ADDENDUM TO:

COMPARATIVE ENVIRONMENTAL LCA OF THE IMPOSSIBLE BURGER WITH CONVENTIONAL GROUND BEEF BURGER

CLIENT:

IMPOSSIBLE™

Final version

FEBRUARY 7, 2022

WSP CANADA

WSP.COM/CA

LIFE CYCLE ASSESSMENT REPORT

Addendum to Quantis (2019): Comparative Environmental LCA of the Impossible Burger with Conventional Ground Beef Burger, which is published here.

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1 EXECUTIVE SUMMARY

Impossible Foods Inc. (Impossible Foods) aims to restore biodiversity and reduce the impact of climate change by transforming the global food system. To do this, Impossible Foods makes meat, fish, and dairy analogs from plants. Impossible Foods has developed two new plant-based meat alternatives (PBMA): 1) the Impossible Meatball Made from Plants (IM), that aims to mimic the flavour and texture of a meat-based meatball (MM)[1] and has a recipe that can be represented by an equal (50% each) mix of two other bulk Impossible products (i.e. uncooked bulk products of the Impossible Burger (IB) and Impossible Sausage Made from Plants (IS)); and 2) a new recipe for its IB product. The ingredients used in these products have generally been examined prior in two critically reviewed LCAs, to be leveraged directly for this work.

Impossible Foods has commissioned WSP Canada Inc. (WSP) work to calculate four specific life cycle potential impact categories (global warming potential, freshwater eutrophication potential, land occupation, and water consumption) of the new IB recipe and compare it against a beef burger (BB) in the US and two different versions of the IM produced in the United States (US) and distributed to the US and compare it against a MM comprised equally of ground beef and ground pork. These impact categories were chosen because they will provide the most business value to Impossible Foods in their discussions with customers and other clients and are the most salient to animal agricultural environmental impacts. As a result, the net new contributions of this addendum related to the new IB recipe and the IM products are as follows:

- Four specific life cycle potential impact categories are calculated for a new IB product produced in the US and distributed to the US and compared against a BB produced and distributed in the domestic markets of the US.
- Four life cycle potential impact categories of two IM products, manufactured in the US and distributed within the US and are compared against functionally equivalent MMs (MM1 for retail consumption and MM2 restaurant-type food service) produced in the domestic markets of the US.

Boundary and scope

The type of inventory is cradle-to-gate of the initial purchaser of finished product, whether a retailer or food services provider, prior to purchase/consumption by an end consumer; the retail, use and end-of-life stages are excluded from the boundary because they are assumed to be identical for the respective comparative scenarios.

The four impact categories for all scenarios are considered on a per kilogram (kg) of delivered final product basis. ReCiPe Midpoint (H) v1.12/World Recipe H was used to quantify all indicators. These four impact categories were quantified using primary data from Impossible Foods manufacturing facilities and secondary data from literature, industry sources and commercial databases. Only the results for the four impact categories were quantified because these are the key environmental areas of concern for Impossible Foods; this specific reporting of impact categories is also consistent with previous PBMA life cycle assessments (LCAs) (Dettling, Tu, Faist, DelDuce, & Mandlebaum, 2016; Khan, Loyola, Dettling, & Hester, 2019) as well as other meat-based LCAs.

This study was conducted with the intention to communicate the LCA results and conclusions internally and externally. Internal communication will aid in internal decision-making and provide information to the company's stakeholders who are interested in the impacts associated with producing the Impossible Foods products. While the results are intended to be communicated externally, the study was not critically reviewed because the only net difference is an examination of the select potential environmental impacts of a new IB recipe and a new IM recipe. The changes to the IB recipe from the product

[1] A note that this LCA does not assess the flavour nor texture of the particular products under study.

examined in Qantis (2019) are very minor. The IM recipe uses ingredients and processes that were previously subject to critical review in both Qantis (2019) and Impossible Foods (2020). The data in Qantis (2019) and Impossible Foods (2020) are used and referenced directly throughout this report and relevant details are referenced when necessary.

Results

In general, the four impact categories of the Impossible products are (IB and IM) lower than the meat-based products (BB and MM, respectively). The following are the key findings from this work:

IB AND BB

- The GWP result for the IB is 91% lower than that of the BB scenario because of the enteric fermentation and manure management emissions for the BB.
- The freshwater eutrophication potential result for the IB is 85% lower than that of the BB scenarios because of the additional crop inputs and manure application for the BB.
- The land occupation result for the IB is 96% lower than that of the BB scenarios because of the additional crop inputs; the land use result for both IB and BB is primarily due to crop production. The primary contributor for the IB is heme and coconut oil.
- The water consumption result for the IB is 92% lower than that of the BB scenarios primarily because of crops used in feed production.

IM AND MM

- The GWP result for the IM is 85% lower than that of the MM scenarios because of the enteric fermentation and manure management emissions for the BB and PS, as noted prior. The GWP results for the IM1-US and IM2-US scenarios do not differ significantly because the only difference in the life cycle stages is packaging.
- The freshwater eutrophication potential result for the IM is 82% lower than that of the MM scenarios because of the additional crop inputs and manure application for the BB and PS, as noted prior.
- The land occupation result for the IM is 88% lower than that of the MM scenarios because of the additional crop inputs for the BB and PS.
- The water consumption result for the IM is 87% lower than that of the MM scenarios primarily because of crops used in feed production.

The application of the results, interpretation, and conclusions of this study are limited to the products considered in this study. Furthermore, the results calculated for the Impossible Foods products are limited to the unique recipe and cannot be extrapolated or applied to the production of other PBMAs by other means.

In summary, the study has found that there are clear potential environmental benefits in the impact categories of concern discussed in this study, to using Impossible Foods products examined in this work compared to the meat-based products examined in this work.

Assessment Summary

Life Cycle Assessment (LCA)	
Addendum to: Comparative environmental LCA of the Impossible Burger® with conventional ground beef burger	
Parameter	**Description**
Company Name and Contact Information	*Study Commissioner:* Impossible Foods Redwood City, California, USA *Client Contact:* Arjun Lev Pillai Hausner Impact Strategy Senior Analyst arjun.hausner@impossiblefoods.com *Study Practitioners:* WSP Canada Inc. Colin Powell Colin.powell@wsp.com Darius Tolkien-Spurr Darius.tolkien-spurr@wsp.com
Standards Used	ISO 14040 2006: Environmental management – Life cycle assessment – Principals and framework ISO 14044 2006: Environmental management – Life cycle assessment – Requirements and guidelines
Product Name	There are two products under study in this LCA: 1) a new Impossible Burger (IB) recipe for which new comparative claims will be made against a beef-based burger (BB) in the US (IB-US, BB-US); 2) an Impossible Meatball (IM), which has a recipe that is equal amounts IB and IS, for which new comparative claims will be made against a meat-based meatball (MM) comprised of equal amounts (50% each) beef and pork, in the US (IM-US, MM-US). Two different marketable IM products will be examined here: IM1-US, MM1-US are for retail delivery and IM2-US, MM2-US are for food service delivery (the only difference between the products is packaging).
Product Description	The products above are a frozen plant-based meat alternative (PBMA) meant to mimic ground meat (beef, pork sausage, and a combination of both, respectively, as per above for the meatball). The IB is uncooked and frozen. The MM is pre-cooked (fried) and frozen.
Functional Unit (study basis)	The function of the product is food for human consumption. The functional unit is one kilogram (kg) of product manufactured in the US in 2021 and delivered to an end user (retailer or food service). The functional unit scenarios are discussed in the LCA.
Temporal Boundary	Data from Impossible Foods are up to date and relevant for the current year. Secondary data from Ecoinvent v3.6 cut-off databases have a validity range up to 2021. The time period in which the results should be considered valid is five years from publication date of this study.
Country/Region of Product Consumption	The IB and IM products are produced in the Midwest US. Then, they are distributed to the US (IB-US, IM-US). The functionally equivalent beef, pork and meatball products studied in this work are produced and distributed in the US.
Version and Date of Issue	Version 1 – February 7, 2022

Glossary of Terms

BB: Beef Burger

GaBi®: Life cycle assessment software program

GWP: Global Warming Potential

IB: Impossible Burger

IM: Impossible Meatball

IM1 and 2: Specific recipe formulations of the IM

IS: Impossible Sausage Made from Plants

ISO: International Organization for Standardization

kg: kilogram

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

MM: Meat-based Meatball

PBMA: Plant-based meat alternative

PS: Pork Sausage

US: United States

1 GOAL OF THE STUDY

Impossible Foods Inc. (Impossible Foods) has developed two new plant-based meat alternatives (PBMA): 1) a new Impossible Burger (IB) replacing one currently on the market; and 2) the Impossible Meatball Made from Plants (IM), that aims to mimic the flavour and texture of a meat-based meatball (MM)[2] and has a recipe comprised of ingredients equivalent to a 50/50 equal split of the IB and the Impossible Sausage Made from Plants (IS, an existing product).

Impossible Foods has commissioned WSP Canada Inc. (WSP) to calculate four potential impact categories (global warming potential, freshwater eutrophication potential, land occupation, and water consumption (only withdrawals)), using the ReCiPe Midpoint (H) v1.12/World Recipe H (RIVM, 2018) method, of the new IB recipe produced and distributed within the United States (US) and two different versions of the IM produced and distributed within the US. These impact categories were chosen because they will provide the most business value to Impossible Foods in their discussions with customers and other clients and are the most salient to animal agricultural environmental impacts. As a result, the net new contributions of this addendum related to the new IB recipe and the IM products are as follows:

- Four specific life cycle potential impact categories are calculated for a new IB product produced in the US and distributed to the US and compared against a beef burger (BB) produced and distributed in the domestic markets of the US.
- Four life cycle potential impact categories of two IM products, manufactured in the US and distributed within the US and are compared against functionally equivalent MMs (MM1 for retail consumption and MM2 restaurant-type food service) produced in the domestic markets of the US.

The nature of this study is current and the IB and IM are currently being (or will soon be) produced in the US.

The goal of this study is twofold:

- Determine the absolute values of the above four potential impact categories of the new IB and IM scenarios; and,
- Calculate the difference in the above four impact categories between the IB and IM scenarios and their respective meat-based scenarios.

This study analyzes only the recipes and products used by Impossible Foods for the IB and IM and cannot be applied to that of other PBMAs or Impossible Foods products. The IB and IM are not functionally equivalent and not meant to be compared to each other. Only the results for the four impact categories were quantified because these are the key environmental areas of concern for Impossible Foods; this specific reporting of impact categories is also consistent with previous PBMA life cycle assessments (LCAs) subject to critical review (Dettling, Tu, Faist, DelDuce, & Mandlebaum, 2016; Khan, Loyola, Dettling, & Hester, 2019; Heller & Keoleian, 2018) well as other meat-based LCAs. We recognize this as a limitation to the overall presentation of results but are confident that these four impact categories are most relevant for food products and there is precedent for disclosure over only these impact categories.

[2] A note that this LCA does not assess the flavour nor texture of the particular products under study.

1.1 REASONS FOR CARRYING OUT THE STUDY

This study was conducted to inform internal decision-making and to provide information to the public who are interested in the potential environmental impacts of Impossible Foods' products. These four potential impact categories are of interest to Impossible Foods and their stakeholders. Only the results for the four impact categories were quantified because these are the key environmental areas of concern for Impossible Foods; this specific reporting of impact categories is also consistent with previous PBMA LCAs.

Impossible Foods commissioned this study to determine the absolute values of four potential impact categories from the life cycle of their IB and IM products and compare those values against meat-based benchmarks. Therefore, the results of this study include absolute and comparative values that are intended to be communicated externally.

1.2 INTENDED APPLICATIONS

This project report is intended to support Impossible Foods in quantifying those four particular impact categories associated with IB and IM ingredients, production, and distribution and in supporting the comparative assertions of those four particular impact categories associated with the IB and IM products studied here against their respective functionally equivalent meat-based products, intended to be disclosed to the public.

1.3 TARGET AUDIENCE

Specific audiences may include the company's employees, business partners, customers, and the general public. The study results are prepared for both Impossible Foods' internal use and to be communicated externally in conformance with ISO 14040, 14044, and 14062 (ISO, 2018).

1.4 COMPARATIVE ASSERTION FOR PUBLIC DISCLOSURE

This LCA is intended to be compliant with the requirements of ISO 14044 (ISO, 2006), which governs the requirements for public product-to-product comparisons for LCAs. A comparative assertion is intended to be made with the products described in this report. A critical review panel was not convened for this report for the following reasons:

- the IB recipe used in this report is only slightly different than that examined in Qantis (2019) and Impossible Foods (2020) and the ingredients and processes have been previously critically reviewed;
- the beef and pork models that are used in the BB and PS (which make up the MM) have been published and critically reviewed previously in Qantis (2019) and Impossible Foods (2020), respectively, and are used for this report.

2 SCOPE OF THE STUDY

2.1 FUNCTION

The primary functions of the food products under study are to provide food for consumers to eat.

2.2 FUNCTIONAL UNIT

In order to maintain functional equivalence, the functional unit is one kilogram (kg) of product produced in 2021/2022. There are a number of functionally equivalent scenarios examined here, specifically with respect to location of production and the destination. These scenarios are detailed in Table 1.

Table 1 – Functionally equivalent scenarios

Functionally equivalent scenario	Impossible Foods product	Meat-based comparator product
Scenario 1	IB-US	BB-US
Scenario 2	IM1-US	MM1-US
Scenario 3	IM2-US	MM2-US

All Impossible Foods products are produced in the US and delivered to the destination in the name (i.e. IB-US is produced in the US and distributed in the US). For all meat-based comparator products, all products are produced and distributed in the same location (i.e. BB-US is produced in the US and distributed in the US.

While it is acknowledged that there is not a single measurement on which to set a functional basis for food consumed due to the multiple reasons people eat food (i.e., for nutrition, to reduce or mitigate hunger, social gathering, etc., which are not addressed in this study), the Impossible Foods products examined in this study (IB, IS, IM1 and IM2) were designed to be nutritionally and aesthetically similar to their meat counterparts (BB, PS, MM1 and MM2). Table 2 provides the nutritional data comparison for the Impossible Foods and meat-based products.

Table 2 – Nutritional data for IB, BB, IS, PS, IM, MM

Nutrient	Units	IB 100 g (provided by Impossible Foods)	BB - Beef, ground, 80% lean meat, raw 100 g (USDA, 2018)	IS 100 g (provided by Impossible Foods)	PS - pork sausage, link/patty, unprepared 100 g (USDA, 2019)	IM 85 g (provided by Impossible Foods)	MM - Italian Style Meatball (pork and beef blend) per 85g (Cooked Perfect, 2021)
Calories	kcal	201.51	254	237	288	164.91	250
Fat	g	11.37	20	16.68	24.80	11.45	19
Saturated fat	g	5.18	7.581	7.19	7.57	3.94	7
Trans fat	g	0	1.18	0	0.101	0.00	unk
Cholesterol	mg	0	71	0	70	0.00	55
Sodium	mg	324.95	66	588.17	739.00	361.43	630
Total carbohydrate	g	8.17	0	9.07	0.93	5.53	5
Total dietary fiber	g	4.76	0	1.16	0	0.69	1
Total sugars	g	0.59	0	1.30	0.93	0.40	1
Protein	g	16.65	17.17	12.58	15.39	9.94	14

The products are compared in this LCA on a per-mass basis, as was done in the other LCAs for Impossible Foods (Impossible Foods, 2020). It is noted, though, that human bodies digest animal proteins differently than vegetables and thus the specific digestion of the PBMA and the meat-based product may differ; this effect was not examined in this specific study. An additional limitation to using the per-weight basis to examine the impact categories would be the fact that some people eat to satiate specific dietary needs, for example, protein intake. An analysis is completed in Section 5.3.2 to examine the impact categories on a caloric and protein functional-unit basis to understand if the conclusions change based on a different functional unit.

2.3 DESCRIPTIONS OF THE SYSTEMS

As noted above, the Impossible Foods products examined in this study are compared against their respective functionally equivalent meat alternatives. These systems studied are discussed in this section.

2.3.1 IMPOSSIBLE FOOD PRODUCTS UNDER STUDY – IB AND IM

There are three varieties of Impossible Foods Products under study in this LCA:

- IB: a PBMA that mimics the taste and texture of a meat-based beef burger patty and is delivered uncooked and frozen to a retailer;
- IM1: a PBMA that mimics the taste and texture of a meat-based meatball and has a recipe that is equivalent to an equal mix of the ingredients of IB and IS, that is delivered pre-cooked and frozen to a distributor, with packaging that is designed to be sold direct to consumers at retail locations; and,
- IM2: a PBMA that mimics the taste and texture of a meat-based meatball and has a recipe that is equivalent to an equal mix of the ingredients of IB and IS, that is delivered pre-cooked and frozen to a distributor, with packaging that is designed to be sold direct to food service establishments for consumption by consumers in food service establishments.

IM1 and IM2 have the same ingredient recipe but different packaging. All Impossible Foods products studied are intended to be included in recipes and meals as a direct and equivalent substitute for their meat-based alternatives. Again, it is noted that while the IM recipe has ingredient quantities comprised of a 50/50 split of the ingredients in the IB and IS bulk mix, the IM is produced separately using the raw ingredients and not produced by combining the IB and IS bulk mixes.

IMPOSSIBLE BURGER – IB

The IB is a PBMA and a direct alternative for its meat counterpart, beef. It is intended to be included in recipes and meals as direct substitutes for a hamburger patty. This specific IB is an update to a previous recipe that was subject to a critical review (Qantis, 2019). The primary difference between the previous IB recipe and this IB recipe is the removal of potato protein. There are slight modifications to the quantities of other ingredients. The IB is to be compared to its BB functional equivalents only. The IB examined in this study is manufactured in the US and delivered to retailers in the US (IB-US). The product is a plant-based product comprising grains, legumes, and oils, and heme, which gives the product its characteristic meat flavor, color, and behavior.

Heme is manufactured through a fermentation and isolation process wherein a genetically modified yeast strain is produced in culture and expresses leghemoglobin protein, which is then isolated downstream (Khan, Loyola, Dettling, & Hester, 2019). It is shipped from its manufacturing facilities to the IB bulk product processing facilities in the Midwest US. There, it is mixed and processed with other plant-based proteins and fats.

The scope of the system studied includes all activities to produce one functional unit of IB, packaged and frozen, from "cradle to the gate of the retail/wholesale distributor's truck." Retail, use, and end-of-life stages are excluded from the study as these do not differ significantly between the IB and the reference BB products. Overhead services (i.e., lighting and heating of buildings on site) are considered a non-attributable process (i.e., processes that are not directly connected to the studied product) but are included because they are typically provided with the total electricity and fuel consumption data. Other non-attributable processes such as infrastructure and equipment, corporate activities, transport of employees to and from work, etc. are excluded as either the information is not available or, while it is recognized that these non-attributable processes may have some environmental impacts that can be quantified using hybrid LCA methodologies, they are not significant contributors of impacts in agricultural systems and are thus not included. While it is recognized that some new or retrofitted infrastructure may be required for some processes in this study, it is not possible to allocate all of the impacts to the new activities nor is it possible to quantify that allocation due to the prospect of other uses during and after the study period. Thus, the infrastructure processes were excluded from the inventory calculation.

Figure 1 further details the system under study, including raw materials production, the IB primary and secondary processing stages, packaging and then distribution to retailers. As noted prior, the use and end-of-life stages are not included here because they are not considered to differ from the BB equivalent.

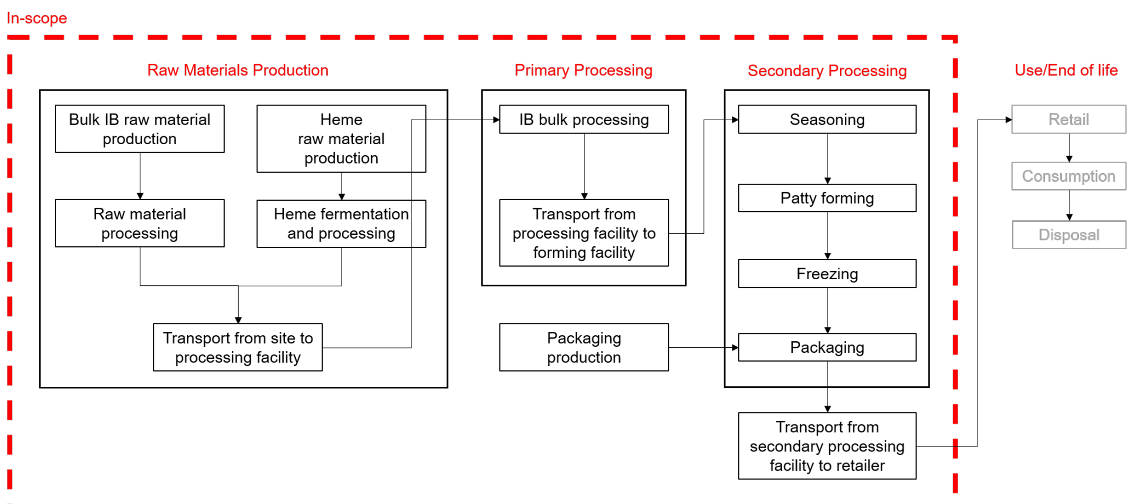

Figure 1 – Inventory boundary for the IB scenarios (WSP analysis)

The in-scope life cycle stages of the IB, with the specific substages that are relevant to the potential environmental impact calculations, are described briefly in Table 3.

Table 3 – Boundary descriptions for IB scenarios (WSP Analysis)

Stages	Sub-stages	Description

Raw materials production	Bulk IB raw material production	The ingredients in the IB include organic and inorganic chemicals, plant fats, proteins and carbohydrates. The organic and inorganic chemical production may require electricity, natural gas and other fossil fuel inputs, as well as other primary chemical inputs. Crop production to obtain the plant fats, proteins, and carbohydrates generally includes soil preparation, which includes applying fertilizer or manure to add nutrients, and tillage and plowing to remove unwanted weeds or grass. Once the soil is prepared, the seeds are sowed, followed by irrigation and further application of fertilizers and/or manure. Once the crops reach maturity, they are harvested using a combine and dried, packaged and stored until ready for shipment. Impacts from this substage primarily arise from fossil fuel use to produce fertilizer and run farm equipment, nitrate and nitrogen emissions from the application of fertilizers and lime, manure management resulting in leaching causing potential eutrophication, water withdrawal and return for irrigation and land occupation for the cropland itself. (Chicken Farmers of Canada, 2018; Dalgaard, Halberg, & Hermansen, 2007; Putman, 2017).
	Heme raw material production and fermentation	The ingredients in the heme include organic and inorganic chemicals, yeast, plant fats and carbohydrates. The organic and inorganic chemical production may require electricity, natural gas and other fossil fuel inputs, as well as other primary chemical inputs. The agricultural processes require fossil fuel inputs, including fertilizers and/or manure, as well as water, to grow the plants. Heme is produced at Impossible Foods' production facility, through fermentation, in which a genetically modified yeast strain expresses the naturally occurring leghemoglobin protein. Following fermentation, the leghemoglobin protein is isolated and concentrated from the fermentation media (Khan, Loyola, Dettling, & Hester, 2019).
	Transport from site to processing facility	The raw materials and crops, including heme, for the IB are delivered via truck to the Impossible Foods production plant in Midwest US from their typical locations.
Primary processing	IB bulk processing	The production process for the IB involves first the development of a bulk product. This includes the mixing of heme and various plant proteins and oil preparations. There is electricity and water withdrawal in all processing steps, as well as small amounts of ammonia consumption from refrigeration.
	Transport from processing facility to forming facility	The bulk IB products are then delivered to a forming facility in Midwest US.
Secondary processing **Packaging**	Seasoning, patty forming, and freezing	After delivery of the bulk IB product to the forming facility, the product is seasoned and formed into patties for sale. The product is then frozen and packaged (packaging occurs at the same site as the seasoning and patty forming).
	Packaging	The IB packaging consists of plastic film that is wrapped around the patties. These wrapped patties are then packed in corrugated cardboard. Packaging and patty production are co-located, obviating transportation emissions between these steps (Khan, Loyola, Dettling, & Hester, 2019). Electricity, natural gas, and water withdrawal are fully considered in the production process.

Distribution	Transport from secondary processing to retailer	The packaged IB is then delivered to retailers, primarily grocery stores and/or restaurants throughout the US via trucks. For Australia and/or New Zealand, trucks deliver the products to the Los Angeles port and ships deliver them to Sydney, where additional truck travel is used to deliver the products to distributors and then onwards.

MEATBALL MADE FROM PLANTS – IM

The IM is intended to be a direct substitute for a meat-based meatball to be used in recipes and other instances where a meatball is consumed. The boundary of the system studied includes all activities necessary to produce the IM1 and IM2 from cradle-to-gate of the initial purchaser of finished product, whether a distributor, food service operator, or traditional retailer, prior to purchase by an end consumer. Retail, use, and end-of-life stages are excluded from the study as these do not differ significantly between the IM and the reference MM products. Overhead services (i.e., lighting and heating of buildings on site) are considered a non-attributable process (i.e., processes that are not directly connected to the studied product) but are included because they are typically provided with the total electricity and fuel consumption data. Other non-attributable processes such as infrastructure and equipment, corporate activities, transport of employees to and from work, etc. are excluded as either the information is not available or, while it is recognized that these non-attributable processes may have some environmental impacts that can be quantified using hybrid LCA methodologies, they are not in-scope for this type of LCA.

Figure 2 further details the system under study, including raw materials production, the IM primary and secondary processing stages, packaging and then distribution to retailers. As noted prior, the use and end-of-life stages are not included here because they are not considered to differ between the IM and MM processes.

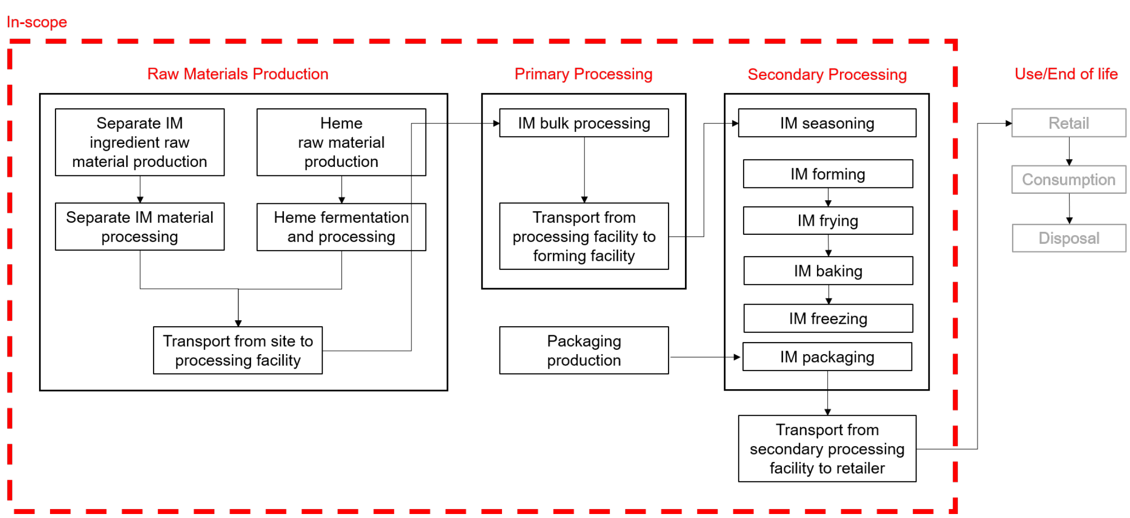

Figure 2 – Inventory boundary for the IM scenarios (WSP analysis)

The in-scope life cycle stages of the IM, with the specific sub-stages that are relevant to the potential environmental impact calculations, are described briefly in Table 4.

Table 4 – Boundary descriptions for IM scenarios (WSP Analysis)

Stages	Sub stages	Description
Raw materials production	Bulk IM raw material production	The ingredients in the IM include organic and inorganic compounds, plant fats, proteins and carbohydrates. The organic and inorganic chemical production may require electricity, natural gas and other fossil fuel inputs, as well as other primary chemical inputs. The agricultural processes require fossil fuel inputs, including fertilizers and/or manure, as well as water, to grow the plants. The recipe of the IM is meant to be a 50/50 split of the IB and IS recipes, but the IM is produced using a stand-alone process.
	Heme Raw material production, processing and heme production	The ingredients used to produce heme in fermentation include yeast substrates (organic and inorganic chemicals and carbohydrates) and the yeast itself. The organic and inorganic chemical production may require electricity, natural gas and other fossil fuel inputs, as well as other primary chemical inputs. The agricultural processes to produce the carbohydrate substrate requires fossil fuel inputs, including fertilizers and/or manure, as well as water, to grow the plants. Heme is produced through fermentation, in which a genetically modified yeast strain expresses the naturally occurring leghemoglobin protein. Following fermentation, the leghemoglobin protein is isolated and concentrated from the fermentation media (Impossible Foods, 2020).
	Transport from site to processing facility	The raw materials and crops for IM are delivered via truck to the IM production plant in the Midwest US from regions that produce and distribute large volumes of the specific ingredients (exact locations not provided publicly for proprietary reasons).
Processing	IM bulk production	The bulk formation process for the IM involves mixing the ingredients. There is electricity and water withdrawal in all processing steps, as well as small amounts of ammonia consumption from refrigeration. The bulk IM product is then delivered to a finishing and cooking facility in another Midwest US location using a refrigerated truck.
	IM forming, frying, baking, freezing	After delivery of the bulk IM product to the finishing and cooking facility, the product is formed, fried, baked, and then packaged. The frying stage uses soybean oil as a cooking oil. The frying and baking stages use natural gas and electricity to heat. This is the same finishing and cooking step as the MM to ensure comparability. This is also borne out in practice where meat-based and plant-based meatballs are prepared and made using the same processes in the same facilities.
	IM packaging	The IM packaging consists of a plastic bag that contains the meatballs. These bags are then packed in corrugated cardboard. Packaging and meatball production are co-located. No other packaging is used. The amount of the plastic and the corrugated cardboard used for IM1 and IM2 differs and is discussed later in this document.

Distribution to retailer	Transport from secondary processing to retail (IM1) and food service (IM2)	The packaged IM products are then distributed via truck throughout the US for IM1-US, IM2-US.

2.3.2 MEAT PRODUCTS UNDER STUDY – BB, PS, AND MM

BEEF BURGER - BB

Cattle production involves the process of feeding and rearing in different stages before going to slaughter. The model includes cow-calf operations lasting 6 months on pasture, 3 months of backgrounding, and 7 months of feedlot finishing. The backgrounding diet was based on hay and distiller's grain, while the finishing diet was primarily grain-based. This represents typical farm management practices from Nebraska, which is one of the largest beef feedlots producing states in the United States. There is also some beef production that comes from dairy operations, estimated to be 22%: 7% from culled dairy cows and 15% from male calves.

The cattle production system for the supply of beef used in this study is described in detail in Qantis (2019) and provides more information related to the type of system, representativeness, and the inputs required to describe and model a US-based beef production system. In Qantis (2019), farm data is reproduced from Asem-Hiamblie et al. (2018) from the US Meat Animal Research Center (USMARC). In Qantis (2019), the dairy operations environmental impacts were modeled using World Food LCA Databases (WFLDB). The model used in Qantis (2019) is leveraged in entirety here as it still represents the best available fulsome dataset to re-produce beef production for this particular purpose. It is recognized that some foreground and background processes may be of lower data quality, as indicated by the authors, the sensitivity analyses of these processes in Qantis (2019) demonstrate no material impact to the results.

It is noted by the authors that this is not necessarily representative of *all* beef production the US; however it represents a significant proportion of the crop, feed, and animal management practices of the US.

After slaughter, the beef is ground into ground beef and seasoned and formed into patties in order to be functionally equivalent to the IB. The final BB product is meant to mimic the IB, to be sold frozen and in the form of a beef patty.

Figure 3 further details the system under study, including feed production, cattle production, dairy cow input to slaughter, beef processing, slaughter, forming, freezing, packaging, and then distribution to retailers. As noted prior, the use and end-of-life stages are not included here because they are not considered to differ from the IB equivalent.

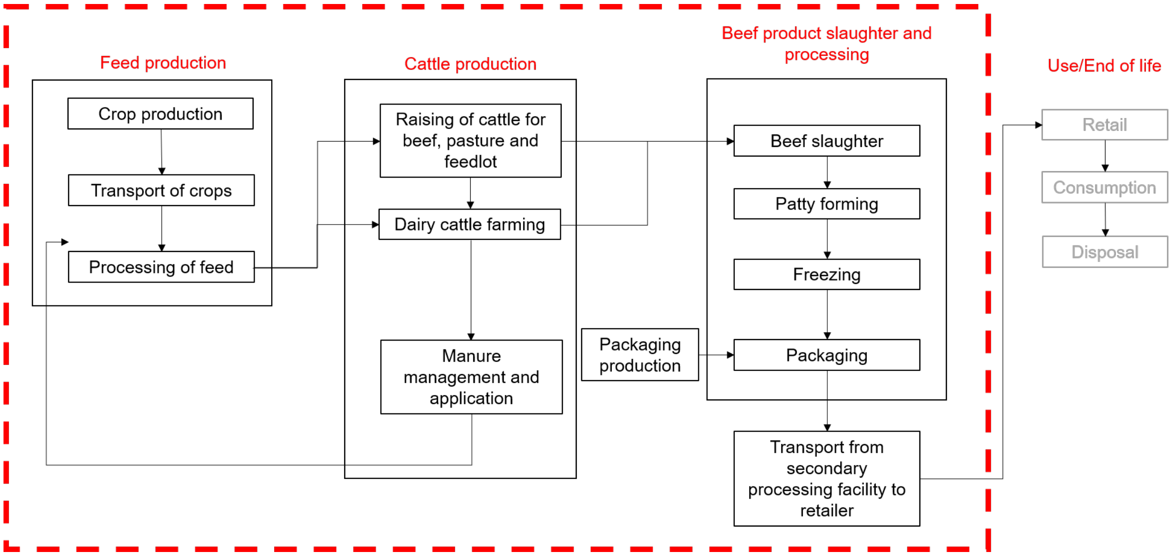

Figure 3 – Inventory boundary for BB scenarios (WSP analysis)

As noted above, overhead services are considered non-attributable but are included because they are typically included in the total electricity and fuel consumption data. Other non-attributable processes such as infrastructure and equipment, corporate activities, transport of employees to and from work, etc. are excluded.

GROUND PORK - PS

The PS system, examined here only because the MM is comprised equally of BB and PS, is detailed in Impossible Foods (2020) which provides more detailed information and the results of PS delivered in the US.

MEAT-BASED MEATBALL - MM

Similar to the system boundaries for IM, the full boundary for the MM includes the production systems for both conventional beef and pork. Figure 6 further details the system under study. The MM is comprised of equal amounts ground beef and pork. In the MM-US scenarios, ground beef and pork are produced in the US locally, respectively, for local processing (and cooking) into MM and then consumption. The products are meant to mimic the IM, to be sold pre-cooked and frozen and in the form of a meatball. There are two varieties of the MM under study in this LCA:

- MM1: a meat-based meatball is delivered pre-cooked and frozen to a distributor for a retail customer; and,
- MM2: a meat-based meatball is delivered pre-cooked and frozen to a distributor for food service establishments.

Consistent with the IM1 and IM2, the differences in the MM1 and MM2 are related to the quantity of packaging.

Figure 4 further details the system under study, including feed production, cattle and pig production (i.e., raising of the animals and slaughter), processing of both the beef and pork, production of the meatball (i.e., blending an equal composite of beef and pork), forming, and frying, baking and freezing (meant to produce functional equivalence to the IM varieties), and then distribution to retailer/food service. As noted prior, the use and end-of-life stages are not included here because they are not considered to differ from the IM equivalent.

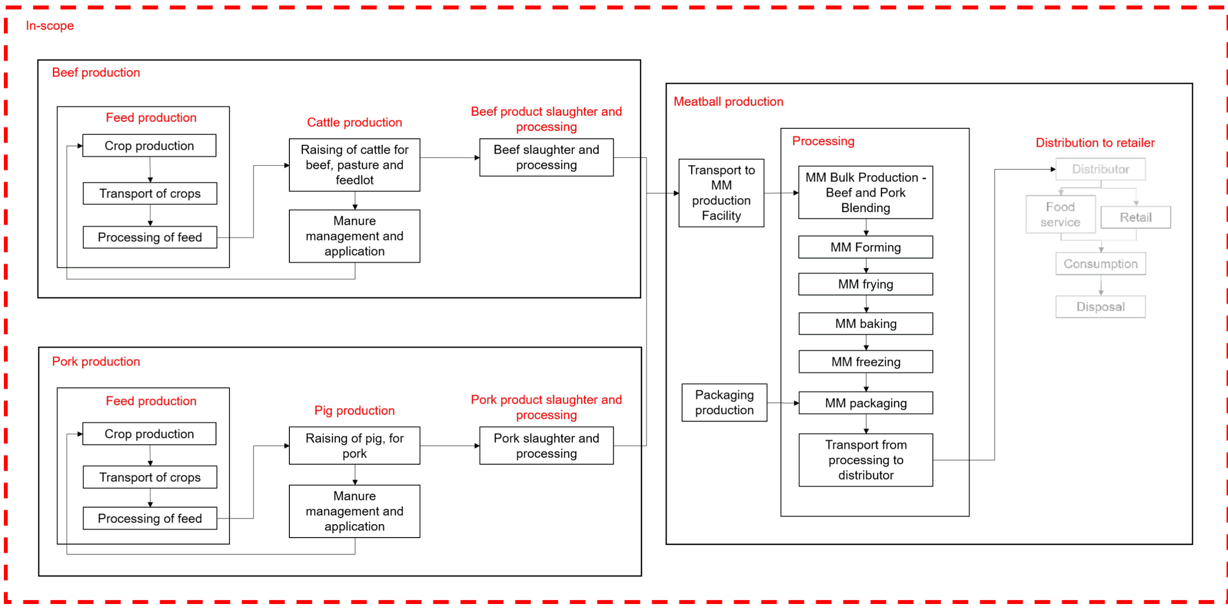

Figure 4 – Inventory boundary for MM scenarios (WSP analysis)

Also as noted above, overhead services and other non-attributable are not specifically examined but are included because they are typically included in the total electricity and fuel consumption data.

Based on WSP analysis, the in-scope life cycle stages of the MM, with the specific sub-stages that are relevant to environmental impact calculations, are described briefly in Table 5.

Table 5 – Boundary descriptions for MM scenarios (WSP analysis)

Stages	Sub-stages	Description
Cattle and pig – Feed production	Crop production	See Qantis (2019) and Impossible Foods (2020) for descriptions related to cattle and pig feed, production, and slaughter processes, respectively.
	Transport of crops to processing plant	
	Processing of feed (crushing, screening, milling and concentration)	
	Transport of crops to farm	
	Cattle production	

Stages	Sub-stages	Description
Cattle production and pig production	Pig production	
	Manure management and application (cattle)	
	Manure management and application (pig)	
Beef product slaughter/Pork product slaughter	Slaughtering	
Meatball production	Transport to MM processing facility	The ground beef and pork are delivered via truck to the meatball production plant, with an assumed distance of 500 km from the slaughterhouses for both.
	MM bulk production – beef and pork blending	After the slaughter and processing, the fresh meat is ground and blended (with an equal blend of ground beef and ground pork), seasoned and formed as necessary, identically to the IM.
	Forming, frying, baking, freezing	The secondary processing stage includes the finishing and cooking activities. The formed meatballs are fried, baked, frozen, and packaged. The frying stage uses soybean oil as a cooking oil. The frying and baking stage uses natural gas and electricity to heat. Secondary processing is assumed to occur in the same facility as the primary processing facility. This is the same finishing and cooking step as the IM to ensure comparability.
Packaging	MM Packaging	Finished meatballs are packaged for sale using similar packaging to that of the IM1 and IM2: plastic film and corrugated cardboard for retail and food service.
Transportation to retailer	Transport from secondary processing to retail (MM1) and food service (MM2)	The packaged IM products are then distributed via truck throughout the US for IM1-US, IM2-US.

2.4 CUT-OFF APPROACH

It is noted that for all scenarios, a mass-based cut-off criterion for the foreground processes was used, where those cumulative inputs that comprised less than 0.5% of the total mass of the final products were not included in the quantification of the impact categories. This is consistent with the previous LCA studies for Impossible Foods (Impossible Foods, 2020). For the background processes, the Ecoinvent 3.6 cut-off database was used (the previous models in Qantis (2019) and Impossible Foods (2020) which have different processes between this database and the database used in that model were updated using more recent factors). The authors recognize that this may introduce some issues related to consistency among the cut-off approaches, but that primarily, the foreground processes where the 0.5% cut off was used were more relevant to the overall magnitude of impacts.

For processes that were above that threshold where no modelled processes were available, proxies were used.

2.5 INVENTORY DATE AND VERSION

This is the first version of the inventory comparing the new recipe for IB, IM1 and IM2 scenarios against BB, MM1 and MM2, respectively. The production data for the systems examined are based on the most recent design and production data provided by Impossible Foods. For the BB, PS, and MM, the inventories are based on representative industrial, market and literature data, where available.

2.6 TIME PERIOD AND GEOGRAPHIES OF THE INVENTORIES

This assessment is intended to be representative of the production of the Impossible Foods products studied and their meat counterparts in the US during the year that the study is conducted (2021). Data and assumptions are intended to reflect current equipment, processes, and market conditions. Data has been selected where possible to best match these geographic and temporal conditions, and the data quality of significant inputs is evaluated using Table 11. Information sources for this report were evaluated as relevant and considered to represent the best available data and conditions in the industry. While certain processes may generate emissions over a longer period than the current year, all data has been selected to represent current conditions, where practical.

For the global warming potential indicator, the 100-year time horizon global warming potentials (GWPs) without carbon feedback from AR5 are utilized (IPCC, 2014). The biogenic methane GWP was used.

2.7 LAND USE CHANGE IMPACTS

Direct land-use changes from the use of crop lands to produce PBMA ingredients and crops for animal (beef and pork) feed production may be significant (Reckmann, Blank, Traulsen, & Krieter, 2016). The quantification of GHG emissions for specific ingredients is sourced from the Ecoinvent v3.6 cut-off database (Wernet, et al., 2016) and all crop-based ingredients include direct land occupation change impacts in their processes. Regardless, direct land-use change emissions may differ depending on the previous land occupation, the type of crop and the region in which the crops are grown.

2.8 ALLOCATION

Allocation or system expansion may be required when a single process has multiple valuable products as outputs (i.e., the refining of crude oil into various petroleum co-products). In these situations, inputs and emissions for the whole process need to be allocated to the various co-products following appropriate methods.

For all existing Ecoinvent v3.6 processes, no modifications to the allocations embedded were performed. For processes that were modified, existing allocations were maintained. For oils, such as sunflower and coconut, allocation was conducted on an economic basis and this approach was applied from Impossible Foods (2020) in order to maintain consistency.

At a cattle and pig farm, prior to slaughter, livestock are the main product and manure is produced as a co-product. In such production, it is not possible to allocate precisely what feed use, land occupation or emissions are related to raising the cattle and pigs, or the manure and therefore system expansion must be used. The manure production replaces fertilizer on the market, resulting in avoided production of fertilizer (that was used in the Ecoinvent processes), and thereby a negative contribution to the potential environmental impact from the life cycle of the livestock. In this study, manure that was produced in the cattle and pig production process was either left on pasture or applied to the crop production processes. The reduced fertilizer requirements as a result were modelled using the manure application process as detailed in this work. More information on these processes for cattle and pig are provided in Qantis (2019) and Impossible Foods (2020), respectively.

For the beef and pork products in this study, an economic allocation procedure was used because the products have such widely different values in the market. The mass and economic allocation used in this study for cattle and pig are provided in Qantis (2019) and Impossible Foods (2020), respectively.

2.9 DATA QUALITY REQUIREMENTS

The life cycle data used in this LCA relies upon the primary data from Impossible Foods and secondary data sources such as the Ecoinvent v3.6 database where appropriate.

Data quality for each process in the inventory boundary that contributed 5% or more of the potential environmental impact were evaluated and the efforts to improve data quality are reported later in the paper, where necessary. The data was assessed using the data quality indicators described in Table 6 (Weidema, et al., 2013).

Table 6 – Data quality indicators

Data quality indicators	Description
Reliability	The degree to which the sources, data collection methods and verification procedures used to obtain the data are dependable.
Completeness	The degree to which the data is statistically representative of the relevant activity. Completeness depends on many factors including the percentage of sites for which data is used out of the total number of relevant sites, coverage of seasonal and other fluctuations in data, etc.
Temporal representativeness	The degree to which the data reflects the actual time (e.g., year) or age of the activity.
Geographical correlation	The degree to which the data reflects the actual geographic location of the activity (e.g., country or site).
Technological representativeness	The degree to which the data reflects the actual technologies used.

The qualitative evaluation for each data quality indicator will be based on the scoring scheme presented in Table 7 (Weidema, et al., 2013).

Table 7 - Pedigree scoring quality criteria

Score	Technology	Temporal	Geography	Completeness	Reliability
Very good	Data for the same technology	Data with less than 3 years of difference	Data from the same area	Data from all relevant sites over an adequate time period	Verified data based on measurements
Good	Data for a similar but different technology	Data with less than 6 years of difference	Average data from larger area in which the area under study is included	Data from more than 50% of sites over an adequate time period	Verified data partly based on assumptions or non-verified data based on measurements
Fair	Data for a different technology	Data with less than 10 years of difference	Data from an area with similar production conditions	Data from less than 50% of sites over an adequate time period or from more than 50% of sites for a short time period	Non-verified data partly based on assumptions or a qualified estimate
Poor	Data from processes and materials under study but from different enterprises	Data with less than 15 years of difference	Data from area with slightly similar production conditions	Data from only one site relevant for the market or some sites but from shorter periods	Qualified estimate
Very poor	Data for an unknown technology	Data with more than 15 years or unknown difference to the time period of the data set	Data from an area that is unknown or distinctly different area	Data from a small number of sites and from shorter periods	Non-qualified estimate

3 LIFE CYCLE INVENTORY ANALYSIS

3.1 DATA SOURCES FOR IM

Depending on its source, data can either be classified as primary or secondary:

- Primary data is specific to the processes included in the product's life cycle boundary. It can be collected in the reporting company or from its suppliers; and
- Secondary data is not specific to the product under study and is taken from commercial databases, industry reports, literature, etc.

When modeling the two product systems under study, the Ecoinvent v3.6 cut-off (Wernet, et al., 2016) database was used as the sole source for background data, with infrastructure processes excluded as noted above. There were cases where an Agri-footprint v1.0 foreground process (Blonk Agri-footprint BV, 2014) was used (economical allocation), as was the case in previous Impossible Foods LCAs (Impossible Foods, 2020) but the background processes were replaced with Ecoinvent v3.6 processes; whenever possible, appropriate country inventories were selected. When neither country-specific nor region-specific inventories were available, global or "RoW" inventories were used. For agricultural processes, local and recent crop yields were used to update inventories and make them more reflective of local condition (see Impossible Foods (2020)). Global inventories are typically average datasets of all the country- or region-specific datasets available in the database for the specific product/process. This is assumed to be a reasonable alternative in the absence of country- or region-specific datasets (Khan, Loyola, Dettling, & Hester, 2019).

3.1.1 RAW MATERIALS PRODUCTION – IB AND IM

Primary data for the stages controlled by Impossible Foods, such as the production of the raw materials, heme, and the forming, seasoning, and cooking (where applicable), for all Impossible Foods products examined in this study were provided by Impossible Foods and their suppliers/manufacturers. WSP has not audited the data in any way and relies on Impossible Foods to provide accurate data. For processes not controlled by Impossible Foods, such as transportation, feed production and distribution, secondary data was used from commercial databases and literature. Appendix A contains the processes used to model IB and IM.

IMPOSSIBLE BURGER - IB

The raw materials that constitute the IB are divided into two primary parts: the bulk IB mix and the ingredients to produce heme. A list of the ingredients and the associated modelled processes and databases for the IB is provided in Table 8. While only the broad categories of ingredients are shown here to ensure the privacy of proprietary information, the actual ingredients, or equivalent proxies, were used to model the IB in the GaBi software.

A fixed distance of 1,500 km by diesel truck was used for each US-based product transported to the Midwest US production facility. We note that this distance may be conservative as some crops would be produced closer to Midwest US than 1,500 km, but it is also assumed that this transport distance is not a significant contributor to the overall impact categories, and this is borne out in previous LCAs (Impossible Foods, 2020). Any ingredients that originated outside North America were modeled using a combination of truck and ocean transport using actual road and sea distances, respectively. Specific ports were determined based on the dominant port cities in the areas where Impossible Foods sources its ingredients.

The ingredients above made from crops were produced using conventional methods (i.e. non-organic) that consume fertilizers, fossil fuels, water, etc. as is typical for crop production in the region of production. It is noted that yields for the relevant crops (i.e. corn, soybean, etc.) were modified according to Impossible Foods (2020).

IMPOSSIBLE MEATBALL - IM

As mentioned prior, the IM is comprised of equal mass IB and IS; thus, the raw materials production for the IM is contingent on the raw materials production modeled for IB and IS.

Table 8 – List of ingredients for heme, IB and IM

Ingredient	Modelled dataset*	Database
Water	Tap water production, conventional treatment {US} - Agg	Ecoinvent v3.6
Yeast Extract	Yeast {EU-28} - Agg	Sphera**
Dextrose	Sugarcane production {ROW} – Agg; Proxy	Ecoinvent v3.6
Soy protein concentrate	Used Agri-footprint v1.0 dataset for foreground process but replaced all background processes with Ecoinvent v3.6 processes (Blonk Agri-footprint BV, 2014)	Ecoinvent v3.6 See Impossible Foods (2020) for process
Coconut Oil	Used Agri-footprint v1.0 dataset for foreground process but replaced all background processes with Ecoinvent v3.6 processes (Blonk Agri-footprint BV, 2014)	Ecoinvent v3.6 See Impossible Foods (2020) for processes and updated crop yields

Sunflower oil	Used Agri-footprint v1.0 dataset for foreground process but replaced all background processes with Ecoinvent v3.6 processes (Blonk Agri-footprint BV, 2014)	Ecoinvent v3.6 See Impossible Foods (2020) for processes and updated crop yields
Starch	Potato starch production {ROW} – Agg; Proxy	Ecoinvent v3.6
Methylcellulose	Methylcellulose {DE} - Agg	Sphera**
Salt	Sodium chloride production, powder {ROW} - Agg	Ecoinvent v3.6
Soybean oil	Soybean oil {US}, production	Ecoinvent v3.6

*All processes were default allocation. **A GaBi-sourced process for methylcellulose was used because the only similar process in Ecoinvent was for carboxy methylcellulose from synthetic/meat-based sources.

3.1.2 PROCESSING – IB AND IM

IMPOSSIBLE BURGER

The respective ingredients for the IB undergo a processing and freezing stage, where the ingredients are combined, mixed, formed and frozen in Midwest US.

The data for this stage were collected by the manufacturer and is based on total facility usage normalized by the mass of functional unit produced. As noted prior, WSP has not audited this data and relies on Impossible Foods and their suppliers to ensure accuracy of provided data. The electricity grid for Midwest US was modelled using subregion data based on eGRID2019 data (US EPA, 2021) using a modified Ecoinvent v3.6 process.

It is assumed that there is a loss of 5% by weight from the mixing and forming stage of the IB based on past experience of food lost in the process. Thus, the process was modelled with 5% of the output going to landfill. This is a conservative assumption as all efforts are made to conserve the product mass. Regardless, this approach was also used by Dettling, Tu, Faist, DelDuce, & Mandlebaum (2016) and in previous Impossible Foods LCAs (Impossible Foods, 2020).

IMPOSSIBLE MEATBALL

To produce the IM, the ingredients are blended into a bulk material in Midwest US.

The data for this stage were collected by the manufacturer and is based on total facility usage normalized by the mass of functional unit produced. As noted prior, WSP has not audited this data and relies on Impossible Foods and their suppliers to ensure accuracy of provided data. The electricity grid for Midwest US was modelled using the utility provider subregion data based on eGRID2019 data (US EPA, 2021) using a modified Ecoinvent v3.6 process. The same assumption of a 5% loss by weight in the forming stage also applies for the IM system.

The IM base meat is transported to another facility in another Midwest US location, where it undergoes finishing (i.e., seasoning), forming, baking, and frying stages in the area which includes the use of conveyer belts, mixers, ovens, frying vats, motors, refrigerators, and other equipment to cook the meatball and prepare the meatball for distribution and sale.

The data for this stage were collected by the manufacturer and is based on total facility usage normalized by the mass of functional unit produced by Impossible Foods. As noted prior, WSP has not audited this data and relies on Impossible Foods and their suppliers to ensure accuracy of provided data. The electricity grid for this other Midwest US location was modelled using the 2021 energy mix data provided by local utility provider, using a modified Ecoinvent v3.6 process. It is assumed, as well, there is a loss of 5% by weight of the IM from this stage.

3.1.3 PACKAGING – IB AND IM

The IB, IM1 and IM2 are packed using a flexible plastic pouch, suitable for use for frozen food applications, and this packaging is marketed to retail locations and restaurants using corrugated cardboard secondary packaging. The amount of plastic and corrugated cardboard used for the packaging used in the products studied can be found in Table 9.

Table 9 – Packaging amounts, per kg of product

Packaging Type	IB	IM1	IM2
Plastic Pouch (g)	2.3	0.4	0.908
Cardboard (g)	10	3.1	0.00454

3.1.4 TRANSPORTATION TO DISTRIBUTOR – IB AND IM

For IB, IM1 and IM2 going to US distributors (IB-US, IM1-US, IM2-US), a fixed distance of 1,500 km of freezer truck travel was used to model the distribution to the distributor gate.

It is noted that the in-scope life cycle stages stop at the gate of the distributor; they do not include any activity beyond the gate of the distributor as it expected to be equivalent between the Impossible Foods products and their functionally equivalent meat-based scenarios, as they are expected to be equivalent.

3.2 DATA SOURCES FOR MEAT-BASED PRODUCTS

For cattle (to make the BB and MM) and pig (to make the MM) production and slaughter processes to make ground beef and ground pig, respectively, the models used in the previous LCAs for Impossible Foods (Qantis (2019) which compared the previous recipe for the Impossible burger against BB-US and Impossible Foods (2020) which compared a current IS recipe against PS-US) were used directly. Both studies were subject to critical review and are used in their entirety here. As such, those studies provide more specific data source information on cattle and pig feed production, cattle and pig production (rearing), manure management and application processes, and cattle and pig slaughterhouse activities to produce ground beef and ground pork, respectively. These are not discussed here for brevity. What follows is a description of how the ground beef and ground pork from those processes are used in the BB and MM products to ensure comparability with the IB and IM products.

3.2.1 PROCESSING – BB AND MM

BEEF BURGER - BB

At a facility after the slaughterhouse, for the BB (not for the MM), the fresh ground beef is processed and formed into BB patties, using the same data from the primary processing stage for the IB. For this stage in the BB product life cycle, the data for energy, water, refrigerant, and waste to season, form, and freeze and package the IB was used due to a lack of available data for a BB (the data are available in Table 57). A loss of 5% by weight of the fresh meat from this stage is assumed, and that the specific heating capacities of the IB and BB are equivalent.

MEAT-BASED MEATBALL - MM

The MM is comprised of equal parts ground beef and ground pork with seasonings (to be comparable to the IM). The bulk processing, seasoning, and forming activities used for the IM1 and IM2 are used for the MM1 and MM2, respectively. Although the IM and the MM processing steps occur in different facilities, it is assumed that the energy consumption and the required inputs are identical. The processes used in processing, seasoning, and forming, as well as cooking are all identical and allocated based on mass of production for the facility (see Table 67).

3.2.2 COOKING AND FINISHING – MM ONLY

The BB is shipped frozen and uncooked.

The frying, baking, freezing, packaging, and transport activities used for the IM1 and IM2 are used for the MM1 and MM2, respectively.

3.2.3 MM – TRANSPORTATION TO DISTRIBUTOR

For BB, MM1 and MM2 going to US retailers, a fixed distance of 1,500 km of frozen truck travel was used to model the distribution to typical US retailers.

It is noted that the in-scope life cycle stages stop at the gate of the distributor; they do not include any activity at the retailer as it is expected to be equivalent between the PBMA and meat-based scenarios.

4 LIFE CYCLE IMPACT ASSESSMENT

4.1 LCIA PROCEDURES AND CALCULATIONS

LCIA was carried out using characterization factors programmed into GaBi®. ReCiPe Midpoint (H) v1.12/World Recipe H (RIVM, 2018) was used to quantify global warming potential (GWP), freshwater eutrophication potential, land occupation, and water consumption.

4.2 LCIA RESULTS

The GaBi® software calculates LCIA results in its balance function and computes the environmental impact results according to pre-defined characterization methods in the selected LCIA methodology.

4.2.1 COMPARATIVE SCENARIOS

The impact category results are provided in Table 10, on a per kg of food delivered to the retailer/food service operator basis, for IB-US, IM1-US and IM2-US, and their respective meat counterparts BB-US, MM1-US and MM2-US.

Table 10 – All scenario indicator category results, per functional unit

Impact categories				
Scenario	**Global warming potential (kg CO_2e)**	**Freshwater eutrophication potential (g P-eq)**	**Land occupation (annual m^2 crop eq)**	**Water consumption (m^3)**
IB - US	2.94	0.91	2.52	0.07
BB - US	31.11	5.95	62.04	0.86
Difference	**-91%**	**-85%**	**-96%**	**-92%**
IM1 - US	3.73	0.98	4.52	0.10
MM1 - US	24.19	5.51	37.06	0.79
Difference	**-85%**	**-82%**	**-88%**	**-87%**
IM2 - US	3.73	0.98	4.52	0.10

MM2 - US	24.19	5.51	37.06	0.79
Difference	**-85%**	**-82%**	**-88%**	**-87%**

The impact category results for the Impossible Foods scenarios studied are lower than those of scenarios of their meat analogs for the four selected impact categories. Note that although the results for IM1-US and IM2-US (and subsequently MM1-US and MM2-US) show as identical in Table 10, this is only because the numbers are rounded to two decimal places. The difference in packaging results in differences that are only seen when going to more decimal places.

IB AND BB

- The GWP result for the IB is 91% lower than that of the BB scenario because of the enteric fermentation and manure management emissions for the BB.
- The freshwater eutrophication potential result for the IB is 85% lower than that of the BB scenarios because of the additional crop inputs and manure application for the BB.
- The land occupation result for the IB is 96% lower than that of the BB scenarios because of the additional crop inputs; the land use result for both IB and BB is primarily due to crop production. The primary contributor for the IB is heme and coconut oil.
- The water consumption result for the IB is 92% lower than that of the BB scenarios primarily because of crops used in feed production.

IM AND MM

- The GWP result for the IM is 85% lower than that of the MM scenarios because of the enteric fermentation and manure management emissions for the BB and PS, as noted prior. The GWP results for the IM1-US and IM2-US scenarios do not differ significantly because the only difference in the life cycle stages is packaging.
- The freshwater eutrophication potential result for the IM is 82% lower than that of the MM scenarios because of the additional crop inputs and manure application for the BB and PS, as noted prior.
- The land occupation result for the IM is 88% lower than that of the MM scenarios because of the additional crop inputs for the BB and PS.
- The water consumption result for the IM is 87% lower than that of the MM scenarios primarily because of crops used in feed production.

4.2.2 CONTRIBUTION ANALYSIS

The stage-specific contribution to the overall potential environmental impact categories for the IB-US and BB-US (Table 11), IM1-US and MM1-US (Table 12), and the IM2-US and MM2-US (Table 13), are presented below.

Table 11 – Contribution of each stage to the IB-US and BB-US scenarios

Life cycle stage	Impact categories							
	Global warming potential (kg CO_2e)		Freshwater eutrophication potential (g P-eq)		Land occupation (annual m^2 crop eq)		Water consumption (m^3)	
	IB – US	BB – US	IB – US	BB – US	IB – US	BB – US	IB – US	BB – US
Base meat production	38%	94%	34%	82%	98%	100%	64%	97%
Processing	47%	5%	60%	17%	1%	0%	34%	3%
Packaging	1%	0%	1%	0%	0%	0%	1%	0%
Distribution	14%	1%	4%	1%	1%	0%	1%	0%

Table 12 – Contribution of each stage to the IM1-US and MM1-US scenarios

Life cycle stage	Impact categories							
	Global warming potential (kg CO_2e)		Freshwater eutrophication potential (g P-eq)		Land occupation (annual m^2 crop eq)		Water consumption (m^3)	
	IM1 – US	MM1 – US	IM1 – US	MM1 – US	IM1 – US	MM1 – US	IM1 – US	MM1 – US
Base meat production	52%	93%	62%	92%	74%	97%	77%	97%
Processing	37%	6%	33%	7%	26%	3%	22%	3%
Packaging	0%	0%	0%	0%	0%	0%	0%	0%
Distribution	11%	2%	4%	1%	0%	0%	1%	0%

Table 13 - Contribution of each stage to the IM2-US and MM2-US scenarios

Life cycle stage	Impact categories							
	Global warming potential (kg CO_2e)		Freshwater eutrophication potential (g P-eq)		Land occupation (annual m^2 crop eq)		Water consumption (m^3)	
	IM2 – US	MM2 – US	IM2 – US	MM2 – US	IM2 – US	MM2 – US	IM2 – US	MM2 – US
Base meat production	52%	93%	62%	92%	74%	97%	77%	97%
Processing	37%	6%	33%	7%	26%	3%	22%	3%
Packaging	0%	0%	0%	0%	0%	0%	0%	0%
Distribution	11%	2%	4%	1%	0%	0%	1%	0%

Raw materials production for the 'base meat' contributes significantly to all selected impact category results for the Impossible and meat-based products, as expected. The processing contribution for the Impossible products is more pronounced than in the meat-based due to a smaller contribution from base meat production to GWP than for the meat-based products. Processing has a significant contribution to the GWP and freshwater eutrophication potential result primarily because of energy demand in this life cycle stage. For land occupation, raw materials production, as expected, contributes close to 100% of the result.

4.2.3 PROCESS CONTRIBUTION ANALYSIS

For the studied impact categories, processes that contributed more than 5% to the overall potential impact of the products are discussed in this section. Only process contributions for the IB-US and IM1-US are provided (the IM2-US, MM2-US do not differ from that of IM1-US and MM1-US). Where no value is given under a specific indicator, the process noted contributed less than 5% to that overall indicator.

Table 14 provides the significantly contributing processes for IB-US.

Table 14 - Significant contributing processes (i.e. those than contribute 5% or more to overall total) for the IB-US

Process	Global warming potential (kg CO_2e)	Freshwater eutrophication potential (g P-eq)	Land occupation (annual m^2 crop eq)	Water consumption (m^3)
Textured soy protein concentrate process	8%	6%	31%	
Sunflower oil process	7%	7%	52%	37%
Carbon dioxide process	23%	19%		5%
Heme	11%	14%		16%
Electricity process	14%	40%		
Tap water process (processing)				20%
Freezer truck distribution process	14%			
Coconut oil			13%	
Ammonia (refrigeration)				5%

For GWP, in addition to soy products, electricity, carbon dioxide, and freezer truck distribution to retailer provide significant contributions. For freshwater eutrophication potential, impacts associated with carbon dioxide and electricity used in processing comprise the majority of the value. For land occupation, sunflower oil and soy products contribute the most significantly to this value. For water consumption, water consumption in processing and the production of heme and sunflower oil contribute the most significantly.

Table 15 provides the significantly contributing processes for IM1-US.

Table 15 - Significant contributing processes (i.e. those than contribute 5% or more to overall total) for the IM1-US

Process	Global warming potential (kg CO_2e)	Freshwater eutrophication potential (g P-eq)	Land occupation (annual m^2 crop eq)	Water consumption (m^3)
Textured soy protein concentrate process	5%		14%	
Sunflower oil process	10%	1%	49%	40%
Carbon dioxide process	7%	7%		5%
Heme	5%	7%		6%
Electricity process	18%	44%		
Natural gas	14%			
Tap water process (processing)				20%
Freezer truck distribution process	11%			
Coconut oil			7%	
Ammonia (refrigeration)				5%
Soybean oil (cooking)	6%		25%	9%
Potato starch				9%

For GWP, in addition to soy products, electricity, carbon dioxide, natural gas, and freezer truck distribution to retailer provide significant contributions. For freshwater eutrophication potential, impacts associated with carbon dioxide and electricity used in processing comprise the majority of the value. For land occupation, sunflower oil and soy products contribute the most significantly to this value. For water consumption, water consumption in processing and the production of heme and sunflower oil contribute the most significantly.

4.3 LCIA RESULTS LIMITATIONS RELATIVE TO DEFINED GOALS

Other impact categories were not quantified in the results of the study because they do not serve to answer the questions defined in the goal and scope of the study for the intended audience stated in Section 1. As such, the application of the results of this study are limited to interpretations based on all potential impact categories included and cannot be generalized or applied to other impact categories.

4.4 DESCRIPTION OF PRACTITIONER VALUE CHOICES

The practitioner value choices have been limited to the selected LCIA. All results are presented on a mid-point basis, using the methods noted in Section 4.1; normalization and weighting are not used. Other impact categories have been excluded from the results because they do not answer the questions defined as the goal and scope for the intended audience in Section 1 of this report.

4.5 STATEMENT OF RELATIVITY

LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks. No grouping of impact categories has been performed; all impacts are presented at the mid-point level. LCIA impacts presented in this report are based on mid-point characterization factors (e.g., kg CO_2 equivalent for GWP), and this study does not refer to the ultimate damage to human health and the environment. For example, GWP may be a negative or a positive environmental impact depending on the conditions in locations where emissions occur. Since this study does not present end-point results, it does not draw any conclusions about the relative impact (positive or negative) for the categories considered by the study.

5 LIFE CYCLE INTERPRETATION

5.1 IDENTIFICATION OF RELEVANT FINDINGS

Based on the results presented in Section 4.2, the IB, IM1 and IM2 have lower selected potential environmental impact results over the BB, MM1 and MM2, respectively, among the four impact categories of concern.

5.2 DATA QUALITY ASSESSMENT

Data quality for each process in the inventory boundary that contributed 5% or more of the potential environmental impact was evaluated and the efforts to improve data quality are reported in the following sections, where necessary. The data was assessed using the data quality indicators described in Table 6 generally first and is discussed in Table 16.

Table 16 – Data quality evaluation

Data Quality Requirement	Explanation
Technology coverage	For the Impossible Foods ingredients and other products, proxies were used for some additives and flavourings, but these ingredients have relatively minor contributions (and do not meet the indicated cut-off criteria) to the overall mass of the product. Processing inputs, such as electricity and natural gas and all beef, pork, and meatball processes, are consistent with the technologies they are meant to represent. For secondary data, where used, changes over time are captured through updates to the Ecoinvent databases. Therefore, technology coverage is considered good to very good for all scenarios examined in this study.
Temporal coverage	Activity factors for Impossible Foods reflect data from 2020 and 2021. Estimates for all utility and other data was from utility bills for direct operations and allocated according to Impossible Foods production data. Secondary data, including impact factors for electricity, natural gas combustion, and carbon dioxide use cover the time period 2010-2021. Generally, activity data quality for IB, IM1 and IM2 are considered very good whereas for impact data quality can be considered fair to good. Activity data for the BB, PS, MM1 and MM2, including on farm activities and livestock performance data represents US modelled or actual data from between 2010 and 2020; modelled data were based on actual farm data from 2017 time and would be considered fair. Emissions for enteric fermentation and manure management for beef production are from the IPCC (2006) Tier 2 and WFLDB v3.1 guidelines (as per Qantis (2019)) and pig production are from GLEAM (FAO, 2017) based on 2017 farming activity. Both are considered fair to very good.

Data Quality Requirement	Explanation
Geographical coverage	The ingredients for IB, IM1 and IM2 are generally sourced from the US and where not, geographically relevant impact factors were used to the extent possible. Where this was not possible, this is recognized. Impossible Foods manufacturing data comes from manufacturing data in the US and the impact factors for electricity, natural gas, etc. are all US-based. Geographical coverage for the IB, IM1 and IM2 are considered good to very good. The performance data used in the modelling of the meat systems, BB, PS, and MM1 and MM2 for both the US are meant to be representative of the respective domestic production, and the impact factors for electricity, natural gas, etc. have been selected such that they are all US-based for US production. Geographical coverage for the BB, PS, and MM are considered fair to good.
Completeness	Data for the IB, IM1 and IM2, including ingredients and manufacturing processes is considered complete within the cut-off criteria and data quality is very good. Data for the BB, PS, MM1 and MM2 are based on typical emissions sources for beef, pork, and meatball processes and was obtained from previous studies that obtained data directly form the farms and productions facilities being studied. Data quality for completeness could be considered fair to good for the BB, PS, and MM.
Reliability	Because primary data for modeling the Impossible products are based on primary data from Impossible Foods, the data quality for reliability is considered to be very good. Variability in primary activity data has not been assessed. All background data is from Ecoinvent and is well documented for its reliability. With respect to the BB, PS, and MM, as noted above, on-farm data and performance is based on farm-specific data and is considered to be reliable. However, the manure management and application emission factors from the IPCC (2006) or GLEAM (FAO, 2017) are a combination of best estimates and non-verified data. Data quality for BB, PS, and MM for reliability is considered fair to good.

5.2.1 DATA QUALITY ASSESSMENT – IB-US AND BB-US

The IB-US and BB-US scenario data quality are discussed specifically here, aligning with the process contribution analysis shown in Section 4.2.3.

IB-US

The processes contributing significantly (greater than 5%) to the IB-US potential environmental impact categories (namely, in this case, four impact categories: GWP, freshwater eutrophication potential, land occupation, and water consumption) were provided in Table 14. Data quality for these processes is more directly discussed in Table 17.

Table 17 - Data quality commentary for the IB-US significant processes

Significant process and relevant stage	Data sources	Data quality commentary	Efforts made to improve data quality
Textured soy protein concentrate process	**Activity data:** Data provided by Impossible Foods. **Environmental impact data:** Data from Ecoinvent v3.6 database (Wernet, et al., 2016).	Soybean yield updated to US yields and as per USDA (2020). See Impossible Foods (2020) for more information. Data quality considered good to very good.	US yields and fertilizer use as per USDA (2020). See Impossible Foods (2020) for more information.
Sunflower oil process	**Activity data:** Data provided by Impossible Foods. **Environmental impact data:** Data from Ecoinvent v3.6 database (Wernet, et al., 2016) and Agifootprint database (v1.0) (Blonk Agri-footprint BV, 2014).	Sunflower seed yield updated to US yields as per USDA (2020). See Impossible Foods (2020) for more information. Data quality considered good to very good.	US yields and fertilizer use as per USDA (2020). See Impossible Foods (2020) for more information.
Carbon dioxide process	**Activity data:** Data provided by Impossible Foods. **Environmental impact data:** Data from Ecoinvent v3.6 database (Wernet, et al., 2016).	Data quality considered good to very good.	None required.
Heme	**Activity data:** Data provided by Impossible Foods. **Environmental impact data:** Data from Ecoinvent v3.6 database (Wernet, et al., 2016) and Agifootprint database (v1.0) (Blonk Agri-footprint BV, 2014).	Heme ingredient yields updated to US yields as per USDA (2020). See Impossible Foods (2020) for more information. Data quality considered good to very good.	US yields and fertilizer use as per USDA (2020). See Impossible Foods (2020) for more information.
Electricity process	**Activity data**: Amount of electricity used quantified from Impossible Food manufacturers. Data for share of electricity generation overall embedded in electricity processes specific to the region as discussed prior in this work. **Environmental impact data**: Data from Ecoinvent v3.6 database (Wernet, et al., 2016).	The specific contributions for each generation source are from data from 2014, but these factors were not expected to change significantly over time. Data quality considered good.	Proportion of electricity generation sources in the grid was updated as per See Impossible Foods (2020) for electricity grid factors.

Tap water process (processing)	**Activity data:** Data provided by Impossible Foods. **Environmental impact data:** Data from Ecoinvent v3.6 database (Wernet, et al., 2016).	Tap water for US generally used. Data quality considered good.	None required.
Freezer truck distribution process	**Activity data:** Data provided by Impossible Foods. **Environmental impact data:** Data from Ecoinvent v3.6 database (Wernet, et al., 2016) but updated for freezer transportation as per Table 34.	Updated for freezer transportation as per Table 34. Data quality considered good.	Updated for freezer transportation as per Table 34. Data quality considered good.
Coconut oil process	**Activity data:** Data provided by Impossible Foods. **Environmental impact data:** Data from Ecoinvent v3.6 database (Wernet, et al., 2016) and Agifootprint database (v1.0) (Blonk Agri-footprint BV, 2014)	Coconut yield updated to 2015-2018 averaged data. Data for contributions is from 1995. See Appendix C for more information.	Coconut yield updated to 2015-2018 averaged data. See Impossible Foods (2020) for more information.
Ammonia process	**Activity data:** Data provided by Impossible Foods. **Environmental impact data:** Data from Ecoinvent v3.6 database (Wernet, et al., 2016).	Data quality considered good to very good.	None required.

The evaluation of each data quality criterion for significant processes in the IB-US scenarios, based on preceding comments, is provided in Table 18.

Table 18 – Evaluation of data quality criteria for the IB-US scenarios

Process	Data	Tech.	Time	Geo.	Comp.	Rel.
Textured soy protein concentrate process	Activity data	1	1	1	1	1
	Environmental impact data	1	2	3	2	2
Sunflower oil process	Activity data	1	1	1	1	1
	Environmental impact data	1	2	1	2	2
Carbon dioxide process	Activity data	1	1	1	1	1
	Environmental impact data	1	2	2	2	2
Heme	Activity data	1	1	1	1	1

	Environmental impact data	1	2	2	2	2
Electricity process	Activity data	1	1	1	1	1
	Environmental impact data	1	3	1	2	2
Tap water process	Activity data	1	1	1	1	1
	Environmental impact data	1	3	1	2	2
Freezer truck distribution process	Activity data	1	1	1	1	1
	Environmental impact data	1	3	1	2	2
Coconut oil process	Activity data	1	1	1	1	1
	Environmental impact data	1	4	1	2	2
Ammonia process	Activity data	1	1	1	1	1
	Environmental impact data	1	2	2	2	2

In general, data quality for all data used in the IB-US scenario is rated between fair and very good, with the majority of the processes rated good and very good and only four out of the 80 indicators in Table 18 rated below good. Activity data is considered fair to very good because of data provided by the manufacturer, with the fair data quality related to assumptions that are made with respect to travel distances. The quality of the environmental impact data was rated from fair to very good, depending on the criteria.

BB-US

The data quality for the ground beef part of the BB-US model is discussed in Qantis (2019) and has been subject to sensitivity analyses and critical review. The processing, cooking, packaging and downstream transportation stages subsequent to ground beef production are not significant contributors to the overall total of the potential impact indicators and thus are not discussed here.

IM1-US/IM2-US

The processes contributing significantly (greater than 5%) to the IM1/IM2-US potential environmental impact categories (namely, in this case, four impact categories: GWP, freshwater eutrophication potential, land occupation, and water consumption) were provided in Table 14. Data quality for these processes is more directly discussed in Table 19.

Table 19 - Data quality commentary for the IM1/IM2-US significant processes

Significant process and relevant stage	Data sources	Data quality commentary	Efforts made to improve data quality

Textured soy protein concentrate process	**Activity data:** Data provided by Impossible Foods. **Environmental impact data:** Data from Ecoinvent v3.6 database (Wernet, et al., 2016).	Soybean yield updated to US yields and as per USDA (2020). See Impossible Foods (2020) for more information. Data quality considered good to very good.	US yields and fertilizer use as per USDA (2020). See Impossible Foods (2020) for more information.
Sunflower oil process	**Activity data:** Data provided by Impossible Foods. **Environmental impact data:** Data from Ecoinvent v3.6 database (Wernet, et al., 2016) and Agifootprint database (v1.0) (Blonk Agri-footprint BV, 2014).	Sunflower seed yield updated to US yields as per USDA (2020). See Impossible Foods (2020) for more information. Data quality considered good to very good.	US yields and fertilizer use as per USDA (2020). See Impossible Foods (2020) for more information.
Carbon dioxide process	**Activity data:** Data provided by Impossible Foods. **Environmental impact data:** Data from Ecoinvent v3.6 database (Wernet, et al., 2016).	Data quality considered good to very good.	None required.
Heme	**Activity data:** Data provided by Impossible Foods. **Environmental impact data:** Data from Ecoinvent v3.6 database (Wernet, et al., 2016) and Agifootprint database (v1.0) (Blonk Agri-footprint BV, 2014).	Heme ingredient yields updated to US yields as per USDA (2020). See Impossible Foods (2020) for more information. Data quality considered good to very good.	US yields and fertilizer use as per USDA (2020). See Impossible Foods (2020) for more information.
Electricity process	**Activity data**: Amount of electricity used quantified from Impossible Food manufacturers. Data for share of electricity generation overall embedded in electricity processes specific to the region as discussed prior in this work. **Environmental impact data**: Data from Ecoinvent v3.6 database (Wernet, et al., 2016).	The specific contributions for each generation source are from data from 2014, but these factors were not expected to change significantly over time. Data quality considered good.	Proportion of electricity generation sources in the grid was updated as per See Impossible Foods (2020) for electricity grid factors.
Natural gas	**Activity data:** Data provided by Impossible Foods. **Environmental impact data:** Data from Ecoinvent v3.6 database (Wernet, et al., 2016).	Tap water for US generally used. Data quality considered good.	None required.
Tap water process (processing)	**Activity data:** Data provided by Impossible Foods. **Environmental impact data:** Data from Ecoinvent v3.6 database (Wernet, et al., 2016) but updated for freezer transportation as per Table 34.	Updated for freezer transportation as per Table 34. Data quality considered good.	Updated for freezer transportation as per Table 34. Data quality considered good.

Freezer truck distribution process	**Activity data:** Data provided by Impossible Foods. **Environmental impact data:** Data from Ecoinvent v3.6 database (Wernet, et al., 2016) and Agifootprint database (v1.0) (Blonk Agri-footprint BV, 2014)	Coconut yield updated to 2015-2018 averaged data. Data for contributions is from 1995. See Appendix C for more information.	Coconut yield updated to 2015-2018 averaged data. See Impossible Foods (2020) for more information.
Coconut oil	**Activity data:** Data provided by Impossible Foods. **Environmental impact data:** Data from Ecoinvent v3.6 database (Wernet, et al., 2016).	Data quality considered good to very good.	None required.
Ammonia (refrigeration)	**Activity data:** Data provided by Impossible Foods. **Environmental impact data:** Data from Ecoinvent v3.6 database (Wernet, et al., 2016) and Agifootprint database (v1.0) (Blonk Agri-footprint BV, 2014).	Heme ingredient yields updated to US yields as per USDA (2020). See Impossible Foods (2020) for more information. Data quality considered good to very good.	US yields and fertilizer use as per USDA (2020). See Impossible Foods (2020) for more information.
Soybean oil (cooking)	**Activity data:** Data provided by Impossible Foods. **Environmental impact data:** Data from Ecoinvent v3.6 database (Wernet, et al., 2016).	Soybean yield updated to US yields and as per USDA (2020). See Impossible Foods (2020) for more information. Data quality considered good to very good.	US yields and fertilizer use as per USDA (2020). See Impossible Foods (2020) for more information.
Potato starch	**Activity data:** Data provided by Impossible Foods. **Environmental impact data:** Data from Ecoinvent v3.6 database (Wernet, et al., 2016).	Potato yield updated to US yields and as per USDA (2020). Data quality considered good to very good.	US yields and fertilizer use as per USDA (2020).

The evaluation of each data quality criterion for significant processes in the IM1/IM2-US scenarios, based on preceding comments, is provided in Table 20.

Table 20 – Evaluation of data quality criteria for the IM1/IM2-US scenarios

Process	Data	Tech.	Time	Geo.	Comp.	Rel.
Textured soy protein concentrate process	Activity data	1	1	1	1	1
	Environmental impact data	1	2	3	2	2
Sunflower oil process	Activity data	1	1	1	1	1
	Environmental impact data	1	2	1	2	2
Carbon dioxide process	Activity data	1	1	1	1	1

	Environmental impact data	1	2	2	2	2
Heme	Activity data	1	1	1	1	1
	Environmental impact data	1	2	2	2	2
Electricity process	Activity data	1	1	1	1	1
	Environmental impact data	1	3	1	2	2
Tap water process	Activity data	1	1	1	1	1
	Environmental impact data	1	3	1	2	2
Freezer truck distribution process	Activity data	1	1	1	1	1
	Environmental impact data	1	3	1	2	2
Coconut oil process	Activity data	1	1	1	1	1
	Environmental impact data	1	4	1	2	2
Ammonia (refrigeration)	Activity data	1	1	1	1	1
	Environmental impact data	1	2	2	2	2
Soybean oil (cooking)	Activity data	1	1	1	1	1
	Environmental impact data	1	2	3	2	2
Potato starch	*Activity data*	1	1	1	1	1
	Environmental impact data	1	3	2	2	2

In general, data quality for all data used in the IM1/IM2-US scenarios is rated between fair and very good, with the majority of the processes rated good and very good and only six out of the 80 indicators in Table 20 rated below good. Activity data is considered fair to very good because of data provided by the manufacturer, with the fair data quality related to assumptions that are made with respect to travel distances. The quality of the environmental impact data was rated from fair to very good, depending on the criteria.

MM1/MM2-US

The data quality for the MM1/MM2-US models is not evaluated because the contributing processes have been discussed in Qantis (2019) and Impossible Foods (2020) and has been subject to sensitivity analyses and critical review. It is noted that with the primary contributing process, such as enteric fermentation (and manure management processes), there were different quantification approaches used. In Qantis (2019), IPCC (2006) was used to quantify those emissions, whereas in Impossible Foods (2020), GLEAM was used to model those emissions. There have been no studies to date comparing these two approaches but it is recognized that each model has its own limitations and using the same model for both may not reduce these limitations. The processing, cooking, packaging and downstream transportation stages subsequent to ground beef and pork production are not significant contributors to the overall total of the potential impact indicators and thus are not discussed here.

5.3 SENSITIVITY ANALYSIS

Inventory uncertainty is assessed on a qualitative and quantitative basis. Three types of uncertainty are addressed: parameter uncertainty, scenario uncertainty and model uncertainty (Table 21) with sensitivity analyses. These are discussed in the next sections.

Table 21 – Uncertainty types

Uncertainty types	Sources	Description
Parameter uncertainty	■ Activity data ■ LCIA impact category characterization factors	Uncertainty on the accuracy of values used in the inventory. Parameter uncertainty can be assessed through the evaluation of data quality indicators.
Scenario uncertainty	■ Methodological choices	Uncertainty related to assumptions or methods used for allocation or to model product use or product end-of-life. Scenario uncertainty is assessed via sensitivity analysis.
Model uncertainty	■ Model limitations	Uncertainty associated with the use of simplified models to represent real life phenomena. Model uncertainty can partly be evaluated with data quality indicators or sensitivity analysis. However, some aspects are very difficult to quantify.

5.3.1 PARAMETER SENSITIVITY

Parameter sensitivity for direct emissions data, activity data and impact factor data were discussed in the previous section. In general, data quality for Impossible Foods product processes was very good or good for main contributing processes, both for activity data and impact factors. Qantis (2019) and Impossible Foods (2020) provide more details on data quality assessments for these meat-based processes.

It is recognized that the MM recipes are a combination of ground beef and pork and this combination has yet to be evaluated for data quality. However, it is recognized that the sensitivity analyses previously done in Qantis (2019) and Impossible Foods (2020) showed no change in the conclusions that the Impossible products had significantly lower select potential environmental impacts than their meat analogs. It is reasonable to expect that an equal mix of the meat-based products would perform the same under different sensitivity analyses.

5.3.2 SCENARIO SENSITIVITY

Due to the nature of the product and the inventory boundary, typical sources of scenario uncertainty (e.g., use profile, end-of-life profile) are not assessed through sensitivity analysis, as no assumptions were made regarding those aspects. For meat-based products, often the choice of functional unit or the allocation scenarios may have an impact on the conclusions of the LCA study. However, the use of economic allocation to assign the contribution to the impact categories of the livestock slaughterhouse activities has been shown in the Qantis (2019) and Impossible Foods (2020) to not have a significant impact on the conclusions, thus it is not expected to have a significant expect on the conclusions here where those products are combined in an equal manner. Thus, below, only sensitivity to the nutritional functional units is examined.

Nutritional functional units

As is noted above, the choice of functional unit is based on mass of food, which aligns with previous studies for PBMAs and their meat-based equivalents. However, as some people eat food for other means, such as for caloric or protein intake, other functional units may be useful to understand sensitivity to these desires.

This analysis leverages the caloric and protein data provided in Table 2 containing the nutritional information for IB, BB, IS, PS, IM and MM. Table 22 shows the impact category results for all scenarios using a functional unit of 100 calories.

Table 22 – Impact category results per 100 calories of food

	Impact categories			
Scenario	**Global warming potential (kg CO_2e)**	**Freshwater eutrophication potential (g P-eq)**	**Land occupation (annual m^2 crop eq)**	**Water consumption (m^3)**
IB - US	0.15	0.05	0.13	0.003
BB - US	1.22	0.23	2.44	0.03
Difference	**-88%**	**-81%**	**-95%**	**-90%**
IM1 - US	0.23	0.06	0.27	0.01
MM1 - US	0.97	0.22	1.48	0.03
Difference	**-77%**	**-73%**	**-82%**	**-80%**
IM2 - US	0.23	0.06	0.27	0.01
MM2 - US	0.97	0.22	1.48	0.03
Difference	**-77%**	**-73%**	**-82%**	**-80%**

There are no significant changes in the differences between the Impossible products and the meat-based products primarily because the nutritional information is relatively similar. Regardless, the results show that when caloric content is used as the functional unit, there is no difference to the conclusion that modeled impact categories are lower for the Impossible scenarios than for the meat-based scenarios.

Table 23 shows the impact category results for all scenarios using a functional unit of 10g of protein.

Table 23 – Impact category results per 10 g of protein in food

	Impact categories	
Scenario	**Global warming potential**	**Land occupation**

	(kg CO_2e)	Freshwater eutrophication potential (g P-eq)	(annual m^2 crop eq)	Water consumption (m^3)
IB - US	0.18	0.05	0.15	0.00
BB - US	1.81	0.35	3.61	0.05
Difference	**-90%**	**-84%**	**-96%**	**-92%**
IM1 - US	0.27	0.07	0.32	0.01
MM1 - US	1.55	0.35	2.38	0.05
Difference	**-83%**	**-80%**	**-86%**	**-85%**
IM2 - US	0.27	0.07	0.32	0.01
MM2 - US	1.55	0.35	2.38	0.05
Difference	**-83%**	**-80%**	**-86%**	**-85%**

Similar to prior findings, there are no significant changes in the differences between the Impossible products and the meat-based products primarily because the nutritional information is relatively similar. Regardless, the results show that when protein content is used as the functional unit, there is no difference to the conclusion that modeled impact categories are lower for the Impossible scenarios than for the meat-based scenarios.

5.3.3 MODEL SENSITIVITY

ReCiPe Midpoint (H) v1.12 was used to quantify the impact categories considered in this study. To examine the differences in impact category results using a different LCIA method, the IM1-US and MM1-US scenarios were run using the CML 2.0 method for the global warming indicator (the 100-year time horizon GWPs without carbon feedback from AR5 are utilized (IPCC, 2014)), IMPACT 2002+ for aquatic eutrophication potential and land use. No other relevant water consumption indicator was compared. The results for the three impact categories for the IM1-US and MM1-US run using CML 2.0 and IMPACT 2002+ are shown in Table 24. Only the IM1-US and MM1-US scenarios were tested because they were assumed to be the most demonstrative of sensitivity to model changes.

Table 24 – Relevant impact category results with different models used

Scenario	Global warming potential (kg CO_2e) – CML 2.0	Aquatic eutrophication potential (g $PO4^{3-}$eq P-lim) – IMPACT 2002+	Land occupation ($m^2 \cdot a$) – IMPACT 2002+
IM1-US	3.81	3.10	4.44
MM1-US	25.10	17.14	37.43

Difference	-85%	-82%	-88%

There are no differences in the conclusions between the impact categories new methods and ReCiPe Midpoint method, indicating that these conclusions are not sensitive to the specific LCIA methods investigated in this work. It is noted that the results are not directly comparable to the baseline results and thus only the individual impact category conclusions are relevant; these do not change. It is noted that no additional water consumption indicator was tested because a relevant indicator in other methods was not found.

5.4 ASSUMPTIONS AND LIMITATIONS

The evidence presented in this report and Impossible Foods (2020) is unique to the assumptions and practices of Impossible Foods and involves assumptions that are used by their production team to collect and record data. The reference scenarios have been specifically developed to be comparable to Impossible Foods production models as much as possible. The results are not intended to be a platform for comparability to other companies and/or other products. Even for similar products, differences in unit of analysis, life cycle stage profiles and data quality may produce incomparable results.

The LCA performed for Impossible Foods compares the life cycle of various Impossible Foods products produced in the US against meat-based products produced in the US. Any conclusion described by this report must be considered only within the context of the study, with considerations of the data, assumptions and limitations used to arrive at those conclusions.

The limitations in this current study should be highlighted to ensure there are mitigating actions made for future studies of Impossible Foods products against their meat-based equivalents:

- The inherent limitations with the meat-based models that are described in the original reports: Qantis (2019) for beef and Impossible Foods (2020) for pork.
- Mass was used as a functional unit in this study although there are other functional units, such as calories or protein content, that could also be relevant; a sensitivity analysis was conducted using calories and protein content as the functional unit and the conclusions of the study did not change.
- Only four impact categories were considered here because they were of most interest to Impossible Foods and they were typical indicators for food-based and plant-based meat alternative LCAs; it is recognized that there are other impact categories available to evaluate the overall environmental performance of the studied products.
- Different LCIA methods were used to calculate the impact category results because they were not all available in a single method; a sensitivity analysis was conducted using the same method for all impact categories and the conclusions did not differ.

Finally, LCA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks.

5.5 CONCLUSIONS AND RECOMMENDATIONS

This LCA compares various Impossible Foods products, PBMAs produced in the US, with their meat-based equivalents produced in their domestic markets. These products are considered to have functional equivalency because of their ability to satiate hunger, but also to provide similar quantities of nutrients.

The goal of this LCA is to compare the environmental profile made up of four impact categories, namely global warming, freshwater eutrophication potential, land occupation, and water consumption, associated with Impossible Foods scenarios and their functionally equivalent meat-based scenarios and understand the extent to which the results for those particular impact categories for the Impossible scenarios are lower than for the meat-based scenarios.

The key findings are presented in this work, but generally, all Impossible scenarios had lower results in the four potential environmental impact categories than the meat-based scenarios.

It should again be noted that the nutritional content, an important feature of food and objective behind the consumption of food, has been considered and the directionality of the results do not change. The intention here is to portray an environmental comparison for the four impact categories of concern as accurately and clearly as possible, which can be used along with nutritional considerations, and other considerations such as taste, cost, and convenience, in helping consumers make food choices.

In summary, the study has found that there are benefits, under the four potential impact categories of concern discussed in this study, to using the Impossible Foods scenarios studied in this work instead of a meat-based equivalent.

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6 APPENDIX A – IB AND BB PROCESSES

Table 25 – IB bulk meat - REDACTED

Table 26 – IB and BB Processing – REDACTED

Table 27 – IB and BB - Packaging

Ingredient/Input	GaBi input	Amount	Units	Comments
Packaging	Packaging for 1 kg of IB and BB	1	pc	
Ingredient/Input	**GaBi input**	**Amount**	**Units**	**Comments**
Plastic film	Packaging film, low density polyethylene, market for {GLO} – U-so	0.0023	kg	
Paper Film	Market for kraft paper, bleached {GLO} - Agg	0.0016	kg	
Cardboard box	Corrugated board box, market for {GLO} – U-so	0.01	kg	

7 APPENDIX B – IM AND MM PROCESSES

Table 28 – IM bulk meat - REDACTED

Table 29 – MM bulk meat - REDACTED

Table 30 – IM and MM – REDACTED

Table 31 – IM1 and MM1 - Packaging

Ingredient/Input	GaBi input	Amount	Units	Comments
Packaging	Packaging for 1 kg of IM1 and MM1	1	pc	
Ingredient/Input	**GaBi input**	**Amount**	**Units**	**Comments**
Plastic film	Packaging film, low density polyethylene, market for {GLO} – U-so	0.0004	kg	
Cardboard box	Corrugated board box, market for {GLO} – U-so	0.0031	kg	

Table 32 – IM2 and MM2 - Packaging

Ingredient/Input	GaBi input	Amount	Units	Comments
Packaging	Packaging for 1 kg of IM2 and MM2	1	pc	
Ingredient/Input	**GaBi input**	**Amount**	**Units**	**Comments**
Plastic film	Packaging film, low density polyethylene, market for {GLO} – U-so	0.000908	kg	
Cardboard box	Corrugated board box, market for {GLO} – U-so	0.00454	kg	

8 APPENDIX C – ANCILLARY PROCESSES

Table 33 - Soybean protein concentrate; modified process (Impossible Foods, 2020)

Output	GaBi input	Amount	Units	Comments
Soybean protein concentrate	Soybean protein concentrate {US}	540	kg	Allocation = 63.68%
Co-product	Soybean hulls, from crushing (solvent, for protein concentrate), at plant/AR Economic	74	kg	Allocation = 0.98%
Co-product	Soybean molasses, from crushing (solvent, for protein concentrate), at plant/AR Economic	290	kg	Allocation = 28.64%
Co-product	Crude soybean oil, from crushing (solvent, for protein concentrate), at plant/AR Economic	180	kg	Allocation = 6.7%
Emissions to air	Hexane	0.8	kg	
Wastewater	Wastewater, unpolluted, market for {GLO} – U-so	164	m^3	
Ingredient/input	**GaBi input**	**Amount**	**Units**	**Comments**
Ethanol for cleaning	Ethanol, without water, in 99.7% solution state, from fermentation, market for {GLO} – U-so	128	kg	
Diesel for heat	Diesel, burned in building machine, market for {GLO} – U-so	410	MJ	
Hexane for refining	Hexane, market for {GLO} – U-so	0.8	kg	
Soybean input	Soybean production {US} – agg	1	ton	
Electricity	Electricity, medium voltage, market for {ConEd} – U-so	1,080	MJ	
Steam	Steam, in chemical industry, market for {GLO} – U-so	720	kg	

Table 34 – Crude sunflower oil; modified process (Impossible Foods, 2020)

Output	GaBi input	Amount	Units	Comments
Crude sunflower oil	Crude sunflower oil, from crushing (solvent), at plant/AR Economic – Agri-footprint process modified	289	kg	To be used in refined sunflower oil (see Impossible Foods (2020)); allocation=80%
Byproduct	Sunflower seed meal, from crushing (solvent), at plant/AR Economic – Agri-footprint process modified	350	kg	Allocation=20%
Ingredient/input	**GaBi input**	**Amount**	**Units**	**Comments**
Hexane	Hexane, market for {GLO} – U-so	1	kg	
Sunflower seed production	Sunflower seed {ROW} – U-so	1	ton	
Transport from sunflower seed to sunflower oil processor	Transport, freight, lorry 16-32 metric ton, EURO3, market for {GLO} – U-so	0.2	t·km	Transport from sunflower seed to sunflower oil processor
Water	Tap water production, conventional treatment {US} - agg	0.248	ton	
Electricity	Electricity, medium voltage, market for {Comed} – U-so	27	MJ	
Steam	Steam, in chemical industry, market for {GLO} – U-so	500	kg	

Table 35 – Refined sunflower oil; modified process (Impossible Foods, 2020)

Output	GaBi input	Amount	Units	Comments
Refined sunflower oil	Refined sunflower oil, from crushing (solvent) – Agri-footprint process modified	1,000	kg	Allocation = 98.75%
Byproduct	Soap stock (sunflower solvent crushing) – Agri-footprint process modified	37.95	kg	Allocation = 1.25%
Ingredient/input	**GaBi input**	**Amount**	**Units**	**Comments**
Crude sunflower oil	Crude sunflower oil, from crushing (solvent), at plant/AR Economic – Agri-footprint process modified	1,046.84	kg	See Impossible Foods (2020)
Activated charcoal for removal of impurities	Activated bentonite, market for {GLO} – U-so	8.08	kg	
Diesel for refining	Diesel, burned in building machine {GLO}| market for | Alloc Def, U	342.45	MJ	
Electricity	Electricity, medium voltage, market for {Comed} – U-so	54.8	kWh	
Steam	Steam, in chemical industry, market for {GLO} – U-so	731.5	kg	

Table 36 – Freezer truck transportation (Impossible Foods, 2020)

Output	GaBi input	Amount	Units	Comments
Freezer transport	Freezer transport	1	t·km	
Removed additional emissions from these because only energy increases 27%	Road wear emissions, lorry, market for {GLO} – U-so	-3.52E-6	kg	Removed additional emissions from these because only energy increases 27%
	Brake wear emissions, lorry, market for {GLO} – U-so	-3.03E-6	kg	
	Tyre wear emissions, lorry, market for {GLO} – U-so	-3.49E-5	kg	
Ingredient/input	**GaBi input**	**Amount**	**Units**	**Comments**
R-134a	Refrigerant R134a, market for {GLO} – U-so	2.22E-6	kg	Based on 5 kg charge and 10% leakage per year calculated on a per km basis
Transportation from processing facility to retailer	Transport, freight, lorry 7.5-16 metric ton, EURO3, market for {GLO} – U-so	1.27	tkm	Freezer transport requires 27% more energy than non-refrigerated, as per Tassou et al. (2009)
Emissions to air	**GaBi input**	**Amount**	**Units**	**Comments**
R-134a	Ethane, 1, 1, 1-2-tetrafluoro-, HFC-134a	2.22E-6	kg	Amount adjusted to reflect 100 year GWPs.

Table 37 – Freezer freighter transportation (Impossible Foods, 2020)

Output	GaBi input	Amount	Units	Comments
Freezer transport	Freezer transport	1	tkm	
Ingredient/input	**GaBi input**	**Amount**	**Units**	**Comments**

R-134a	Refrigerant R134a, market for {GLO} – U-so	2.22E-6	kg	Based on 5 kg charge and 10% leakage per year, calculated on a per km basis
Transportation from processing facility to retailer	Transport, freight, sea, transoceanic ship, market for {GLO} – U-so	1.27	t·km	Freezer transport requires 27% more energy than non-refrigerated, as per Tassou et al. (2009)
Emissions to air	**GaBi input**	**Amount**	**Units**	**Comments**
R-134a	Ethane, 1, 1, 1-2-tetrafluoro-, HFC-134a	2.22E-6	kg	Amount adjusted to reflect 100 year GWPs.

Table 38 – Coconut oil, including transport

Output	GaBi input	Amount	Units	Comments
Coconut oil	Coconut oil	1	kg	
Ingredient/input	GaBi input	Amount	Units	Comments
Coconut oil	Coconut oil, crude {PH}| production | Alloc Def, U - Mod	1	kg	
Transportation of coconut oil from the Philippines to the US	Transport, freight, sea, transoceanic tanker {GLO}| market for | Alloc Def, U	23.1963	t·km	Distance from Los Angeles to Manila
Transportation of coconut oil from the Philippines to the US	Transport, freight, lorry 7.5-16 metric ton, EURO3 {GLO}| market for | Alloc Def, U	0.2	t·km	200 km truck distance within the Philippines