, Human health	kg NOx eq	7.66E-04	0.00E+00	1.47E-05	7.05E-06	9.38E-05	3.03E-05	1.23E-06	7.36E-06	1.27E-06	6.34E-06	7.88E-08	5.61E-04	1.25E-05	8.17E-06	6.58E-06	2.88E-06	0.00E+00	0.00E+00	1.24E-05
Fine particulate matter formation	kg PM2.5 eq	2.01E-03	0.00E+00	9.54E-06	7.16E-06	2.99E-05	2.38E-05	1.55E-06	6.75E-06	1.09E-06	5.94E-06	6.71E-08	1.90E-03	1.15E-05	7.52E-06	1.30E-06	1.48E-06	0.00E+00	0.00E+00	6.36E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	8.01E-04	0.00E+00	1.51E-05	7.42E-06	1.08E-04	3.13E-05	1.25E-06	7.43E-06	1.28E-06	6.40E-06	8.56E-08	5.80E-04	1.27E-05	8.27E-06	6.62E-06	3.00E-06	0.00E+00	0.00E+00	1.27E-05
Terrestrial acidification	kg SO2 eq	1.38E-03	0.00E+00	2.89E-05	1.33E-05	6.41E-05	4.17E-05	4.30E-06	1.16E-05	2.09E-06	1.02E-05	1.54E-07	1.14E-03	1.98E-05	1.36E-05	3.48E-06	3.55E-06	0.00E+00	0.00E+00	1.90E-05

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Freshwater eutrophication	kg P eq	6.20E-04	0.00E+00	2.77E-06	3.32E-06	4.49E-06	5.42E-06	4.76E-07	1.73E-06	2.84E-07	1.51E-06	1.36E-08	5.46E-04	2.95E-06	2.30E-06	1.62E-06	2.05E-07	0.00E+00	0.00E+00	4.71E-05
Marine eutrophication	kg N eq	5.20E-05	0.00E+00	3.85E-07	1.64E-07	3.61E-07	5.18E-07	1.55E-08	1.58E-07	1.81E-08	1.32E-07	6.77E-08	3.44E-05	2.68E-07	1.74E-07	2.30E-07	9.75E-08	0.00E+00	0.00E+00	1.51E-05
Terrestrial ecotoxicity	kg 1,4-DCB	6.46E-01	0.00E+00	2.87E-02	5.17E-02	5.79E-02	3.40E-02	2.88E-03	9.59E-03	1.82E-03	9.39E-03	9.17E-05	3.76E-01	1.63E-02	2.55E-02	5.18E-03	2.25E-03	0.00E+00	0.00E+00	2.45E-02
Freshwater ecotoxicity	kg 1,4-DCB	2.82E-02	0.00E+00	1.81E-04	4.94E-04	8.24E-04	4.70E-04	3.35E-05	1.06E-04	1.97E-05	1.01E-04	1.03E-06	1.90E-02	1.80E-04	2.35E-04	6.35E-03	1.58E-05	0.00E+00	0.00E+00	2.34E-04
Marine ecotoxicity	kg 1,4-DCB	3.77E-02	0.00E+00	2.61E-04	7.08E-04	1.08E-03	6.40E-04	4.93E-05	1.49E-04	2.78E-05	1.43E-04	1.03E-06	2.54E-02	2.53E-04	3.35E-04	8.31E-03	2.32E-05	0.00E+00	0.00E+00	3.24E-04
Human carcinogenic toxicity	kg 1,4-DCB	4.51E-02	0.00E+00	4.33E-04	1.87E-03	2.18E-03	5.60E-03	2.56E-04	1.46E-04	2.44E-05	1.31E-04	9.66E-07	3.29E-02	2.49E-04	2.29E-04	4.67E-04	6.39E-05	0.00E+00	0.00E+00	5.20E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	8.21E-01	0.00E+00	6.85E-03	2.20E-02	1.35E-02	1.13E-02	1.35E-03	4.42E-03	8.43E-04	4.31E-03	2.14E-05	6.07E-01	7.52E-03	1.04E-02	1.23E-01	6.94E-04	0.00E+00	0.00E+00	7.49E-03
Land use	m2a crop eq	1.00E-02	1.51E-03	7.22E-04	5.90E-05	5.24E-04	2.23E-04	9.69E-05	6.57E-05	1.50E-05	6.01E-05	4.48E-05	6.26E-03	1.12E-04	1.15E-04	1.06E-05	1.03E-04	0.00E+00	0.00E+00	1.10E-04
Mineral resource scarcity	kg Cu eq	9.31E-04	0.00E+00	7.39E-05	1.29E-04	1.02E-04	8.69E-05	1.99E-05	8.25E-06	1.78E-06	8.64E-06	9.17E-08	3.87E-04	1.40E-05	2.71E-05	3.22E-06	3.92E-06	0.00E+00	0.00E+00	6.58E-05
Fossil resource scarcity	kg oil eq	1.54E-01	0.00E+00	9.97E-04	5.80E-04	3.75E-02	2.92E-03	1.44E-04	7.34E-04	1.46E-04	6.44E-04	3.96E-06	1.07E-01	1.25E-03	7.41E-04	1.25E-04	4.66E-04	0.00E+00	0.00E+00	7.34E-04
Water consumption	m3	6.63E-03	0.00E+00	3.80E-05	3.13E-05	8.09E-05	1.31E-02	3.74E-05	7.38E-05	4.76E-06	5.85E-05	2.62E-06	3.59E-03	1.26E-04	5.97E-05	2.52E-05	6.72E-06	0.00E+00	0.00E+00	-1.06E-02

Table A-34. Life cycle impacts for producing 1 kg ground food with meat or meat alternatives ready to be cooked, from cradle-to-manufacturing gate, before packaging or cooling, System #1-6. Comparison of final meat recipes.
Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	System 1, Protein from Yellow Peas - DF - LME	System 2, Protein from Yellow Peas - WF - HME	System 3, Protein from Soy - WF - HME	System 4, Conventional. Beef Meat, Ground	System 5, Conventional, Pork Meat, Ground	System 6, Conventional, Chicken Meat, Ground
Global warming	kg CO2 eq	7.47E-01	9.82E-01	8.57E-01	1.45E+01	7.01E+00	2.59E+00
Stratospheric ozone depletion	kg CFC11 eq	2.47E-06	2.49E-06	4.11E-06	1.21E-04	2.43E-05	2.38E-05
Ionizing radiation	kBq Co-60 eq	2.28E-02	3.05E-02	2.51E-02	2.09E-01	1.98E-01	1.40E-01
Ozone formation, Human health	kg NOx eq	1.46E-03	1.65E-03	1.85E-03	9.39E-03	1.36E-02	5.00E-03
Fine particulate matter formation	kg PM2.5 eq	1.59E-03	1.89E-03	1.67E-03	1.91E-02	1.86E-02	1.01E-02
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.51E-03	1.72E-03	2.00E-03	9.66E-03	1.42E-02	5.16E-03
Terrestrial acidification	kg SO2 eq	4.24E-03	4.43E-03	4.28E-03	8.80E-02	6.90E-02	3.97E-02
Freshwater eutrophication	kg P eq	3.76E-04	4.44E-04	3.61E-04	7.85E-03	2.74E-03	1.83E-03
Marine eutrophication	kg N eq	7.59E-04	7.69E-04	8.10E-04	1.95E-02	7.45E-03	4.98E-03
Terrestrial ecotoxicity	kg 1,4-DCB	1.91E+00	1.97E+00	2.06E+00	1.67E+01	2.36E+01	5.52E+00
Freshwater ecotoxicity	kg 1,4-DCB	3.47E-02	3.75E-02	3.36E-02	3.52E-01	2.82E-01	9.95E-02
Marine ecotoxicity	kg 1,4-DCB	3.25E-02	3.63E-02	3.12E-02	4.08E-01	3.70E-01	1.24E-01
Human carcinogenic toxicity	kg 1,4-DCB	2.94E-02	3.68E-02	3.13E-02	4.47E-01	1.00E+00	1.36E-01
Human non-carcinogenic toxicity	kg 1,4-DCB	4.64E-01	7.01E-01	9.28E-01	1.09E+03	4.65E+00	2.10E+00
Land use	m2a crop eq	2.20E+00	1.90E+00	2.09E+00	2.21E+01	5.20E+00	2.30E+00
Mineral resource scarcity	kg Cu eq	2.12E-03	2.17E-03	1.90E-03	1.93E-02	5.02E-02	5.77E-03
Fossil resource scarcity	kg oil eq	1.24E-01	1.98E-01	1.42E-01	8.02E-01	1.07E+00	5.05E-01
Water consumption	m3	1.79E-02	1.85E-02	1.70E-02	2.45E-01	4.64E-01	3.24E-01

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Table A-35. Life cycle impacts for producing 1 kg ground food with meat or meat alternatives ready to be cooked, from cradle-to-manufacturing gate, before packaging or cooling, System #1–3, plant-based systems. Comparison of final meat recipes for plant-based systems.
Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	System 1 - Peas - DF - LME	System 2 - Peas - WF - HME	System 3 - Soy - WF - HME
Global warming	kg CO2 eq	7.47E-01	9.82E-01	8.57E-01
Stratospheric ozone depletion	kg CFC11 eq	2.47E-06	2.49E-06	4.11E-06
Ionizing radiation	kBq Co-60 eq	2.28E-02	3.05E-02	2.51E-02
Ozone formation, Human health	kg NOx eq	1.46E-03	1.65E-03	1.85E-03
Fine particulate matter formation	kg PM2.5 eq	1.59E-03	1.89E-03	1.67E-03
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.51E-03	1.72E-03	2.00E-03
Terrestrial acidification	kg SO2 eq	4.24E-03	4.43E-03	4.28E-03
Freshwater eutrophication	kg P eq	3.76E-04	4.44E-04	3.61E-04
Marine eutrophication	kg N eq	7.59E-04	7.69E-04	8.10E-04
Terrestrial ecotoxicity	kg 1,4-DCB	1.91E+00	1.97E+00	2.06E+00
Freshwater ecotoxicity	kg 1,4-DCB	3.47E-02	3.75E-02	3.36E-02
Marine ecotoxicity	kg 1,4-DCB	3.25E-02	3.63E-02	3.12E-02
Human carcinogenic toxicity	kg 1,4-DCB	2.94E-02	3.68E-02	3.13E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	4.64E-01	7.01E-01	9.28E-01
Land use	m2a crop eq	2.20E+00	1.90E+00	2.09E+00
Mineral resource scarcity	kg Cu eq	2.12E-03	2.17E-03	1.90E-03
Fossil resource scarcity	kg oil eq	1.24E-01	1.98E-01	1.42E-01
Water consumption	m3	1.79E-02	1.85E-02	1.70E-02

Table A-36. Life cycle impacts for producing extruded meat analogues required to deliver 0.15 kg of extrudate-only protein content to final meat recipe, System #1: 0.283 kg, System #2: 0.441 kg, System #3: 0.714 kg, Systems #1–3, plant -based systems. Comparison of meat extrudates for plant-based systems.
Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	System 1 - Peas - DF - LME	System 2 - Peas - WF - HME	System 3 - Soy - WF - HME
Global warming	kg CO2 eq	2.13E-01	4.48E-01	3.23E-01
Stratospheric ozone depletion	kg CFC11 eq	1.08E-07	1.37E-07	1.75E-06
Ionizing radiation	kBq Co-60 eq	1.40E-02	2.17E-02	1.64E-02
Ozone formation, Human health	kg NOx eq	3.54E-04	5.46E-04	7.45E-04
Fine particulate matter formation	kg PM2.5 eq	6.02E-04	9.04E-04	6.82E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.74E-04	5.90E-04	8.74E-04
Terrestrial acidification	kg SO2 eq	6.25E-04	8.13E-04	6.64E-04
Freshwater eutrophication	kg P eq	2.15E-04	2.84E-04	2.01E-04
Marine eutrophication	kg N eq	1.24E-05	2.20E-05	6.30E-05
Terrestrial ecotoxicity	kg 1,4-DCB	4.17E-01	4.77E-01	5.66E-01
Freshwater ecotoxicity	kg 1,4-DCB	9.96E-03	1.28E-02	8.88E-03
Marine ecotoxicity	kg 1,4-DCB	1.33E-02	1.70E-02	1.20E-02
Human carcinogenic toxicity	kg 1,4-DCB	1.54E-02	2.29E-02	1.75E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	-1.82E-01	5.52E-02	2.83E-01
Land use	m2a crop eq	8.80E-01	5.87E-01	7.76E-01
Mineral resource scarcity	kg Cu eq	8.50E-04	8.95E-04	6.33E-04
Fossil resource scarcity	kg oil eq	5.93E-02	1.34E-01	7.74E-02
Water consumption	m3	1.21E-03	1.95E-03	7.15E-04

Table A-37. Life cycle impacts for producing protein concentrates and isolates required to deliver 0.15 kg of extrudate-only protein content to final meat recipe, System #1: 0.291 kg, System #2: 0.190 kg, System #3: 0.215 kg, Systems #1–3, plant -based systems. Comparison of protein concentrates and isolates for plant-based systems.
Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	System 1 – Pea protein concentrate - DF	System 2 – Pea protein isolate - WF	System 3 - Soy protein concentrate - WF
Global warming	kg CO2 eq	1.59E-01	3.52E-01	2.10E-01
Stratospheric ozone depletion	kg CFC11 eq	9.42E-08	1.08E-07	1.70E-06
Ionizing radiation	kBq Co-60 eq	1.12E-02	1.13E-02	4.19E-03
Ozone formation, Human health	kg NOx eq	2.92E-04	4.17E-04	5.82E-04
Fine particulate matter formation	kg PM2.5 eq	4.88E-04	4.79E-04	1.96E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.08E-04	4.57E-04	7.06E-04
Terrestrial acidification	kg SO2 eq	5.31E-04	5.54E-04	3.43E-04
Freshwater eutrophication	kg P eq	1.84E-04	1.59E-04	4.24E-05
Marine eutrophication	kg N eq	1.03E-05	1.17E-05	1.83E-05
Terrestrial ecotoxicity	kg 1,4-DCB	3.73E-01	3.90E-01	4.44E-01
Freshwater ecotoxicity	kg 1,4-DCB	8.69E-03	8.51E-03	3.75E-03
Marine ecotoxicity	kg 1,4-DCB	1.16E-02	1.13E-02	5.12E-03
Human carcinogenic toxicity	kg 1,4-DCB	1.30E-02	1.52E-02	6.30E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	-2.20E-01	-8.31E-02	9.55E-02
Land use	m2a crop eq	8.79E-01	5.85E-01	7.74E-01
Mineral resource scarcity	kg Cu eq	8.02E-04	8.01E-04	4.85E-04
Fossil resource scarcity	kg oil eq	4.33E-02	1.09E-01	4.88E-02
Water consumption	m3	9.35E-04	1.13E-03	2.40E-03

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A.3 Sensitivity analysis

Table A-38. Life cycle impacts for producing agricultural feedstocks required to deliver 0.15 kg of extrudate-only protein content to final meat recipe, System #1: 1.748 kg of Canada-MB grown peas, System #2: 1.416 kg of Canada-MB grown peas, System #3: 0.42 kg of U.S. grown soybeans, Systems #1–3, plant -based systems. Comparison of agricultural feedstocks for plant-based systems.
Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	System 1 – Peas – Canada-MB	System 2 – Peas – Canada-MB	System 3 – Soybeans - US
Global warming	kg CO2 eq	2.79E-02	1.85E-02	9.06E-02
Stratospheric ozone depletion	kg CFC11 eq	4.29E-08	2.85E-08	1.65E-06
Ionizing radiation	kBq Co-60 eq	1.11E-03	7.36E-04	1.56E-03
Ozone formation, Human health	kg NOx eq	1.23E-04	8.19E-05	2.93E-04
Fine particulate matter formation	kg PM2.5 eq	7.42E-05	4.92E-05	8.58E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.29E-04	8.58E-05	3.00E-04
Terrestrial acidification	kg SO2 eq	2.39E-04	1.59E-04	2.15E-04
Freshwater eutrophication	kg P eq	6.72E-05	4.46E-05	1.49E-05
Marine eutrophication	kg N eq	2.43E-06	1.62E-06	1.40E-05
Terrestrial ecotoxicity	kg 1,4-DCB	2.18E-01	1.45E-01	3.31E-01
Freshwater ecotoxicity	kg 1,4-DCB	4.19E-03	2.78E-03	2.07E-03
Marine ecotoxicity	kg 1,4-DCB	5.53E-03	3.67E-03	2.89E-03
Human carcinogenic toxicity	kg 1,4-DCB	5.01E-03	3.32E-03	2.64E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	-3.62E-01	-2.40E-01	5.43E-02
Land use	m2a crop eq	8.78E-01	5.83E-01	7.70E-01
Mineral resource scarcity	kg Cu eq	6.73E-04	4.47E-04	3.54E-04
Fossil resource scarcity	kg oil eq	7.14E-03	4.74E-03	1.05E-02
Water consumption	m3	1.77E-04	1.17E-04	1.84E-03

Table A-39. Life cycle impacts for producing 1 kg of protein pea and soybeans, agricultural feedstocks, original ecoinvent 3.9.1 datasets (Protein pea {CA-MB}| protein pea production | Cut-off, U, and Soybean {US}| soybean production | Cut-off, U, cradle-to-manufacturing gate.
Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	1 kg of peas – Canada-MB	1 kg of soybeans - US
Global warming	kg CO2 eq	8.23E-02	4.26E-01
Stratospheric ozone depletion	kg CFC11 eq	1.27E-07	7.74E-06
Ionizing radiation	kBq Co-60 eq	3.27E-03	7.31E-03
Ozone formation, Human health	kg NOx eq	3.64E-04	1.38E-03
Fine particulate matter formation	kg PM2.5 eq	2.19E-04	4.03E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.81E-04	1.41E-03
Terrestrial acidification	kg SO2 eq	7.05E-04	1.01E-03
Freshwater eutrophication	kg P eq	1.98E-04	7.02E-05
Marine eutrophication	kg N eq	7.18E-06	6.56E-05
Terrestrial ecotoxicity	kg 1,4-DCB	6.43E-01	1.56E+00
Freshwater ecotoxicity	kg 1,4-DCB	1.24E-02	9.72E-03
Marine ecotoxicity	kg 1,4-DCB	1.63E-02	1.36E-02
Human carcinogenic toxicity	kg 1,4-DCB	1.48E-02	1.24E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	-1.07E+00	2.55E-01
Land use	m2a crop eq	2.59E+00	3.62E+00
Mineral resource scarcity	kg Cu eq	1.99E-03	1.66E-03
Fossil resource scarcity	kg oil eq	2.11E-02	4.92E-02
Water consumption	m3	5.22E-04	8.65E-03

Table A-40. Sensitivity analysis, energy source (baseline MRO vs. solar), life cycle impacts for producing 1 kg ground food with meat or meat alternatives ready to be cooked.
Cradle-to-manufacturing gate, before packaging or cooling, plant-based systems, Systems #1–3, cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	System 1 - Baseline MRO	System 1 - Solar	System 2 - Baseline MRO	System 2 - Solar	System 3 - Baseline MRO	System 3 - Solar
Global warming	kg CO2 eq	7.47E-01	6.38E-01	9.82E-01	8.11E-01	8.57E-01	7.37E-01
Stratospheric ozone depletion	kg CFC11 eq	2.47E-06	2.43E-06	2.49E-06	2.44E-06	4.11E-06	4.07E-06
Ionizing radiation	kBq Co-60 eq	2.28E-02	1.06E-02	3.05E-02	1.15E-02	2.51E-02	1.17E-02
Ozone formation, Human health	kg NOx eq	1.46E-03	1.32E-03	1.65E-03	1.43E-03	1.85E-03	1.69E-03
Fine particulate matter formation	kg PM2.5 eq	1.59E-03	1.09E-03	1.89E-03	1.12E-03	1.67E-03	1.12E-03

Ozone formation, Terrestrial ecosystems	kg NOx eq	1.51E-03	1.35E-03	1.72E-03	1.48E-03	2.00E-03	1.84E-03
Terrestrial acidification	kg SO2 eq	4.24E-03	3.94E-03	4.43E-03	3.96E-03	4.28E-03	3.95E-03
Freshwater eutrophication	kg P eq	3.76E-04	2.33E-04	4.44E-04	2.21E-04	3.61E-04	2.04E-04
Marine eutrophication	kg N eq	7.59E-04	7.50E-04	7.69E-04	7.55E-04	8.10E-04	8.00E-04
Terrestrial ecotoxicity	kg 1,4-DCB	1.91E+00	1.81E+00	1.97E+00	1.81E+00	2.06E+00	1.95E+00
Freshwater ecotoxicity	kg 1,4-DCB	3.47E-02	2.97E-02	3.75E-02	2.98E-02	3.36E-02	2.82E-02
Marine ecotoxicity	kg 1,4-DCB	3.25E-02	2.59E-02	3.63E-02	2.60E-02	3.12E-02	2.39E-02
Human carcinogenic toxicity	kg 1,4-DCB	2.94E-02	2.08E-02	3.68E-02	2.34E-02	3.13E-02	2.18E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	4.64E-01	3.05E-01	7.01E-01	4.53E-01	9.28E-01	7.54E-01
Land use	m2a crop eq	2.20E+00	2.20E+00	1.90E+00	1.90E+00	2.09E+00	2.09E+00
Mineral resource scarcity	kg Cu eq	2.12E-03	2.02E-03	2.17E-03	2.01E-03	1.90E-03	1.79E-03
Fossil resource scarcity	kg oil eq	1.24E-01	9.57E-02	1.98E-01	1.54E-01	1.42E-01	1.11E-01
Water consumption	m3	1.79E-02	1.70E-02	1.85E-02	1.70E-02	1.70E-02	1.60E-02

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Table A-41. Sensitivity analysis, energy improvement consumption (baseline vs. ±5 and 10%), life cycle impacts for producing 1 kg ground food with meat or meat alternatives ready to be cooked. Cradle-to-manufacturing gate, before packaging or cooling. Plant-based systems, System #1, cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	Baseline	+10% Energy Consumption	+ 5% Energy Consumption	-5% Energy Consumption	-10% Energy Consumption
Global warming	kg CO2 eq	7.47E-01	7.59E-01	7.53E-01	7.41E-01	7.35E-01
Stratospheric ozone depletion	kg CFC11 eq	2.47E-06	2.47E-06	2.47E-06	2.46E-06	2.46E-06
Ionizing radiation	kBq Co-60 eq	2.28E-02	2.37E-02	2.32E-02	2.23E-02	2.19E-02
Ozone formation, Human health	kg NOx eq	1.46E-03	1.48E-03	1.47E-03	1.46E-03	1.45E-03
Fine particulate matter formation	kg PM2.5 eq	1.59E-03	1.63E-03	1.61E-03	1.57E-03	1.55E-03
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.51E-03	1.52E-03	1.51E-03	1.50E-03	1.49E-03
Terrestrial acidification	kg SO2 eq	4.24E-03	4.26E-03	4.25E-03	4.23E-03	4.22E-03
Freshwater eutrophication	kg P eq	3.76E-04	3.86E-04	3.81E-04	3.70E-04	3.65E-04
Marine eutrophication	kg N eq	7.59E-04	7.60E-04	7.60E-04	7.59E-04	7.59E-04
Terrestrial ecotoxicity	kg 1,4-DCB	1.91E+00	1.92E+00	1.91E+00	1.90E+00	1.90E+00
Freshwater ecotoxicity	kg 1,4-DCB	3.47E-02	3.51E-02	3.49E-02	3.45E-02	3.43E-02
Marine ecotoxicity	kg 1,4-DCB	3.25E-02	3.31E-02	3.28E-02	3.23E-02	3.20E-02
Human carcinogenic toxicity	kg 1,4-DCB	2.94E-02	3.01E-02	2.98E-02	2.91E-02	2.87E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	4.64E-01	4.76E-01	4.70E-01	4.58E-01	4.52E-01
Land use	m2a crop eq	2.20E+00	2.20E+00	2.20E+00	2.20E+00	2.20E+00
Mineral resource scarcity	kg Cu eq	2.12E-03	2.13E-03	2.13E-03	2.12E-03	2.11E-03
Fossil resource scarcity	kg oil eq	1.24E-01	1.27E-01	1.25E-01	1.22E-01	1.20E-01
Water consumption	m3	1.79E-02	1.80E-02	1.80E-02	1.79E-02	1.79E-02

Table A-42. Sensitivity analysis, energy improvement consumption (baseline vs. ±5 and 10%), life cycle impacts for producing 1 kg ground food with meat or meat alternatives ready to be cooked. Cradle-to-manufacturing gate, before packaging or cooling. Plant-based systems, System #2, cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	Baseline	+10% Energy Consumption	+ 5% Energy Consumption	-5% Energy Consumption	-10% Energy Consumption
Global warming	kg CO2 eq	9.82E-01	1.02E+00	1.00E+00	9.62E-01	9.42E-01
Stratospheric ozone depletion	kg CFC11 eq	2.49E-06	2.50E-06	2.50E-06	2.49E-06	2.49E-06
Ionizing radiation	kBq Co-60 eq	3.05E-02	3.24E-02	3.14E-02	2.95E-02	2.86E-02
Ozone formation, Human health	kg NOx eq	1.65E-03	1.70E-03	1.68E-03	1.63E-03	1.61E-03
Fine particulate matter formation	kg PM2.5 eq	1.89E-03	1.97E-03	1.93E-03	1.85E-03	1.81E-03
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.72E-03	1.77E-03	1.74E-03	1.70E-03	1.68E-03
Terrestrial acidification	kg SO2 eq	4.43E-03	4.48E-03	4.46E-03	4.40E-03	4.37E-03
Freshwater eutrophication	kg P eq	4.44E-04	4.66E-04	4.55E-04	4.33E-04	4.23E-04
Marine eutrophication	kg N eq	7.69E-04	7.70E-04	7.70E-04	7.68E-04	7.68E-04
Terrestrial ecotoxicity	kg 1,4-DCB	1.97E+00	2.00E+00	1.98E+00	1.95E+00	1.94E+00
Freshwater ecotoxicity	kg 1,4-DCB	3.75E-02	3.84E-02	3.80E-02	3.71E-02	3.66E-02
Marine ecotoxicity	kg 1,4-DCB	3.63E-02	3.75E-02	3.69E-02	3.57E-02	3.51E-02
Human carcinogenic toxicity	kg 1,4-DCB	3.68E-02	3.86E-02	3.77E-02	3.60E-02	3.51E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	7.01E-01	7.27E-01	7.14E-01	6.88E-01	6.75E-01
Land use	m2a crop eq	1.90E+00	1.91E+00	1.91E+00	1.90E+00	1.90E+00
Mineral resource scarcity	kg Cu eq	2.17E-03	2.20E-03	2.19E-03	2.15E-03	2.13E-03
Fossil resource scarcity	kg oil eq	1.98E-01	2.10E-01	2.04E-01	1.92E-01	1.86E-01
Water consumption	m3	1.85E-02	1.87E-02	1.86E-02	1.84E-02	1.84E-02

Table A-43. Sensitivity analysis, energy improvement consumption (baseline vs. ±5 and 10%), life cycle impacts for producing 1 kg ground food with meat or meat alternatives ready to be cooked. Cradle-to-manufacturing gate, before packaging or cooling. Plant-based systems, System #3, cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	Baseline	+10% Energy Consumption	+ 5% Energy Consumption	-5% Energy Consumption	-10% Energy Consumption
Global warming	kg CO2 eq	8.57E-01	8.76E-01	8.67E-01	8.48E-01	8.38E-01
Stratospheric ozone depletion	kg CFC11 eq	4.11E-06	4.11E-06	4.11E-06	4.11E-06	4.10E-06
Ionizing radiation	kBq Co-60 eq	2.51E-02	2.64E-02	2.58E-02	2.45E-02	2.38E-02
Ozone formation, Human health	kg NOx eq	1.85E-03	1.87E-03	1.86E-03	1.84E-03	1.83E-03
Fine particulate matter formation	kg PM2.5 eq	1.67E-03	1.72E-03	1.69E-03	1.64E-03	1.61E-03
Ozone formation, Terrestrial ecosystems	kg NOx eq	2.00E-03	2.03E-03	2.02E-03	1.99E-03	1.98E-03
Terrestrial acidification	kg SO2 eq	4.28E-03	4.31E-03	4.30E-03	4.26E-03	4.24E-03
Freshwater eutrophication	kg P eq	3.61E-04	3.76E-04	3.69E-04	3.53E-04	3.46E-04
Marine eutrophication	kg N eq	8.10E-04	8.11E-04	8.10E-04	8.09E-04	8.09E-04
Terrestrial ecotoxicity	kg 1,4-DCB	2.06E+00	2.07E+00	2.06E+00	2.05E+00	2.04E+00
Freshwater ecotoxicity	kg 1,4-DCB	3.36E-02	3.42E-02	3.39E-02	3.33E-02	3.30E-02
Marine ecotoxicity	kg 1,4-DCB	3.12E-02	3.20E-02	3.16E-02	3.09E-02	3.05E-02
Human carcinogenic toxicity	kg 1,4-DCB	3.13E-02	3.23E-02	3.18E-02	3.07E-02	3.02E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	9.28E-01	9.46E-01	9.37E-01	9.20E-01	9.11E-01
Land use	m2a crop eq	2.09E+00	2.09E+00	2.09E+00	2.09E+00	2.09E+00
Mineral resource scarcity	kg Cu eq	1.90E-03	1.92E-03	1.91E-03	1.89E-03	1.89E-03
Fossil resource scarcity	kg oil eq	1.42E-01	1.47E-01	1.44E-01	1.39E-01	1.36E-01
Water consumption	m3	1.70E-02	1.71E-02	1.71E-02	1.70E-02	1.69E-02

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Table A-44. Sensitivity analysis, allocation approach (baseline mass vs. economic), life cycle impacts for producing 1 kg ground food with meat or meat alternatives ready to be cooked. Cradle-to-manufacturing gate, before packaging or cooling. Plant-based systems, Systems #1–3, cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	System 1 – Baseline Mass	System 1 - Economic	System 2 - Baseline Mass	System 2 - Economic	System 3 - Baseline Mass	System 3 - Economic
Global warming	kg CO2 eq	7.47E-01	9.58E-01	9.82E-01	1.11E+00	8.57E-01	9.36E-01
Stratospheric ozone depletion	kg CFC11 eq	2.47E-06	2.59E-06	2.49E-06	2.62E-06	4.11E-06	4.53E-06
Ionizing radiation	kBq Co-60 eq	2.28E-02	3.73E-02	3.05E-02	3.95E-02	2.51E-02	2.67E-02
Ozone formation, Human health	kg NOx eq	1.46E-03	1.86E-03	1.65E-03	1.96E-03	1.85E-03	2.07E-03
Fine particulate matter formation	kg PM2.5 eq	1.59E-03	2.23E-03	1.89E-03	2.29E-03	1.67E-03	1.74E-03
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.51E-03	1.93E-03	1.72E-03	2.05E-03	2.00E-03	2.28E-03
Terrestrial acidification	kg SO2 eq	4.24E-03	4.96E-03	4.43E-03	5.01E-03	4.28E-03	4.39E-03
Freshwater eutrophication	kg P eq	3.76E-04	6.22E-04	4.44E-04	6.22E-04	3.61E-04	3.77E-04
Marine eutrophication	kg N eq	7.59E-04	7.73E-04	7.69E-04	7.82E-04	8.10E-04	8.16E-04
Terrestrial ecotoxicity	kg 1,4-DCB	1.91E+00	2.43E+00	1.97E+00	2.43E+00	2.06E+00	2.18E+00
Freshwater ecotoxicity	kg 1,4-DCB	3.47E-02	4.65E-02	3.75E-02	4.69E-02	3.36E-02	3.49E-02
Marine ecotoxicity	kg 1,4-DCB	3.25E-02	4.83E-02	3.63E-02	4.87E-02	3.12E-02	3.30E-02
Human carcinogenic toxicity	kg 1,4-DCB	2.94E-02	4.70E-02	3.68E-02	5.04E-02	3.13E-02	3.36E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	4.64E-01	1.29E-01	7.01E-01	3.15E-01	9.28E-01	9.60E-01
Land use	m2a crop eq	2.20E+00	3.46E+00	1.90E+00	3.12E+00	2.09E+00	2.28E+00
Mineral resource scarcity	kg Cu eq	2.12E-03	3.26E-03	2.17E-03	3.26E-03	1.90E-03	2.05E-03

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Fossil resource scarcity	kg oil eq	1.24E-01	1.81E-01	1.98E-01	2.33E-01	1.42E-01	1.63E-01
Water consumption	m3	1.79E-02	1.92E-02	1.85E-02	1.95E-02	1.70E-02	1.77E-02

Table A-45. Sensitivity analysis, allocation approach (baseline mass vs. economic), life cycle impacts for producing 1 kg ground food with meat or meat alternatives ready to be cooked.
Cradle-to-manufacturing gate, before packaging or cooling. Animal-based systems, Systems #4–6, cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	System 4 – Baseline Mass	System 4 - Economic	System 5 - Baseline Mass	System 5 - Economic	System 6 - Baseline Mass	System 6 - Economic
Global warming	kg CO2 eq	1.45E+01	2.72E+01	7.01E+00	1.02E+01	2.59E+00	3.34E+00
Stratospheric ozone depletion	kg CFC11 eq	1.21E-04	2.29E-04	2.43E-05	3.57E-05	2.38E-05	3.13E-05
Ionizing radiation	kBq Co-60 eq	2.09E-01	3.70E-01	1.98E-01	2.78E-01	1.40E-01	1.76E-01
Ozone formation, Human health	kg NOx eq	9.39E-03	1.75E-02	1.36E-02	1.99E-02	5.00E-03	6.48E-03
Fine particulate matter formation	kg PM2.5 eq	1.91E-02	3.52E-02	1.86E-02	2.69E-02	1.01E-02	1.29E-02
Ozone formation, Terrestrial ecosystems	kg NOx eq	9.66E-03	1.80E-02	1.42E-02	2.07E-02	5.16E-03	6.69E-03
Terrestrial acidification	kg SO2 eq	8.80E-02	1.66E-01	6.90E-02	1.01E-01	3.97E-02	5.21E-02
Freshwater eutrophication	kg P eq	7.85E-03	1.46E-02	2.74E-03	3.88E-03	1.83E-03	2.30E-03
Marine eutrophication	kg N eq	1.95E-02	3.70E-02	7.45E-03	1.10E-02	4.98E-03	6.56E-03
Terrestrial ecotoxicity	kg 1,4-DCB	1.67E+01	3.15E+01	2.36E+01	3.47E+01	5.52E+00	7.20E+00
Freshwater ecotoxicity	kg 1,4-DCB	3.52E-01	6.57E-01	2.82E-01	4.09E-01	9.95E-02	1.27E-01
Marine ecotoxicity	kg 1,4-DCB	4.08E-01	7.59E-01	3.70E-01	5.37E-01	1.24E-01	1.58E-01
Human carcinogenic toxicity	kg 1,4-DCB	4.47E-01	8.28E-01	1.00E+00	1.47E+00	1.36E-01	1.73E-01
Human non-carcinogenic toxicity	kg 1,4-DCB	1.09E+03	2.07E+03	4.65E+00	6.68E+00	2.10E+00	2.65E+00

Land use	m2a crop eq	2.21E+01	4.19E+01	5.20E+00	7.66E+00	2.30E+00	3.03E+00
Mineral resource scarcity	kg Cu eq	1.93E-02	3.65E-02	5.02E-02	7.38E-02	5.77E-03	7.53E-03
Fossil resource scarcity	kg oil eq	8.02E-01	1.46E+00	1.07E+00	1.55E+00	5.05E-01	6.45E-01
Water consumption	m3	2.45E-01	4.62E-01	4.64E-01	6.82E-01	3.24E-01	4.26E-01

Table A-46. Sensitivity analysis, crop geography (baseline pea cultivation in Canada vs. Germany and France), life cycle impacts for producing 1 kg ground food with meat or meat alternatives ready to be cooked.
Cradle-to-manufacturing gate, before packaging or cooling. System #1, cradle-to-manufacturing gate.
Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	System 1 – Pea - Canada-MB	System 1 – Pea - Germany	System 1 – Pea - France
Global warming	kg CO2 eq	7.47E-01	8.69E-01	8.33E-01
Stratospheric ozone depletion	kg CFC11 eq	2.47E-06	4.05E-06	4.19E-06
Ionizing radiation	kBq Co-60 eq	2.28E-02	2.64E-02	2.81E-02
Ozone formation, Human health	kg NOx eq	1.46E-03	2.04E-03	1.79E-03
Fine particulate matter formation	kg PM2.5 eq	1.59E-03	1.76E-03	1.70E-03
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.51E-03	2.09E-03	1.84E-03
Terrestrial acidification	kg SO2 eq	4.24E-03	4.54E-03	4.47E-03
Freshwater eutrophication	kg P eq	3.76E-04	3.60E-04	3.62E-04
Marine eutrophication	kg N eq	7.59E-04	1.37E-03	1.89E-03
Terrestrial ecotoxicity	kg 1,4-DCB	1.91E+00	2.34E+00	2.99E+00
Freshwater ecotoxicity	kg 1,4-DCB	3.47E-02	3.92E-02	3.87E-02
Marine ecotoxicity	kg 1,4-DCB	3.25E-02	3.84E-02	4.15E-02
Human carcinogenic toxicity	kg 1,4-DCB	2.94E-02	3.49E-02	3.03E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	4.64E-01	8.52E-01	7.90E-01
Land use	m2a crop eq	2.20E+00	2.21E+00	2.21E+00
Mineral resource scarcity	kg Cu eq	2.12E-03	2.53E-03	2.28E-03
Fossil resource scarcity	kg oil eq	1.24E-01	1.46E-01	1.36E-01
Water consumption	m3	1.79E-02	4.47E-02	5.38E-02

Table A-47. Sensitivity analysis, crop geography (baseline pea cultivation in Canada vs. Germany and France), life cycle impacts for producing 1 kg ground food with meat or meat alternatives ready to be cooked.
Cradle-to-manufacturing gate, before packaging or cooling. System #2, cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	System 2 – Pea - Canada-MB	System 2 – Pea - Germany	System 2 – Pea - France
Global warming	kg CO2 eq	9.82E-01	1.06E+00	1.04E+00
Stratospheric ozone depletion	kg CFC11 eq	2.49E-06	3.55E-06	3.64E-06
Ionizing radiation	kBq Co-60 eq	3.05E-02	3.29E-02	3.40E-02
Ozone formation, Human health	kg NOx eq	1.65E-03	2.03E-03	1.87E-03
Fine particulate matter formation	kg PM2.5 eq	1.89E-03	2.01E-03	1.97E-03
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.72E-03	2.11E-03	1.95E-03
Terrestrial acidification	kg SO2 eq	4.43E-03	4.62E-03	4.58E-03
Freshwater eutrophication	kg P eq	4.44E-04	4.34E-04	4.36E-04
Marine eutrophication	kg N eq	7.69E-04	1.17E-03	1.52E-03
Terrestrial ecotoxicity	kg 1,4-DCB	1.97E+00	2.26E+00	2.69E+00
Freshwater ecotoxicity	kg 1,4-DCB	3.75E-02	4.05E-02	4.02E-02
Marine ecotoxicity	kg 1,4-DCB	3.63E-02	4.02E-02	4.22E-02
Human carcinogenic toxicity	kg 1,4-DCB	3.68E-02	4.05E-02	3.74E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	7.01E-01	9.59E-01	9.17E-01
Land use	m2a crop eq	1.90E+00	1.91E+00	1.91E+00
Mineral resource scarcity	kg Cu eq	2.17E-03	2.44E-03	2.27E-03
Fossil resource scarcity	kg oil eq	1.98E-01	2.13E-01	2.06E-01
Water consumption	m3	1.85E-02	3.63E-02	4.23E-02

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Table A-48. Sensitivity analysis, crop geography (baseline soybean cultivation in the U.S. vs. Canada and Brazil), life cycle impacts for producing 1 kg ground food with meat or meat alternatives ready to be cooked.
Cradle-to-manufacturing gate, before packaging or cooling. System #3, cradle-to-manufacturing gate. Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	System 3 – Soybean - US	System 3 – Soybean - Canada	System 3 – Soybean - Brazil
Global warming	kg CO2 eq	8.57E-01	8.28E-01	1.02E+00
Stratospheric ozone depletion	kg CFC11 eq	4.11E-06	3.57E-06	3.69E-06
Ionizing radiation	kBq Co-60 eq	2.51E-02	2.37E-02	2.41E-02
Ozone formation, Human health	kg NOx eq	1.85E-03	1.82E-03	1.87E-03
Fine particulate matter formation	kg PM2.5 eq	1.67E-03	1.67E-03	1.91E-03
Ozone formation, Terrestrial ecosystems	kg NOx eq	2.00E-03	1.96E-03	2.05E-03
Terrestrial acidification	kg SO2 eq	4.28E-03	4.42E-03	4.47E-03
Freshwater eutrophication	kg P eq	3.61E-04	4.65E-04	3.58E-04
Marine eutrophication	kg N eq	8.10E-04	1.74E-03	1.27E-03
Terrestrial ecotoxicity	kg 1,4-DCB	2.06E+00	1.93E+00	3.57E+00
Freshwater ecotoxicity	kg 1,4-DCB	3.36E-02	3.92E-02	1.66E-01
Marine ecotoxicity	kg 1,4-DCB	3.12E-02	3.69E-02	8.32E-02
Human carcinogenic toxicity	kg 1,4-DCB	3.13E-02	3.22E-02	3.08E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	9.28E-01	2.95E-01	1.25E+00
Land use	m2a crop eq	2.09E+00	1.83E+00	1.50E+00
Mineral resource scarcity	kg Cu eq	1.90E-03	1.92E-03	2.36E-03
Fossil resource scarcity	kg oil eq	1.42E-01	1.33E-01	1.36E-01
Water consumption	m3	1.70E-02	1.65E-02	8.82E-02

Table A-49. Synthesis table of comparison between plant-based (Systems #1–3) and conventional animal-based (Systems #4–6) meat recipes, baseline and sensitivity analysis results, per each impact category.
Mass allocation, the plant-based scenario with the highest impacts is compared to the animal-based baseline scenario, the decrease % is based on the conventional scenario. Method: ReCiPe 2016 Midpoint (H) V1.03.

Impact category	Unit	Maximum Plant-Based Impacts	Maximum Plant-Based Impact Scenario	Lowest Animal-Based Impacts	Lowest Animal-Based Scenario	% of Decrease
Global warming	kg CO_2 eq	1.06E+00	Crop geography - German peas (System #2)	2.59E+00	Baseline chicken meat (System #6)	59%
Stratospheric ozone depletion	kg CFC11 eq	4.19E-06	Crop geography - French peas (System #1)	2.38E-05	Baseline chicken meat (System #6)	82%
Ionizing radiation	kBq Co-60 eq	3.40E-02	Crop geography - French peas (System #2)	1.40E-01	Baseline chicken meat (System #6)	76%
Ozone formation, Human health	kg NOx eq	2.04E-03	Crop geography - German peas (System #1)	5.00E-03	Baseline chicken meat (System #6)	59%
Fine particulate matter formation	kg PM2.5 eq	2.01E-03	Crop geography - German peas (System #2)	1.01E-02	Baseline chicken meat (System #6)	80%
Ozone formation, Terrestrial ecosystems	kg NO_x eq	2.11E-03	Crop geography - German peas (System #2)	5.16E-03	Baseline chicken meat (System #6)	59%
Terrestrial acidification	kg SO_2 eq	4.62E-03	Crop geography - German peas (System #2)	3.97E-02	Baseline chicken meat (System #6)	88%

Freshwater eutrophication	kg P eq	4.66E-04	Energy improvement - +10% consumption (System #2)	1.83E-03	Baseline chicken meat (System #6)	74%
Marine eutrophication	kg N eq	1.89E-03	Crop geography - French peas (System #1)	4.98E-03	Baseline chicken meat (System #6)	62%
Terrestrial ecotoxicity	kg 1,4-DCB	3.57E+00	Crop geography - Brazilian soybeans (System #3)	5.52E+00	Baseline chicken meat (System #6)	35%
Freshwater ecotoxicity	kg 1,4-DCB	1.66E-01	Crop geography - Brazilian soybeans (System #3)	9.95E-02	Baseline chicken meat (System #6)	-67%
Marine ecotoxicity	kg 1,4-DCB	8.32E-02	Crop geography - Brazilian soybeans (System #3)	1.24E-01	Baseline chicken meat (System #6)	33%
Human carcinogenic toxicity	kg 1,4-DCB	4.05E-02	Crop geography - German peas (System #2)	1.36E-01	Baseline chicken meat (System #6)	70%
Human non-carcinogenic toxicity	kg 1,4-DCB	1.25E+00	Crop geography - Brazilian soybeans (System #3)	2.10E+00	Baseline chicken meat (System #6)	41%
Land use	m2a crop eq	2.21E+00	Crop geography - German peas (System #1)	2.30E+00	Baseline chicken meat (System #6)	4%
Mineral resource scarcity	kg Cu eq	2.53E-03	Crop geography - German peas (System #1)	5.77E-03	Baseline chicken meat (System #6)	56%

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Fossil resource scarcity	kg oil eq	2.13E-01	Crop geography - German peas (System #2)	5.05E-01	Baseline chicken meat (System #6)	58%
Water consumption	m^3	8.82E-02	Crop geography - Brazilian soybeans (System #3)	2.45E-01	Baseline beef meat (System #4)	64%

A.4 Data quality and statistical significance

In practice, all data used in an LCA study are a mixture of measured, estimated, and calculated data. The quality of data is rarely homogenous. In this study, some data are very reliable while some have been estimated. To evaluate the quality of data used for modeling the two manufacturing systems, data quality indicators (DQI) have been assigned to each flow using the data quality matrix approach. These scores have also been used to assess uncertainties on the data and subsequently assess the uncertainty of the model and the results.

Six types of DQI are evaluated by the Pedigree matrix (Weidema 1996) by using scores from 1 to 5:

DQI	1	2	3	4	5
Reliability	Verified data based on measurements.	Verified data partly based on measurements OR non-verified data based on measurements.	Non-verified data partly based on qualified estimates.	Qualified estimates (e.g., by industrial expert) data derived from theoretical information.	Non-qualified estimate.
Completeness	Representative data from all sites relevant to the market considered over an adequate period to even out normal fluctuations.	Representative data from >50% of the sites relevant to the market considered over an adequate period to even out normal fluctuations.	Representative data from only some sites (<50%) relevant for the market considered OR >50% of the sites but from shorter periods.	Representative data from only one site for the market considered OR some but from shorter periods.	Representativeness unknown or data from a small number of sites AND from short periods.
Temporal correlation	Fewer than 3 yrs. of difference to reference year.	Fewer than 6 yrs. of difference to reference year.	Fewer than 10 yrs. of difference to reference year.	Fewer than 15 yrs. of difference to reference year.	Age of data unknown OR more than 15 yrs. difference from reference year.

Geographical correlation	Data from area under study.	Average data from smaller area than area under study or from similar area.	Data from smaller area than area under study, or from similar area.	Data from an area with slightly similar production conditions	Data from unknown or distinctly different area.
Further technological correlation	Data from enterprises, processes, and materials under study (i.e., identical technology).	Data from processes and materials under study (i.e., identical technology) but from different enterprises.	Data from related processes or materials but same technology, OR data from processes and materials under study but from different technology OR process partially represented.	Data from related processes or materials but different technology, OR data on laboratory scale processes and same technology.	Data on related processes or materials but on laboratory scale of different technology.

A.5 Impact categories explanation

Impact assessment methods are used to convert life cycle inventory (LCI) data (environmental emissions and raw material extractions) into a set of environmental impacts. ISO 14044 does not dictate which impact assessment method to use for a full LCA; however, the chosen method needs to be an internationally accepted method.

According to ISO 14044, there are mandatory and optional elements of an LCI assessment.

The **mandatory** elements include classification and characterization. Classification consists of grouping the LCI according to the relevant **impact category**. For example, all the inputs/outputs substances (flows) that result in emissions of greenhouse gases are assigned to Global Warming.

For the characterization step, the following are needed:

- One **category indicator** (unit of measure) that represents each impact category; for example, kg. of CO_2-eq for Global Warming, or kg. of SO_2-eq for Acidification.
- One **characterization factor** for every flow within each impact category. This characterization factor represents the magnitude of the contribution of each one of them, to the impact category. For example, for Global Warming, the characterization factor of CO_2 is 1, the characterization factor of CH_4 is 27–30 (depending on the source), and the characterization factor of N_2O is 273.
- To obtain the **category indicator result**, the amount of each flow is multiplied times its characterization factor, and then all of them are added together. Following the same example, if the LCI result is 30 kg of CO_2 and 2 kg of N_2O, the category indicator result is (30x1) + (2x273) = 576 kg. of CO_2-eq.

In an LCI assessment, there could be **optional** elements, to provide a better understanding of the results. These elements include normalization, grouping, weighting, and data quality analysis. ISO 14044, section 4.4.3.1 provides the following description for each:

- **Normalization**: calculating the magnitude of category indicator results relative to reference information.
- **Grouping**: sorting and possibly ranking the impact categories.
- **Weighting**: converting and possibly aggregating indicator results across impact categories using numerical factors based on value-choices; data prior to weighting should remain available.
- **Data quality analysis:** better understanding the reliability of the collection of indicator results, the LCI assessment profile.

Every LCI usually includes thousands of flows, but every impact category only accounts for the ones within its method, the LCI flows that are not represented in a particular method are known as **uncharacterized flows**. For example, when analyzing Global Warming, more than 200 substances (flows) are included, but many of them are left uncharacterized, such as those that cause toxicity. To capture as many flows as possible represented in impact categories, it is necessary to use methods that include several impact categories, like ReCiPe.

In Section 2, it is stated that the Good Food Institute (GFI) commissioned this study to understand the environmental impacts of plant- and animal-based meat products, and that GFI intends to communicate the results of this study publicly, to an audience of internal and external stakeholders (including retailers, customers, suppliers, shareholders, and other interested parties); therefore, this report needed a method that provides a robust assessment that the average stakeholder could grasp. So, the life cycle impacts are presented via the ReCiPe midpoint 2016 (H) method.

ReCiPe

ReCiPe is one of the most recent and updated impact assessment methods available to LCA practitioners. According to RIVM (2020), ReCiPe was developed in 2008 by the Dutch National Institute for Public Health and the Environment (RIVM), the Dutch Institute of Environmental Sciences (CML), PRé Consultants, and the Radboud University Nijmegen on behalf of the Dutch Ministry of Infrastructure and the Environment. In 2016, the ReCiPe method was revised thoroughly. A new version of both the model and the background report were published, developed by RIVM and Radboud University Nijmegen.

This method addresses a number of environmental concerns at the midpoint level and then aggregates the midpoints into a set of three endpoint categories, which measure the damage—at the end of the cause-effect chain—caused by a stressor in terms of human life years lost and the years lived disabled, species disappeared, and resources lost.

ReCiPe midpoint 2016 (H) includes the following impact categories:

- **Global Warming**: Measures the impact of greenhouse gas emissions on global climate change, quantifying their contribution to rising temperatures, sea-level rise, extreme weather events, and disruptions to ecosystems and human societies.
- **Stratospheric Ozone Depletion:** Measures the potential for substances to deplete the ozone layer in the Earth's stratosphere, primarily from ozone-depleting substances like chlorofluorocarbons (CFCs), leading to increased UV radiation reaching the Earth's surface and adverse effects on human health and ecosystems.

- **Ionizing Radiation:** Measures the potential harm to human health and the environment from exposure to ionizing radiation, considering sources such as nuclear power plants, medical procedures, and natural background radiation.
- **Ozone Formation—Human Health**: Assesses the formation of ground-level ozone and its impacts on human health, including respiratory issues such as asthma exacerbation and cardiovascular problems, particularly in urban areas with high pollution levels.
- **Ozone Formation—Terrestrial Ecosystems**: Examines the formation of ground-level ozone and its impacts on terrestrial ecosystems, including damage to vegetation, reduction in crop yields, and alterations in ecosystem composition and structure.
- **Fine Particulate Matter Formation**: Measures the formation of fine particles in the atmosphere, originating from combustion processes and industrial activities, contributing to respiratory and cardiovascular health issues in humans.
- **Terrestrial Acidification**: Assesses the potential for emissions to contribute to acidification of soil and water bodies, primarily through deposition of acidic pollutants such as sulfur and nitrogen oxides, leading to soil degradation, nutrient imbalances, and impacts on terrestrial ecosystems.
- **Freshwater Eutrophication**: Evaluates the excessive nutrient input into freshwater systems, typically from agricultural runoff or wastewater discharge, leading to algae blooms, oxygen depletion, and deterioration of water quality, affecting aquatic life and human uses.
- **Marine Eutrophication**: Evaluates the nutrient enrichment of marine ecosystems, often originating from agricultural runoff or wastewater discharge, leading to algae blooms, oxygen depletion, and habitat degradation in coastal waters.
- **Terrestrial Ecotoxicity:** Examines the potential for substances to harm terrestrial ecosystems, including soil organisms and plants, through toxicity effects and disrupting ecosystem functions and services such as nutrient cycling and soil fertility.
- **Freshwater Ecotoxicity:** Examines the potential for substances to harm freshwater ecosystems, including lakes, rivers, and streams, through toxicity to aquatic organisms, disrupting food chains and biodiversity.
- **Marine Ecotoxicity:** Examines the potential for substances to harm marine ecosystems, including oceans and coastal areas, through toxicity to marine organisms, disrupting marine food webs and ecosystem functioning.
- **Human Carcinogenic Toxicity:** Assesses the potential for substances to cause cancer in humans through exposure pathways such as ingestion, inhalation, and dermal contact, considering the carcinogenic potency and exposure duration.
- **Human Non-Carcinogenic Toxicity:** Evaluates the potential for substances to cause non-cancerous health effects in humans, such as respiratory irritation, neurological disorders, or reproductive issues, through various exposure routes.
- **Land Use:** Assesses the impacts of land occupation and transformation on biodiversity, ecosystem services, and cultural heritage, including habitat loss, soil degradation, and changes in land cover patterns.

- **Mineral Resource Scarcity:** Measures the depletion of non-renewable mineral resources, such as metals and minerals, highlighting the environmental and socio-economic impacts of resource scarcity, including supply chain disruptions and increased extraction pressures.
- **Fossil Resource Scarcity:** Assesses the depletion of finite fossil fuel resources such as coal, oil, and natural gas, highlighting the environmental and socio-economic consequences of resource scarcity, including energy security concerns and geopolitical tensions.
- **Water Consumption:** Assesses the use of freshwater resources during the life cycle of a product or activity, including both direct consumption and indirect impacts such as water withdrawals and pollution, highlighting the strain on water availability and the associated ecological and social consequences. This indicator does not differentiate between blue, green, and grey water typologies.

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A.6 Economic allocation prices (confidential)

Table A-49. Background economic prices of main products and co-products used by secondary data sources to calculate economic allocation factors.

System	Stage	Process	Co-products	Price	Unit[1]	Source
System #1	Pre-processing	Dehulling	**Dehulled peas**	**450.00**	**EUR/ton**	**Agrifootprint 4.0 (Durlinger et al. 2017)**
			Hulls	265.00	EUR/ton	Agrifootprint 4.0 (Durlinger et al. 2017)
	Dry fractionation	Air classification	**Protein concentrate**	**1,600.00**	**EUR/ton**	**Agrifootprint 6.0 (Blonk et al. 2023)**
			Starch	495.00	EUR/ton	Agrifootprint 6.0 (Blonk et al. 2023)
System #2	Pre-processing	Dehulling	**Dehulled peas**	**450.00**	**EUR/ton**	**Agrifootprint 4.0 (Durlinger et al. 2017)**
			Hulls	265.00	EUR/ton	Agrifootprint 4.0 (Durlinger et al. 2017)
	Wet fractionation	Precipitation	**Pea protein slurry**	**1,382.00**	**EUR/ton**	**Agrifootprint 6.0 (Blonk et al. 2023)**
			Starch slurry	274.00	EUR/ton	Agrifootprint 6.0 (Blonk et al. 2023)
			Wet globulin slurry	46.00	EUR/ton	Agrifootprint 6.0 (Blonk et al. 2023)
System #3	Pre-processing	Soybean oil extraction	**Soybean meal**	**0.528**	**EUR/kg**	**ecoinvent 3.9.1 (Wernet et al. 2016)**

			Soybean oil	1.221	EUR/kg	ecoinvent 3.9.1 (Wernet et al. 2016)
	Wet fractionation		**Soy protein concentrate**	**2,000.00**	**EUR/ton**	**Agrifootprint 6.0 (Blonk et al. 2023)**
			Soy fines	313.00	EUR/ton	Agrifootprint 6.0 (Blonk et al. 2023)
			Soy molasses	35.00	EUR/ton	Agrifootprint 6.0 (Blonk et al. 2023)
System #4	Cattle slaughtering		**Fresh beef meat**	**3.00**	**EUR/kg**	**PEFCR (European Commission 2021)**
			Food grade bones	0.19	EUR/kg	PEFCR (European Commission 2021)
			Food grade fat	0.40	EUR/kg	PEFCR (European Commission 2021)
			Category 3 slaughter by-products	0.18	EUR/kg	PEFCR (European Commission 2021)
			Hides and skins	0.80	EUR/kg	PEFCR (European Commission 2021)
			Category 1 and 2 material and waste	0.00	EUR/kg	PEFCR (European Commission 2021)
System #5	Swine slaughtering		**Fresh pork meat**	**1.08**	**EUR/kg**	**PEFCR (European Commission 2021)**

		Food grade bones	0.03	EUR/kg	PEFCR (European Commission 2021)
		Food grade fat	0.02	EUR/kg	PEFCR (European Commission 2021)
		Category 3 slaughter by-products	0.03	EUR/kg	PEFCR (European Commission 2021)
System #6	Broiler slaughtering[2]	**Fresh chicken meat**	**Not available**		**(FAO 2016)**
		Non-meat inedible offal	Not available		(FAO 2016)
		Edible offal	Not available		(FAO 2016)
		Poultry oil	Not available		(FAO 2016)
		Blood meal	Not available		(FAO 2016)
		Pet food slurry	Not available		(FAO 2016)
		Pet food digest	Not available		(FAO 2016)
		Poultry meal	Not available		(FAO 2016)
		Feather meal	Not available		(FAO 2016)

Notes: [1]Actual prices per kg and ton basis are not communicated directly by the cited references but are instead shown as relative value to be internally used as input for building the economic allocation ratios and factors. Also, per the original references, there are no consistent units (some prices may be in USD and others in EUR). [2]Prices for the broiler slaughtering in System #6 are not available, since the referenced report only shows direct economic allocation factors.

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