Report 2023

Beyond Burger® 3.0 Life Cycle Assessment

Commissioned by Beyond Meat®

Blonk CONSULTANTS

www.blonksustainability.nl

About us

Blonk, a Mérieux NutriSciences Company is a leading international expert in food system sustainability, inspiring and enabling the agri-food sector to give shape to sustainability. Blonk's purpose is to create a sustainable and healthy planet for current and future generations. We support organizations in understanding their environmental impact in the agri-food value chain by offering advice and developing tailored software tools based on the latest scientific developments and data.

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Authors	Marty Heller	Blonk Consultants
	Iana Salim	Blonk Consultants

Summary

This cradle-to-distribution life cycle assessment (LCA) study of latest Beyond Burger® (version 3.0) from Beyond Meat® utilizes North American production data from the first half of 2022 to estimate the environmental impact of a ¼ lb. Beyond Burger in the retail format packaging of two patties in a sealed PET tray. Primary data were provided by Beyond Meat on product formulation, packaging materials and weights, processing utility demands, processing locations, intermediary transport distances and cold storage, and final product cold storage and distribution distances. Secondary (background) data were used for ingredient and packaging material production, electricity generation, municipal water supply, and transportation impacts. LCA modeling follows ISO 14040 / 14044 recommendations, and the study has been critically reviewed by a panel of three independent, external reviewers, as recommended for comparative LCA studies that are to be externally communicated business to business or business to consumer.

Table S1 provides the environmental impact results for one ¼ lb. patty of Beyond Burger, alongside the impacts of a ¼ lb. patty of US-produced beef, based on the recent industry benchmarking LCA on US beef production (Putman, Rotz, and Thoma 2023). In both cases, the ReCiPe 2016 hierarchical impact assessment method was used. The four indicators presented were chosen as the most relevant (based on previous experience) in comparisons between plant- and animal-based protein sources.

TABLE S1. SUMMARY OF ENVIRONMENTAL IMPACT INTENSITIES PER ¼ LB. BEYOND BURGER PATTY RELATIVE TO A 80/20 ¼ LB. BEEF PATTY.

indicator	Unit (per ¼ lb)	Beyond Burger 3.0	Beef Patty	% reduction (Beef Patty →Beyond Burger 3.0)
global warming	kg CO_2 eq	0.43	4.26	90%
fossil resource scarcity	kg oil eq	0.12	0.19	37%
land use	m^2a crop eq	0.53	17.52	97%
water consumption	liters	6.45	219.24	97%

Based on a comparative assessment of the Beyond Burger 3.0 production system in 2022 with the 2023 beef LCA by Putman et al, the Beyond Burger 3.0 generates 90% less global warming impact (aka, greenhouse gas (GHG) emissions), and requires 37% less fossil resources, 97% less land use, and 97% less water consumption, as shown in Table S1.

Production of ingredients for the Beyond Burger 3.0 represents 35% of global warming (greenhouse gas emission) impacts, 28% of energy use, 81% of land use, and 70% of water use. Refrigerated transport – intermediary and final distribution stages combined – is also a notable contributor to global warming and energy use, at 40% and 42%, respectively.

A limited uncertainty assessment shows coefficient of variation of less than 5% across all four reported impact categories. Sensitivity assessment around key parameters that were either based on limited data or could be expected to change through fairly routine business operation adjustments, such as the energy used in cold storage warehousing, time in storage, and distance to storage, demonstrated minimal influence on the final results. Chosen proxy assignments for natural flavor components that represent less than 2% of the Beyond Burger 3.0 recipe, however, do demonstrate a notable influence on final results. These uncertainties, however, do not affect the conclusion that the Beyond Burger 3.0 has significantly better environmental performance than a US industry-average produced beef patty.

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List of acronyms & abbreviations

AFP – Agri-footprint (LCI database)

APOS – Allocation at Point of Substitution

Original Beyond Burger 1.0 = first generation Beyond Burger

Beyond Burger 3.0 = third generation Beyond Burger

COMO – Beyond Meat facility in Columbia, Missouri

EC – European Commission

FAO – Food & Agriculture Organization of the United Nations

ISO – International Organization for Standardization

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

LEAP – Livestock Environmental Assessment and Performance Partnership

LUC – land use change

PE – polyethylene. LDPE = low density polyethylene; LLDPE = linear low density polyethylene

PEF – Product Environmental Footprint

PET – polyethylene terephthalate

PPI – pea protein isolate

USDA – United States Department of Agriculture

WIP – work in progress

1 Introduction

Beyond Meat® is a US-based company producing plant-based meat substitutes. The Original Beyond Burger® 1.0, initially released in 2015, is a pea protein-based patty designed to look, cook and taste like fresh ground beef. On September 14, 2018, the Center for Sustainable Systems at the University of Michigan (Marty Heller, principle researcher) published a report commissioned by Beyond Meat documenting a life cycle assessment (LCA) of the original Beyond Burger (version 1.0) and comparisons against a typical American ground beef patty (Heller and Keoleian 2018). The current study, conducted by Blonk Consultants and commissioned by Beyond Meat, uses the LCA methodology outlined below to calculate the environmental impact of Beyond Burger (version 3.0) produced in North America in 2022, and compare it with a ground beef patty, based on US industry-average production. The study serves as an update to the Original Beyond Burger 1.0 LCA from 2018, addressing product reformulation as well as changes in business and manufacturing practices. In addition, a more recent and thorough LCA of beef patty production in the U.S. is used as the basis for comparison.

LCA is a framework that allows the quantitative analysis of the environmental burdens of a product or system throughout all the stages of its life cycle. LCAs provide a holistic approach, allowing to observe how individual life cycle stages contribute to the overall environmental impact of the product in scope. This can result in the identification of opportunities for direct and indirect environmental management actions that may lead to a reduction of emissions throughout the life cycle.

This LCA is conducted according to the iterative, multi-step methodology proposed in ISO 14040 and 14044 LCA methodological standards (ISO 2006a; 2006b), including an external review.

The LCA is conducted according to the following steps, as defined by abovementioned ISO standards.

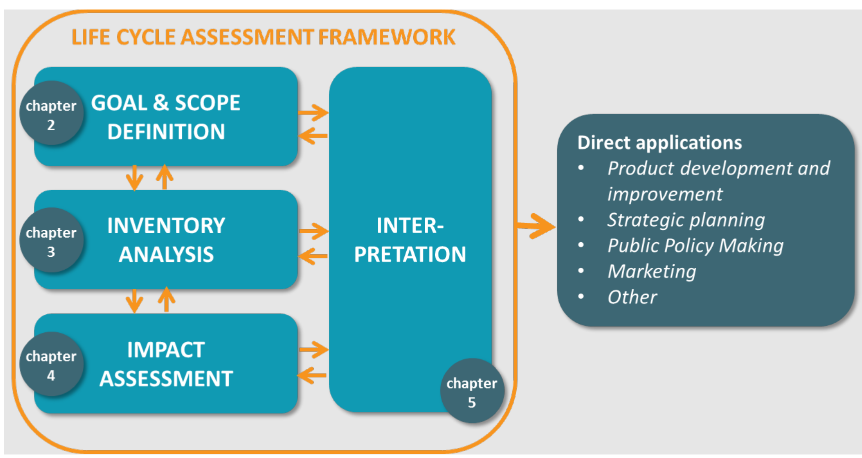

FIGURE 1: METHODOLOGICAL PHASES IN LCA BASED ON ISO 14040

- **Goal & scope definition**: This phase provides a description of the product system in terms of system boundary and functional unit.
- **Life cycle inventory analysis**: (LCI) is a methodology for estimating the consumption of resources and the quantities of waste flows and emissions caused by or otherwise attributable to a product's life cycle.
- **Life cycle impact assessment:** (LCIA) provides indicators and the basis for analyzing the potential contributions of the resource extractions and emissions in an inventory to a number of potential impacts.
- **Interpretation**: in this phase the results of the analysis and all choices and assumptions made during the analysis are evaluated in terms of soundness and robustness. After this, overall conclusions are drawn.

This report follows the steps as defined above: it describes the goal and scope of the study, the data and methodology used to model the products, after which it provides the results and interpretation for the main analyses and for a number of sensitivity analyses.

2 LCA Methodology

2.1 Goal

The goals of this study are to evaluate the environmental impact of producing and distributing the Beyond Burger 3.0 product for purposes of identifying hotspots (inputs or activities driving environmental impact) and directing continued improvement in environmental performance, and to compare the environmental performance of the Beyond Burger 3.0 against a beef patty represented by U.S. national-average beef production, for purposes of making comparative claims.

While references to the Original Beyond Burger 1.0 LCA are made, the goal of this study is not to track progress in environmental performance between Beyond Burger versions 1.0 and 3.0, as results are not readily comparable due to methodological and data differences (see Section 3.2.7 for a comparison of approaches). Instead, this study is intended to update environmental performance data to reflect Beyond's burger re-formulation and its evolved supply chain practices.

The intended audiences for this report are internal stakeholders at Beyond Meat and external customers and consumers. Results from this study are intended to be used in comparative assertions to be disclosed to the public.

2.2 Scope of study

The scope of the study generally follows that of the 2018 Original Beyond Burger 1.0 LCA (Heller and Keoleian 2018)[1]. The product systems to be assessed, the product function(s), functional unit, system boundary, and representative coverage of the study are described in this section.

2.2.1 Product System

This is a cradle-to-distribution attributional LCA study of a plant-based protein burger with production located in North America. Comparisons are made with a beef patty produced in the U.S.

- The Beyond Burger is a pea protein-based patty designed to look, cook and taste like fresh ground beef. While Beyond Meat markets beef analogue products in different formats, this LCA focuses on the Beyond Burger 3.0 offered through retail sales as two quarter pound (4 oz.) patties packaged in a sealed tray. The product system is defined and informed through direct communications with the product developer and manufacturer, Beyond Meat.
- The U.S. beef industry is complex and multi-faceted. Here, we rely on a recently published LCA study of industry-average beef production in the U.S. (Putman, Rotz, and Thoma 2023) in order to quantify impacts of a beef burger patty. An author of this study has provided, through direct communications with Blonk, data not specifically available in the published journal article. See Section 3.3 for further details on the study employed to evaluate the environmental impact of beef production, and the adjustments necessary to align the published study with the boundary conditions of this study.

2.2.2 Product Functions and Functional Unit

Establishing the function of foods, and in turn, the functional unit, is difficult (Schau and Fet, 2008) as foods supply a variety of functions. Supplying human nutrition can be considered the primary function of food, but nutrition is multi-dimensional and quite complex, and not easily reduced to a straightforward quantifiable parameter. Foods also provide additional non-nutritional functions including pleasure, emotional and psychological value, and cultural identity. While important, these additional functions are equally challenging to quantify. In the case of the Beyond

[1] The 2018 Original Beyond Burger 1.0 report is publicly available at: https://css.umich.edu/sites/default/files/publication/CSS18-10.pdf

Burger 3.0, as its flavor and texture profiles are designed to mimic beef, it is reasonable to assume qualitatively that the two products provide similar non-nutritional functions.

A serving size of Beyond Burger 3.0, one quarter pound (¼ lb.) plant-based patty, delivers an equivalent amount of protein as a ¼ lb. 80/20 beef patty[2], the most commonly sold animal-based beef patty found in retail[3] (Table 1). 80/20 ground beef is composed of 80% lean meat and 20% fat. Note that while 80/20 ground beef is assumed in the nutritional comparison in Table 1, the ratio of lean meat to fat does not influence the LCA results, as all edible beef, regardless of cut/quality, has the same footprint (as recommended by international guidelines (FAO LEAP 2016)). As in the 2018 Original Beyond Burger 1.0 LCA (Heller and Keoleian 2018), the functional unit for this study is defined as **one 4 oz. (¼ lb., 0.113 kg) uncooked patty delivered to retail distribution outlets**.

TABLE 1. NUTRITIONAL COMPARISON OF BEYOND BURGER 3.0 AND 80/20 BEEF PATTY[2]

	4 oz. Beyond Burger 3.0 patty[4]	4 oz. 80/20 beef patty[2]
Protein (g)	20	20
Iron (mg)	4	2.2
Saturated fat (g)	5	9
Cholesterol (mg)	0	77
Total fat (g)	14	22
Calories	230	280

2.2.3 System Boundaries

Figure 2 provides a graphical representation of the system boundaries considered in this study. The study represents a cradle-to-distribution assessment of the Beyond Burger 3.0 product chain. As such, the study will exclude activities at the retail and consumer level. This cradle-to-distribution boundary scope was chosen primarily because, especially given the uncertainties present in generic modeling of these downstream stages, retail and consumer activities are considered to be equivalent between the Beyond Burger 3.0 and beef product systems. Further, the "cradle-to-distribution" boundary also corresponds with the supply chain controlled by Beyond Meat. Table 2 provides additional detail of items included and excluded from system boundaries. The system boundary for the beef patty comparison (Putman, Rotz, and Thoma 2023) is provided in Section 3.3.

Note that packaging end-of-life disposal as implemented in the initial LCA made negligible contributions across all impact categories, informing decisions about packaging options is *not* a goal of the current study, and it is expected that there will be little to no difference in packaging end-of-life impacts between Beyond Burger 3.0 and the beef comparison. Packaging end-of-life has therefore been excluded from the scope in this update. Capital goods and infrastructure have also been excluded, based on EC Product Environmental Footprint guidelines (Zampori and Pant 2019), as such capital goods have been repeatedly demonstrated in previous LCAs to be negligible after amortization over expected lifetimes.

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[2] Beef nutritional data from USDA FoodData Central (https://fdc.nal.usda.gov/) "Beef, ground, 80% lean meat / 20% fat, raw", Foundational Foods database; except saturated fat which is from the SR Legacy Foods database.
[3] https://www.beefitswhatsfordinner.com/retail/sales-data-shopper-insights/ground-beef-at-retail-and-foodservice
[4] https://www.beyondmeat.com/en-US/products/the-beyond-burger

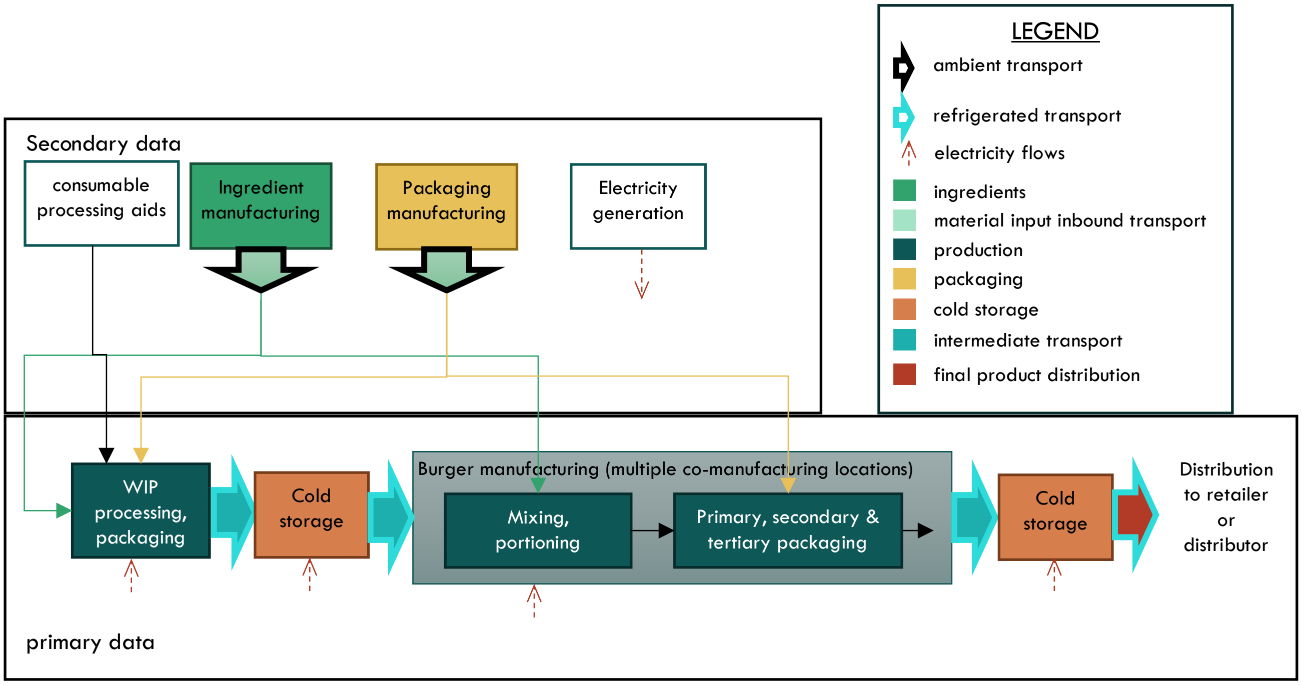

FIGURE 2. LIFE CYCLE STAGES INCLUDED IN THE CRADLE-TO-DISTRIBUTION SYSTEM BOUNDARY OF THE BEYOND BURGER 3.0 PRODUCT. WIP (WORK IN PROGRESS) REPRESENTS INTERMEDIARY PRODUCT COMPONENTS. NOTE THAT COLOR DESIGNATIONS CORRESPOND WITH CONTRIBUTION GROUPINGS USED IN RESULTS PRESENTATION.

TABLE 2. DESCRIPTION OF ITEMS INCLUDED AND EXCLUDED FROM SYSTEM BOUNDARY.

included	*excluded*
• Raw material supply, including ingredients, primary, secondary and tertiary packaging	• Retail and consumer stages
• Production and packaging operations	• Packaging disposal
• Facility-level energy use (including lighting and other overhead uses)	• Capital goods and infrastructure
• Facility-level water use	• Employee travel
• Inbound transport of ingredients and packaging	• Additional production facility overhead such as forklift operation
• Cold storage of intermediaries and final product	• Food waste disposal
• Refrigerated transport of intermediaries and final product	
• Losses of product and packaging at manufacturing level	• Losses of final packaged product (inventory shrink)

2.2.4 Time coverage

Data collection targeted the production window of January through June, 2022; ingredients, suppliers, facility energy demands, and intermediary and final product distribution transport are representative of this time period.

The beef patty comparison is based on (Putman, Rotz, and Thoma 2023), and is representative of beef produced and consumed in the U.S. circa 2017. As beef production is a very mature industry in the U.S., there is no reason to expect notable changes in environmental impact over the five year difference in time coverage between the comparison products.

2.2.5 Technology coverage

The study represents Beyond Meat's production in North America of the Beyond Burger 3.0 packaged for retail in 2-patty trays (SKU 1B01-003).

The beef comparison represents industry-average beef production in U.S., based on 160 archetypical cattle production systems across all 50 states, and includes contributions to beef supply from dairy operations (both culled animals and excess calves fed to market weight) reflective of market practices in the U.S. See Section 3.3 and (Putman, Rotz, and Thoma 2023) for further detail.

2.2.6 Geographical coverage

The study is to represent Beyond Burger 3.0 production in North America, with electricity grid data specific to the production location. Where known, ingredient production are representative of their place of origin, and transportation is included to Beyond Meat production facilities.

The beef comparison is representative of industry-average beef production in the U.S.

2.3 Allocation principles

Facility-level utility demands at the COMO facility (pea protein pre-treatment) were allocated to specific SKUs based on production rates, as implemented by Beyond Meat in their standard costing methods. Thus, this is in essence a mass allocation.

Energy required for cold storage was approximated by the warehouse manager (Americold Leesport) based on the average percentage of occupation applied to total energy cost over the period of January through June, 2022.

When choosing secondary data, economic allocation was consistently selected for Agri-footprint 5.0 processes. That is, environmental impacts are shared between co-products in agricultural cultivation and processing of ingredients based on the ratio of revenue (price times yield) between co-products. This is aligned with the recommendations from the European Commission's Product Environmental Footprint (PEF) guidelines (Zampori and Pant 2019). For processes from Ecoinvent v 3.6, the Allocation at Point of Substitution (APOS) dataset was chosen (note that Ecoinvent uses economic allocation between co-products in all available dataset options: this choice primarily affects end of life and recycling allocation – relevant to this study as recycled materials are used in packaging).

In the beef comparison study, modified Ecoinvent processes were used for co-product feeds such as distiller's grains, maize gluten meal, soybean oil and soybean meal, and therefore also were based on economic allocation. Biophysical allocation was applied between milk and meat from dairy operations included in the beef study, which is in accordance with International Dairy Federation recommendations (IDF 2022). This method is based on the known relationships between net energy for lactation and net energy for growth, with net energy for lactation (in MJ/kg) being multiplied by the mass of milk produced, and net energy for growth multiplied by the live weight of animals sold. Allocation between edible meat, hides and beef byproducts at the slaughterhouse was made on a generated revenue (i.e., economic allocation) basis.

2.4 Cut-off criteria

All efforts have been made to be as inclusive as possible, and no cut-off criteria, *per se*, are defined for this study. Instead, we follow the EC PEF guidelines (Zampori and Pant 2019) by using a proxy approach. For the processes within the system boundary, all available energy and material flow data have been included in the model. In cases where no matching life cycle inventories are available to represent a flow, proxy data have been applied based on conservative assumptions regarding environmental impacts. The choice of proxy data is documented in Section 3.2.3. The exception to this is the exclusion of capital goods in both the Beyond Burger 3.0 and beef production systems, which, as described in Section 2.2.3, have been excluded as they are known to be negligible in agriculture/food production systems.

2.5 Life Cycle Impact Assessment Methodology and Impact Categories

The impact categories chosen for this study follow those in the initial LCA and include: greenhouse gas emissions (carbon footprint), non-renewable energy use (fossil resource scarcity), water consumption and land use. The ReCiPe 2016 midpoint impact assessment was chosen based on its common contemporary usage. Putman, Rotz, and Thoma (2023) also use ReCiPe 2016 in their beef LCA (comparison for this study), however, they chose to implement global warming potential characterization factors (IPCC 2013 100a) *without* climate-carbon feedback. We also include this adaptation as an additional reporting in our assessment.

Note that the land use indicator in ReCiPe includes characterization factors for different land use types (e.g., differentiation between annual croplands and perennial grasslands). This is relevant in the current comparison because impacts from beef production (which utilizes extensive grass and rangelands in the US) would likely be higher if an unweighted assessment were used. In addition, while the ReCiPe method uses the terminology, 'fossil resource scarcity', this is in essence an indicator of fossil energy use; the only characterization applied 'normalizes' fossil resources by the ratio between the energy content of the fossil resource and the energy content of crude oil, such that the unit for the indicator is kg oil equivalents (kg oil-eq). The water consumption indicator in ReCiPe (as implemented in SimaPro) is essentially a life cycle inventory, tabulating the balance of water withdrawals (characterization of +1) and water emissions or returns (characterization of -1).

Results based on the impact assessment methods used in the Beyond Burger1.0 LCA (Heller and Keoleian 2018) are provided in Appendix I for backwards compatibility.

Life cycle impact assessment results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks.

2.6 Data quality rating

Defining statistical uncertainty for individual input and output data points requires a level of information that simply was not available in this study. Instead, SimaPro's pedigree uncertainty calculator was used to qualitatively evaluate data quality of primary data. This calculator computes a combined uncertainty value based on the rating for each of the four data quality criteria (see Table 3 below). The pedigree uncertainty calculator is used to define the SD^2 (square of the geometric standard deviation, assuming lognormal distribution) for each data point in SimaPro, which is used for the uncertainty analysis. Qualitative evaluation of data quality is a largely subjective process based on expert judgment of the study practitioner.

TABLE 3 DETAILED DATA QUALITY RANKING, BASED ON SIMAPRO'S PEDIGREE UNCERTAINTY CALCULATOR

	1 (Excellent)	2 (Very good)	3 (Good)	4 (Fair)	5 (Poor)
Precision	Verified based on measurements	Non-verified measurements/verified assumptions	non-verified data based on qualified estimate	qualified estimate	non-qualified estimate
Temporal	<3 years	<6 years	<10 years	<15 years	>15 years
Geographical	From area under study	Larger area in which area under study is included	Area with similar production conditions	Area with slightly similar production conditions	Unknown/distinctly different area
Technological	Data from processes under study	Data from processes under study, but different enterprise	Data from processes under study, but different technology	Data on related processes	Data on related processes from different technology

2.7 Type and format of the report

In accordance with the ISO requirements (ISO, 2006) the results, data, methods, assumptions and limitations from this study are presented in a transparent manner and in sufficient detail to convey the complexities, limitations, and tradeoffs inherent in the LCA to the reader. This allows the results to be interpreted and used in a manner consistent with the goals of the study.

2.8 Software and databases

The LCA model was created using the SimaPro 9.4 software system, developed by PRé Sustainability. LCI databases accompanying SimaPro, including Ecoinvent 3.6, USLCI and Agri-footprint 5, were utilized for background materials and processes in the model. In addition, when not available in the above, some data on production of lesser ingredients were taken from a whole diet database prepared for National Institute for Public Health and the Environment, Netherlands (RIVM 2019).

2.9 Critical review

The ISO 14040/14044 standards require a critical review by a panel of at least three independent experts when the study results are intended to support comparative assertions that will be disclosed to the public. The primary goals of a critical review are to provide an independent evaluation of the LCA study and to provide input on how to improve the quality and transparency of the study. The benefits of employing a critical review are to ensure that:

- The methods used to carry out the LCA are consistent with ISO 14040 and 14044,
- The methods used to carry out the LCA are scientifically and technically valid,
- The data used are appropriate and reasonable in relation to the goal of the study,
- The interpretations reflect the limitations identified and the goal of the study, and
- The study report is transparent and consistent.

If applicable, the critical review panel can comment on suggested priorities for potential improvements.

For this study, the critical review panel consisted of

- Prof. Roland Geyer, University of California, Santa Barbara (chair)
- Prof. Jasmina Burek, University of Massachusetts, Lowell
- Prof. Alissa Kendall, University of California, Davis

The review was performed according to section 6.3 of ISO 14044 on comparative assertions to be disclosed to the public. A draft copy of this report was made available to the panel. The panel provided feedback on the methodology, assumptions, and interpretation. The draft report was subsequently revised and a final copy submitted to the review panel along with responses to comments.

The Critical Review Statement can be found in Appendix III. The Critical Review Report containing the comments and recommendations of the independent experts as well as the practitioner's responses is also available in the Appendix.

3 Life Cycle Inventory Analysis

3.1 Beyond Burger 3.0 production system

Key foreground data were provided by Beyond Meat, including information on product formulation, manufacturing, process energy use, packaging, storage and distribution. The following sections describe both the bases for foreground (primary) data, as well as the interconnected background (secondary) data within the LCA model. As electricity and transport processes are relevant across all stages, these are presented first. Descriptions then follow the Beyond Burger 3.0 life cycle stages: ingredient production (Section 3.1.3), manufacturing and packaging (3.1.4), cold storage (3.1.5), and distribution (3.1.6). Note that specifics of life cycle inventories have been withheld from this public-facing document in order to protect proprietary information; however, these specifics were provided to the review panel (under non-disclosure agreements) as a supplemental Appendix.

3.1.1 Electricity grids

For electricity consumption by facilities in the Beyond Burger 3.0 production chain, electricity grid mixes were created to correspond with the geographic location based on the 2020 eGRID resource mix, from https://www.epa.gov/egrid/data-explorer. These included SRMW (Columbia, MO area), RFCE (Malvern, PA area), and CAMX (San Diego, CA area). Processes used to represent different energy sources in the mix are shown in Table 4. Note that USLCI processes were used when available for the energy resources in question as they were assumed to best represent the US, however, ecoinvent datasets were required to fill gaps in availability from USLCI. The USLCI electricity generation datasets also reflect primary data from circa 2000; the assumption here is that the environmental performance of these generation technologies has not changed significantly (on average) in the past decades, but the mix of energy resources has changed significantly, hence the update to 2020 grid mixes. A 13.6% transmission and distribution loss was assumed in all cases; this is a conservative estimate reflecting historical and not current transmission and distribution losses, but was used for consistency with the underlying databases. A sensitivity assessment performed during the review process demonstrated that the LCA results are not sensitive to this transmission loss parameter: completely eliminating transmission losses affected results by less than 1%. In addition, the Ecoinvent process (Electricity, low voltage {CA-QC}| market for | APOS, S) was used for the electricity grid in the Montreal, Canada area.

TABLE 4. DATASETS USED IN MODELING ELCTRICITY GRID MIXES.

Energy resource	% in grid mix			Modeled as:
	SRMW	RFCE	CAMX	
Coal	61.54	8.58	3.59	[USLCI] Electricity, coal, at power plant/US (assumed evenly distributed between anthracite, bituminous, and lignite coal)
natural gas	14.86	50.28	47.05	[USLCI] Electricity, natural gas, at power plant/US
hydroelectric	1.81	1.15	8.55	[USLCI] Electricity from hydroelectric power plant, <1kV
nuclear	15.84	36.28	8.29	[USLCI] Electricity, nuclear, at power plant/US
residual fuel oil	0.5	0.21	1.08	[USLCI] Electricity, residual fuel oil, at power plant/US
wind power	5.38	1.11	7.23	[ELCD] Electricity from wind power, AC, production mix, <1kV RER
photovoltaic	0.07	0.74	17.27	[Ecoinvent] Electricity, low voltage {SERC}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si | APOS, S
biomass		1.65	2.76	[Ecoinvent] Electricity, high voltage {RoW}| heat and power co-generation, wood chips, 6667 kW | APOS, S
geothermal			4.20	[Ecoinvent] Electricity, high voltage {WECC, US only}| electricity production, deep geothermal | APOS, S

3.1.2 Transport

Inbound transport was included for the 10 ingredients with the largest mass contribution, representing 95% of dry ingredients in total. Transport distance was estimated as best as possible based on sourcing information provided by Beyond Meat: sea transport distances were determined using www.ecotransit.org, whereas land-based distances were from Google Maps. Inbound transport was modeled with the following processes from Ecoinvent:

- Transport, freight, lorry 16-32 metric ton, euro5 {RoW}| market for transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S
- Transport, sea ship, 80000 DWT, 80%LF, middle, default/GLO Economic

Transport of 'work in progress' (WIP) components to cold storage and to other manufacturing facilities, as well as transport of finished product to cold storage and in final distribution, occurs in freight trucks with refrigeration units operating at frozen temperatures. These transport legs were modeled using the Ecoinvent process as above, but modified to account for 20% additional energy consumption and emissions as well as refrigerant inputs (17.125 mg

R134a per tkm) and associated refrigerant emissions, mimicking Ecoinvent's approach to modeling refrigerated freight (note that refrigerated freight processes only exist for smaller truck sizes within Ecoinvent).

3.1.3 Ingredients

Beyond Burger 3.0 ingredient quantities were based on batch sheets supplied by Beyond Meat. Modeling approaches for each ingredient are provided in Table 5, where ingredients are named as on the product label. Formulation composition was provided, but redacted here for proprietary reasons. Additional details for prominent ingredients follow.

TABLE 5. BEYOND BURGER 3.0 INGREDIENTS AND LCA MODELING APPROACH (DATABASE KEY BELOW TABLE).

ingredient	Data approach ([xxx] = source database)	Production region based on primary data (✓) or proxy(X)
Water	[Ecoinvent] Tap water {GLO}| market group for | APOS, S-	✓
Pea Protein	[AFP5] pea protein isolate process from AFP (economic allocation), modified so that dry pea sourcing is 80% Canada, 20% France (see Section 3.2.3.1)	✓
Expeller-pressed Canola oil	[AFP5] Refined rapeseed oil (pressing), at processing/CA Economic (process modified to reflect rapeseed cultivation as 75% Canada, 25% Australia per information from supplier)	✓
Sunflower oil	[AFP5] Refined sunflower oil (solvent), at processing/US	✓
Coconut oil	[AFP5] Refined coconut oil, at processing/X Economic (X = coconut sourcing: 75% Phillipines, 25% Indonesia)	✓
Rice Protein	LCA data from manufacturer (see Section 3.2.3.2)	✓
Dried yeast	[RIVM] Yeast, at plant/RER Economic	X
Methylcellulose	PROXY: [Ecoinvent] Carboxymethyl cellulose, powder {GLO}| market for | APOS, S	X
Natural flavors **#1** **#2** **#3** **#4**	• Facility-level average impact data from manufacturer (as described in (Heller and Keoleian 2018)) • PROXY: average of 5 amino acids available in [AFP5]: L-lysine, DL-methionine, L-threonine, L-tryptophan, L-valine • PROXY: [AFP5] Refined sunflower oil (solvent), at processing/US; Refined rapeseed oil (pressing), at processing/CA Economic • PROXY: amino acid average as above	X
Cocoa butter	[RIVM] Cocoa butter, at processing/US Economic	X
Potato starch	[AFP5] Potato starch dried, at processing/DE Economic	✓
Salt (sodium chloride)	[Ecoinvent] Sodium chloride, powder {GLO}| market for | APOS, S	X
Potassium salt	[AFP5] Potassium chloride (NPK 0-0-60), at plant/RER Economic	X
Apple extract	[RIVM] Apple concentrate, at processing/NL Economic	X
Vinegar	[RIVM] Vinegar (wine), at processing/NL Economic	X
Lemon juice concentrate	[RIVM] Lemon juice (concentrate), at processing/NL Economic	X
Beet juice color	Modeled as described in (Heller and Keoleian 2018) [AFP5] carrots and turnips, at farm/NL Economic used as proxy for red beet, [Ecoinvent] Evaporation of milk {CA-QC}|milk evaporation|APOS, S used to represent water removal to make concentrated juice. 10kg beets required for 1 kg juice extract; concentration requires removal of 7.8 kg water.	X
Pomegranate concentrate	Supplier indicates that this product is extracted from pomegranate pulp after juicing; the juice is allocated all of the	

	impacts of pomegranate cultivation; this is therefore considered an 'upcycled' waste product and allocated no impact. Further energy consumed in processing is considered negligible. Thus, this product (<1% of dry ingredient weight) is modeled as zero impact.	
Sunflower lecithin	[PROXY] byproduct of sunflower oil refining [AFP5], average of oil sourced from Argentina and Ukraine	✓
Vitamins and minerals	[Ecoinvent] Zinc monosulfate {RoW}| market for zinc monosulfate | APOS, S	X

Database key: [AFP5] = AgriFootprint 5.0 (Blonk Consultants 2019)
[RIVM] = whole diet database prepared for National Institute for Public Health and the Environment, Netherlands (RIVM 2019)
[Ecoinvent] = Ecoinvent 3.6 (Ecoinvent 2019)

3.1.3.1 Pea protein

The primary ingredient and protein source for the Beyond Burger 3.0 is a pea protein isolate (PPI) which undergoes pre-treatment prior to mixing with other ingredients. One supplier of PPI provided (under confidentiality) an LCA of regional industry-average production. Review of this study identified incompatibilities in allocation methods to the internationally recognized approach taken in this study. In addition, the LCA was based on impact assessment methods found to be incompatible with methods used here. Instead, we use the indicative data for PPI production available in Agri-footprint. Country-level datasets used for dry pea cultivation were based on sourcing information provided by Beyond Meat. A portion of the pea protein used over the analysis window was from a China based supplier: the supplier's website indicated dry peas are sourced from Canada and the US, but for simplicity, we assume that PPI sourced from China utilizes peas cultivated in Canada, and provide sensitivity analysis around this assumption in Section 5.3. Electricity consumed in processing PPI in China was modeled using the Ecoinvent process: Electricity, medium voltage {CN}| market group for | APOS, S. In the baseline, 50% of PPI was sourced from China (with peas cultivated in Canada), 40% sourced from Canada, and 10% sourced from France. While pea cultivation processes and electricity grid were adjusted, the PPI manufacturing processes remain the same (Agri-footprint dataset) for all PPI sources.

Electricity, natural gas and consumable inputs to the pea protein pre-treatment (at Beyond Meat facility) were calculated by compiling facility-level utility invoices and allocating to the appropriate WIP based on production rates (mass allocation). Specific bill of material data was used to reflect actual yield of pre-treated protein, which was then packaged (intermediate packaging included in LCA) and shipped to cold storage. Units of pre-treated protein were assumed to be in cold storage for an average of 5 weeks based on inventory targets before being shipped to manufacturing facilities (cold storage energy use estimates were as described in Section 3.2.5). A weighted average distance from cold storage to manufacturing facilities was calculated using shipping data over the study time period (January to June, 2022).

3.1.3.2 Rice protein

An LCA study on the production of rice protein from Beyond Meat's supplier was provided by the supplier under confidentiality. The study was reviewed and determined to be of sufficient quality. This study used an Agri-footprint 2.0 process for "broken rice" (a by-product of milling) produced in China to represent upstream cultivation. Impact assessment results based on the ReCiPe midpoint method and a mass allocation approach were used as reported to represent production of rice protein. Note that while mass allocation is inconsistent with the allocation methods used in this study, the rice protein report included a sensitivity assessment using economic allocation that showed a *decrease* in global warming impacts relative to mass allocation. However, results from this economic allocation sensitivity did not cover all environmental indicators considered in this study. Thus, the mass allocation results were used as a conservative estimate of impact for the rice protein final product.

3.1.4 Burger manufacturing and packaging

A second WIP mixture was also assembled at the same facility as the pea protein pre-treatment, and followed the same cold storage and intermediate shipping as described above for pea protein. Electricity and water demands per pound processed for this WIP assembly/mixing were provided by Beyond Meat. The remaining burger ingredients and packaging materials were assumed to be delivered directly to co-manufacturer locations.

Manufacture of the Beyond Burger 3.0 product examined here occurred primarily at two co-manufacturer locations over the study time period (a 3rd location, representing less than 2% of total production over the time period, was not included in the study). Co-manufacturer production was assigned 75% to the Montreal, Quebec area, 25% to the San Diego, CA area. Co-manufacturer location affected only two parameters in the LCA model: shipping distances and electricity generation grid.

Facility-level electricity use from January through June, 2022 for the Quebec co-manufacturer was summed and divided by the Beyond Burger 3.0 production from that facility over the time period. This average electricity use per pound of Beyond Burger 3.0 produced was assumed for both co-manufacturing locations (energy use data were not available from the other facility) and assumed to cover all burger manufacturing energy demands including: on-site cold storage, ingredient mixing/blending, burger manufacturing lines including portioning, patty forming and packaging, and overhead usage for lighting, air handling and climate control. Bill of Material records were used to account for losses of ingredients and packaging materials.

Primary packaging trays containing two ¼ pound patties were assembled in tertiary packaging cases at 8 trays per case, then stacked 96 cases per pallet (packaging materials detailed in Section 3.2.4.1). Finished product was then shipped frozen to cold storage warehouses in multiple locations, with a weighted (by number of cases shipped) average shipping distance from transfer order data over the study time period. An average cold storage inventory holding period of 50 days was used based on the average number of inventory turns over the 6 month period. Final product was then distributed frozen to distributors or retailers, with distances averaged as described in Section 3.2.6.

3.1.4.1 Packaging materials

Information on packaging weights per unit and material composition were provided by Beyond Meat. Table 6 summarizes the packaging material weights and background data used to represent each component. Note that while the PET tray used is considered to be 100% recycled PET, 60.6% of this is post-consumer recycled, with the balance being post-industrial recycled; this post-industrial fraction is modeled as virgin PET, as suggested by the EU PEF guidelines (Zampori and Pant 2019).

TABLE 6. PACKAGING MATERIALS AND MODELING APPROACHES

Packaging component	Weight	Data approach (all from Ecoinvent database)
100% recycled PET tray (60.6% post-consumer)	24.15g/tray	Polyethylene terephthalate, granulate, amorphous, recycled {US}| market for polyethylene terephthalate, granulate, amorphous, recycled | APOS, S (post-industrial recycled modeled as virgin) Polyethylene terephthalate, granulate, amorphous {GLO}| market for | APOS, S Thermoforming of plastic sheets {GLO}| market for | APOS, S
PE lid film (assumed 50% LDPE, 50% LLDPE)	2g/tray	Polyethylene, low density, granulate {GLO}| market for | APOS, S Polyethylene, linear low density, granulate {GLO}| market for | APOS, S Extrusion, plastic film {GLO}| market for | APOS, S
Patty paper	2 sheets per tray at 0.5g ea.	90% paper: Tissue paper {GLO}| market for | APOS, S 10% wax Paraffin {GLO}| market for | APOS, S
Cardboard sleeve	13.6g / tray; 0.33g printing ink	Folding boxboard/chipboard {RoW}| chipboard production, white lined | APOS, S Printing ink, offset, without solvent, in 47.5% solution state {RoW}| market for printing ink, offset, without solvent, in 47.5% solution state | APOS, S
Corrugated case	213.2g/case (8 trays)	Corrugated board box {RoW}| market for corrugated board box | APOS, S
Wood pallet	1 per 96 cases	EUR-flat pallet {GLO}| market for | APOS, S

Pallet pad	1.2 lb (0.54kg) per pallet	Corrugated board box {RoW}| market for corrugated board box | APOS, S
Pallet wrap	1 lb (0.45kg) per pallet	Polyethylene, linear low density, granulate {GLO}| market for | APOS, S Extrusion, plastic film {GLO}| market for | APOS, S

3.1.5 Cold storage energy demand

The following approach was used to estimate cold storage energy demand per stored pallet per day. Total energy cost (in dollars) over the January through June, 2022 time period for *one* cold storage warehouse in southeast Pennsylvania was provided, along with total pallet positions at the facility and an electricity price ($/kWh) paid in August. Assuming the August electricity price is applicable over the full 6 months, a total kWh demand for the facility was calculated. This was then divided by the total pallet positions and by 180 days (6 months) to arrive at an energy demand of 0.65 kWh/pallet/day. This cold storage energy demand was then assumed for all cold storage warehouse locations.

Limited data are available on the energy performance of cold storage warehouses, and what data that are available suggests high variability. For comparison with the values cited here, if we assume a pallet volume of 64 ft^3 (4 x 4 x 4 ft) or 5.95 m^3, the above estimate amounts to 39.9 kWh m^{-3} $year^{-1}$. However, it is not obvious whether all of the volume above a pallet should be allocated to a pallet position or if pallets are shelved more than one pallet high in a cold warehouse.

Energy estimates were unavailable for the Original Beyond Burger 1.0 LCA (Heller and Keoleian 2018), and modeling was used assuming a 'reasonable' specific energy consumption of 28 kWh m^{-3} $year^{-1}$. A survey of 28 California facilities found energy consumption from 15 to 132 kWh m^{-3} $year^{-1}$ (Prakash and Singh 2008). A conference proceedings paper directly addressing the specific energy consumption values for various refrigerated food cold stores reported survey data from 262 frozen and mixed (chilled and frozen) warehouses with a mean of 71.5 kWh m^{-3} $year^{-1}$ (standard deviation 40.6 kWh m^{-3} $year^{-1}$) (Evans et al. 2015). Removing the upper and lower 10% from this survey data still left a range of 31 to 119 kWh m^{-3} $year^{-1}$ and a mean of 67. These findings from the literature demonstrate that there is a wide variation in energy demand for cold storage warehouses. Further, additional uncertainty can be introduced in the way energy demand estimates are allocated or assigned to occupation by a specific product. The potential variability in cold store energy demand is addressed as a sensitivity analysis (Section 5.3).

3.1.6 Distribution

Sales order data for the January through June, 2022 time period were used to calculate a weighted average (weighted by number of cases shipped) distribution distance (shipping distance included in sales order data supplied by Beyond Meat) from cold storage to final Beyond Meat customer (typically a distributor or retailer). The weighted average distance was 1342 miles.

3.1.7 Comparison with previous LCA modeling

In addition to changes in ingredient formulation and sourcing, significant differences in data collection approaches, primary data availability, background databases and modeling approaches exist between this study and the Original Beyond Burger 1.0 LCA. Many of these differences were unavoidable due to development and expansion of the Beyond Burger 3.0 manufacturing chain, changes in business structure and data access, and updates and access to background databases. Because of these changes in modeling, it is difficult to make direct comparisons between the Original Beyond Burger 1.0 and Beyond Burger 3.0 LCAs. The most relevant differences are summarized in Table 7.

TABLE 7. COMPARISONS BETWEEN THE ORIGINAL BEYOND BURGER 1.0 AND THE BEYOND BURGER 3.0 LCA MODELING APPROACHES

Data	Original Beyond Burger 1.0 LCA approach	Beyond Burger 3.0 LCA approach
Manufacturing energy demand	Direct measurement of specific pieces of equipment over short	Facility-level energy use over 6 months, divided by product output

	collection periods; only one co-manufacturer	or allocated based on product flow rates (mass allocation). Assume energy estimates apply to other facilities
Product losses	Assumed at 5%	Based on Bill of Material calculations: 4.2%
Cold storage energy demand	Modeled using an assumed specific energy consumption, days in storage and occupied volume (28 kWh m^{-3} $yr^{-1)}$	Estimated using total energy use from one warehouse, divided over pallet positions (40 kWh m^{-3} yr^{-1}, assuming pallet volume of 5.95m^3)
thermal demand of cooling and freezing final product	Modeled and added to cold storage energy demand	Assumed to be captured in facility level energy use
Manufacturing facility lighting	Modeled	Assumed to be captured in facility level energy use
WIP transport	One point-to-point leg included	Numerous production and cold storage locations; required distance weighting, assigned share of production output, etc.
Refrigerated transport	Modeled combining truck transport process and reefer operation process (required assumptions on truck speed and idle time)	Based on refrigerated transport processes in Ecoinvent 3.6
Packaging disposal	Modeled based on EPA's Waste Reduction Model	Not included due to negligible impact in previous study
Plastic production background data (packaging)	USLCI database used	USLCI database unavailable and considered outdated. Ecoinvent database used

3.2 U.S. beef production: baseline for comparison

U.S. beef production has been examined extensively in (primarily) cradle-to-gate LCAs (for example, Capper 2011; Lupo et al. 2013; Pelletier, Pirog, and Rasmussen 2010; Rotz et al. 2013; Stackhouse-Lawson et al. 2012; Webb et al. 2020; Asem-Hiablie et al. 2019). A recent study expands on these efforts to extend the LCA to the full life cycle and include a more comprehensive set of environmental impact categories (Putman, Rotz, and Thoma 2023). Sponsored by The Beef Checkoff Program (a U.S. national marketing and research program overseen by the Cattlemen's Beef Board (CBB), with oversight by the U.S. Department of Agriculture (USDA)), this recent assessment also serves as a current benchmark for the environmental sustainability profile of the production and consumption of beef in the U.S.

The benchmark U.S. beef LCA uses a series of regionalized archetypical simulations of cattle operations along with primary data for post-farm gate activities including processing, packaging, distribution (as well as retail, consumption and disposal). This effort is intended to capture the variation in production practices across supply chain stages throughout the U.S. such that in aggregate, the assessment provides a robust, nationally representative benchmark for the U.S. beef industry. Figure 3 shows a system boundary diagram from the Putman et al. study. Included in the assessment are the roughly 24% of beef supply that are culled from dairy operations, with biophysical allocation applied between milk and culled animals.

Impact assessment results published in Putman et al. were characterized using ReCiPe 2016 Midpoint (H), and therefore directly compatible with this study (with the exception that carbon climate feedback contributions were removed from global warming characterization factors). Note that land use change contributions to global warming were not accounted for in the Putman et al. study; as agricultural land use has been reasonably stable in the U.S. over the past 20 years (the time window for land use change assessments) and it is assumed that all feed is produced within the US, this is not anticipated to be a significant omission. The full life cycle results are summarized per kg of beef consumed in Table 8, including contributions from the different life cycle stages. However, adaptations were required in order to match system boundaries in the current study, as described in the following section.

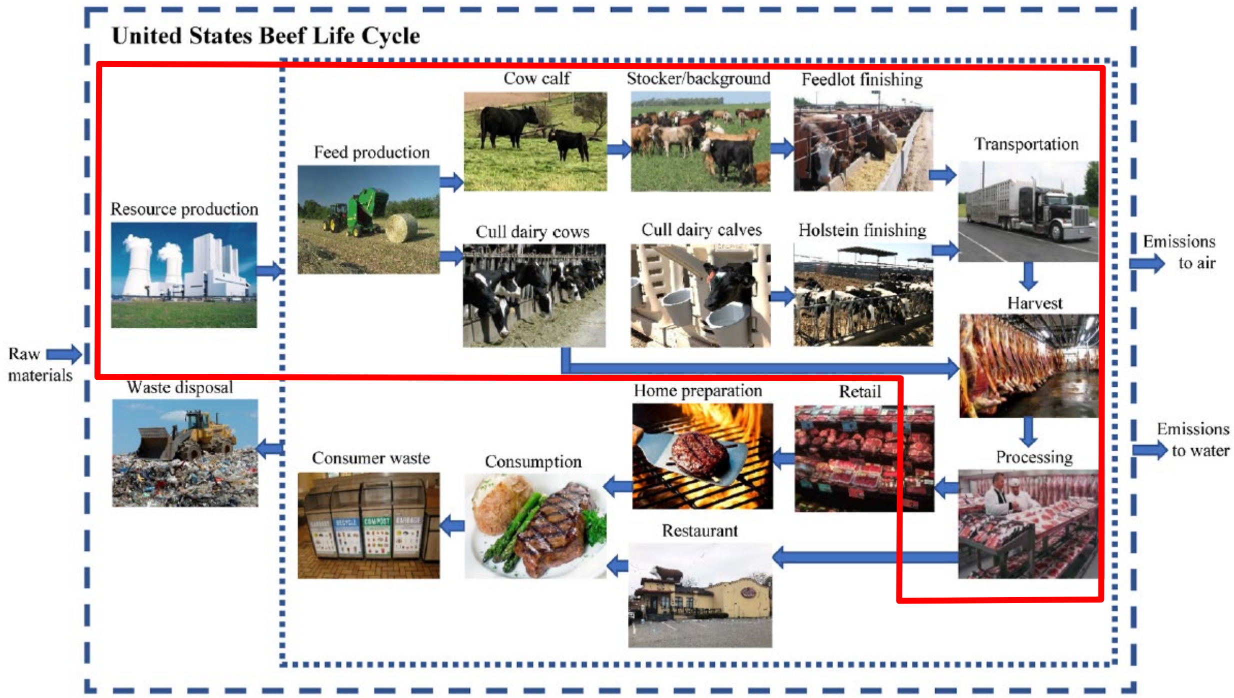

FIGURE 3. U.S. BEEF LIFE CYCLE SYSTEM BOUNDARY DIAGRAM, AS PRESENTED IN (PUTMAN, ROTZ, AND THOMA 2023). THE RED LINE INDICATES THE PORTION OF THE LIFE CYCLE (CRADLE TO DISTRIBUTION) UTILIZED IN THE COMPARISONS WITH BEYOND BURGER 3.0.

TABLE 8. LIFE CYCLE IMPACT ASSESSMENT RESULTS FOR ONE KG BEEF PRODUCED, COOKED, AND CONSUMED IN THE US, AS REPORTED BY (PUTMAN, ROTZ, AND THOMA 2023).

indicator	Unit	TOTAL	production	harvesting	processing	retail	home	Full service restaurant	Limited-service restaurant
					per kg beef produced, cooked and consumed in the U.S.				
global warming	kg CO_2 eq	42.7	33.5	0.95	0.50	1.34	1.38	3.24	1.79
fossil resource scarcity	kg oil eq	3.89	1.4	0.27	0.15	0.33	0.34	0.91	0.48
land use	m^2a crop eq	196	195	0.06	0.01	0.02	0.58	0.04	0.02
water consumption	liters	2479	2422	15.9	2.09	5.75	5.77	19.86	7.82

3.2.1 Adaptations to match system boundaries

The Putman et al, 2023 reporting includes the life cycle stages of retailing as well as storage and preparation at home and in restaurants. Notable shrinkage at retail and food waste at consumption were included in these assessments, which have a multiplicative effect on upstream production and processing. Thus, in order to align with the Beyond Burger 3.0 system boundaries, we received through personal communication with Greg Thoma the life cycle impact assessment results for *1 kg ground beef at processing, including packaging,* which excludes contributions from downstream stages as well as the production impacts of retail- and consumer-level losses. Note that the Putman et al, 2023 study distinguishes between beef cuts and ground beef through the stages of processing, packaging, and preparation/consumption; however, beef production and harvest are identical for beef cuts and ground beef. Therefore, the data received from Thoma includes national average beef production (including contributions from dairy operations), transportation and harvest, as well as processing and packaging for ground beef. Since distribution impacts specific to the ground beef supply chain were not available, we assumed the same distribution impacts as with the Beyond Burger 3.0 life cycle. These results are summarized in Table 9.

TABLE 9. IMPACT ASSESSMENT RESULTS FOR GROUND BEEF (GREG THOMA, PERSONAL COMMUNICATION). NOTE THAT DISTRIBUTION CONTRIBUTIONS ARE ASSUMED TO BE THE SAME AS THE BEYOND BURGER 3.0.

		per kg	per 1/4 lb patty	distribution	total
global warming	kg CO_2 eq	36.8	4.18	0.08	4.26
fossil resource scarcity	kg oil eq	1.5	0.17	0.02	0.19
land use	m^2a crop eq	154.3	17.51	0.01	17.52
water consumption	liters	1930.7	219.14	0.10	219.24

4 Life Cycle Impact Assessment Results

4.1 Beyond Burger 3.0

4.1.1 ReCiPe impact assessment results

Environmental impact of the Beyond Burger 3.0 life cycle based on the ReCiPe 2016 impact assessment method are summarized in Table 10. Note that global warming impacts associated with land use change are presented separately here, in line with reporting guidelines. Figure 4 offers a visual representation of the distribution of impacts across life cycle stages.

TABLE 10. CRADLE-TO-DISTRIBUTION LCA RESULTS FOR ¼ LB. **BEYOND BURGER 3.0**, BASED ON THE RECIPE IMPACT ASSESSMENT METHOD.

indicator	Unit (per ¼ lb patty)	TOTAL	ingredients	ingredient inbound transport	production	packaging	cold storage	intermediate transport	final product distribution
global warming	kg CO_2 eq	0.43	0.15	0.01	0.01	0.06	0.02	0.10	0.08
global warming (land use change)	kg CO_2 eq	0.06	0.06	0.00	0.00	0.00	0.00	0.00	0.00
fossil resource scarcity	kg oil eq	0.12	0.03	0.00	0.00	0.02	0.01	0.03	0.02
land use	m^2a crop eq	0.53	0.43	0.00	0.00	0.08	0.00	0.01	0.01
water consumption	liters	6.45	4.52	0.02	0.91	0.76	0.00	0.13	0.10

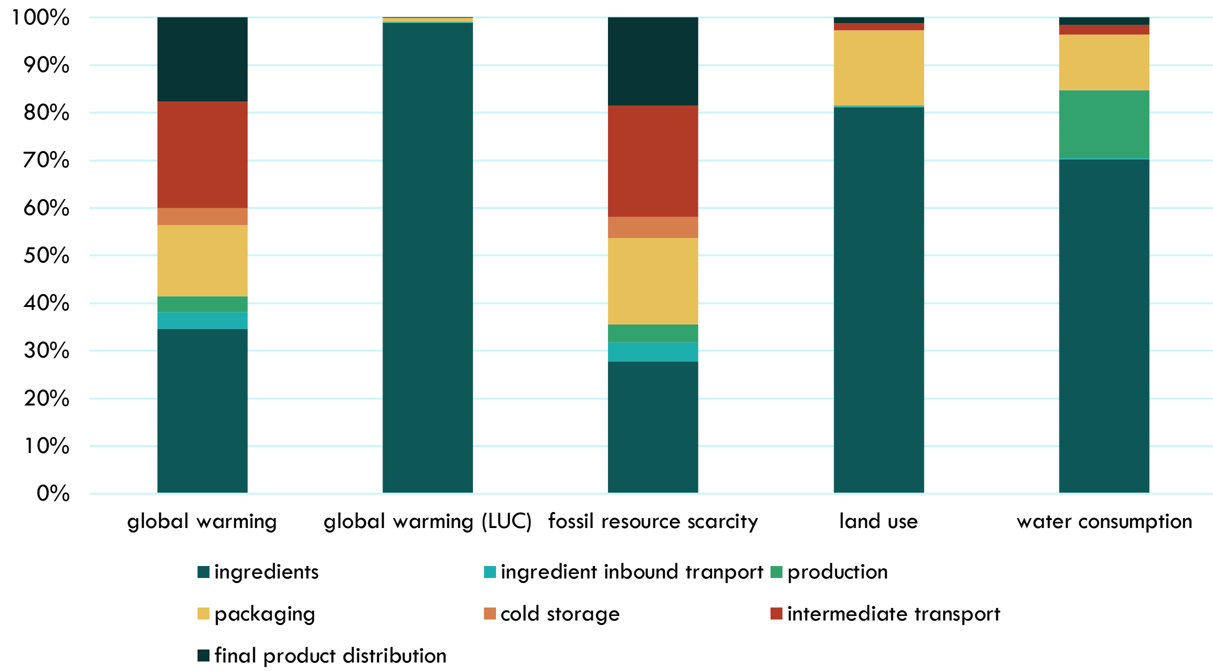

FIGURE 4. DISTRIBUTION OF IMPACTS ACROSS LIFE CYCLE STAGES FOR THE BEYOND BURGER 3.0, USING THE RECIPE LCIA METHOD. LUC = LAND USE CHANGE.

4.1.1.1 Global warming

The global warming (greenhouse gas emissions) associated with producing and delivering a ¼ pound Beyond Burger 3.0 are 0.43 kgCO_2eq/quarter lb Beyond Burger 3.0, plus 0.06 kgCO_2eq/quarter lb from land use change. This equates to 3.75 kg CO_2eq per kg Beyond Burger 3.0 (+0.53 kg CO_2eg per kg from land use change). Table 11 offers additional insight into the important contributors to global warming impact. Global warming due to land use change is attributable primarily to cultivation of pea protein, canola oil and coconut oil (68%, 28%, and 3%, respectively).

Excluding climate-carbon feedback in the impact assessment method as was done in the beef comparison study reduces the global warming impact of a ¼ pound Beyond Burger 3.0 by 0.6% (0.42 kg CO_2eq/quarter lb Beyond Burger 3.0) and does not affect the emissions from land use change. We consider this difference insignificant in the broader context of the LCA and proceed with using the value including climate-carbon feedback as implemented in the ReCiPe impact assessment method.

TABLE 11. PERCENT CONTRIBUTIONS TO GLOBAL WARMING (EXCLUDING LAND USE CHANGE) FROM STAGES AND PROCESSES IN THE BEYOND BURGER 3.0 LIFE CYCLE.

contributor	% contribution
ingredients	**34.6%**
pea protein	11.4%
rice protein	4.3%
natural flavor #2	4.2%
canola oil	3.9%
natural flavor #4	2.0%
dried yeast	2.0%
other	6.8%
ingredient inbound transport	**3.5%**

production	**3.4%**	
pea pre-treatment		2.8%
burger manufacturing		0.5%
packaging	**14.9%**	
tray and lid film		8.2%
cardboard sleeve		2.3%
case		2.2%
other		2.2%
cold storage	**3.6%**	
intermediate cold storage		0.8%
final product cold storage		2.7%
refrigerated transport	**40%**	
intermediate transport		22.4%
final distribution		17.7%

4.1.1.2 Fossil resource scarcity (energy use)

Fossil resource scarcity is an indicator of fossil energy use. As can be seen in Figure 4, distribution across life cycle stages is very similar to global warming. Refrigerated transport (intermediate plus final distribution) represent 42% of fossil resource use. Among ingredients, pea protein is the highest contributor (9% of total), followed by natural flavor #4 and natural flavor #2 (6% and 4%, respectively). Rice protein contributes 3% and canola oil contributes 2.4%. Manufacture of the plastic tray and lid represents 11% of fossil energy use.

4.1.1.3 Land use

The land use indicator within ReCiPe primarily reflects cropping acreage, with characterizations for other land usages including urban, industrial, grasslands, etc. Within the Beyond Burger 3.0 life cycle, land use is dominated by ingredient production (81%) and packaging material production (16%). The top contributors to land use are shown in Table 12.

TABLE 12. TOP CONTRIBUTORS TO LAND USE IN THE BEYOND BURGER 3.0 LIFE CYCLE.

contributor	%
pea protein	43%
canola oil	16%
coconut oil	12%
tertiary case	7%
cocoa butter	7%
pallet	5%
cardboard sleeve	2%

4.1.1.4 Water consumption

The water consumption metric in ReCiPe reflects absolute water consumption (without characterization applied). For Beyond Burger 3.0, it is dominated by ingredient production (70%) with the proxy used to represent natural flavor #2 contributing 20%, rice protein 18%, natural flavor #4 10%, and pea protein 7%. About 10% of water consumption is used directly in the Beyond Burger 3.0 production process, either incorporated into the product or direct use in manufacturing facilities. The remainder of the water consumption associated with production is connected to electricity generation processes. Manufacture of packaging components represents 12% of water consumption, with the thermoformed tray being the largest contributor to this.

4.2 Comparisons with beef

Table 13 provides a direct comparison of the impacts attributable to a ¼ lb. Beyond Burger 3.0 with a ¼ lb. beef patty. Based on the results of this study, ingredient provision, production, packaging and distribution of the Beyond Burger 3.0 generates 90% less greenhouse gas emissions (89% if land use change in the Beyond Burger 3.0 supply chain is included), and requires 37% less fossil resources, 97% less land use, and 97% less water consumption.

TABLE 13. COMPARISON OF CRADLE-TO-DISTRIBUTION IMPACTS OF ¼ LB. BEYOND BURGER 3.0 AND ¼ LB. AVERAGE U.S. BEEF PATTY.

indicator	Unit (per ¼ lb patty)	Beyond Burger 3.0	Beef patty	% reduction (beef→Beyond Burger 3.0)
global warming	kg CO_2 eq	0.43	4.26	90%
global warming (including land use change)	kg CO_2 eq	0.49		89%
fossil resource scarcity	kg oil eq	0.12	0.19	37%
land use	m^2a crop eq	0.53	17.52	97%
water consumption	liters	6.45	219.24	97%

5 Interpretation

5.1 Identification of relevant findings

The Beyond Burger 3.0 LCA demonstrates many relevant findings. Ingredient provision is an important contributor across all impact categories assessed, and ingredients are the dominant contributor to land use and water consumption. Pea protein isolate is the most contributing ingredient, except to water consumption. Refrigerated transport – both of intermediate components and final distribution – contributes 40% of the Beyond Burger 3.0 global warming impact and 42% of fossil resource use.

When compared with a typical US beef patty, the Beyond Burger 3.0 generates 90% less greenhouse gas emissions (89% if land use change in the Beyond Burger 3.0 supply chain is included), and requires 37% less fossil resources, 97% less land use, and 97% less water consumption. While greenhouse gas emissions and fossil resource use are often closely correlated in product life cycles where greenhouse gas emissions are dominated by CO_2 from the combustion of fossil fuels, the beef life cycle has notable contributions from biogenic methane and nitrous oxide. Non-fossil methane from enteric fermentation as well as manure management contributes more than 40% to the beef global warming impact, and nitrous oxide, primarily from field-level emissions during cultivation of feed crops, contributes more than 30% (Putman, Rotz, and Thoma 2023). These factors are the primary reasons why there is less difference in fossil resource scarcity than global warming between Beyond Burger 3.0 and the beef patty. In addition, the Beyond Burger 3.0 plastic packaging is derived from fossil resources, but this fossil carbon is embodied in the plastic (i.e., not released to the atmosphere as with combusted fossil fuels) so contributes less to global warming (note that while packaging end-of-life has not been included in this study, plastics are primarily landfilled or recycled in the US, again avoiding the carbon emissions associated with incineration.)

This study serves as an update to the previous Beyond Burger (v. 1.0) LCA findings, although in many ways, it is more than simply an 'update' as the modeling approach has also evolved due to changes in primary data availability as well as updates in background databases. The main differences in modeling approaches are summarized above in Section 3.2.7. Therefore, comparisons with the previous LCA may offer valuable insights, but require careful interpretation and should not be construed simply as 'better' or 'worse' environmental performance. Refrigerated transport, both in final product distribution, but also intermediary transport stages to cold storage and manufacturing facilities, emerges as an important contributor to global warming and energy use impacts in this study that was less prominent in the Original Beyond Burger 1.0 LCA. This is due to a more dispersed production chain, but also in part to updates in the background data representing this transport. Production shows lower contributions in Beyond Burger 3.0 compared to Original Beyond Burger 1.0 across global warming energy use and water use impacts; this appears to be primarily due to upgraded freezing systems used during the pea-protein pre-treatment. Identifying changes in the impacts from ingredients relative to Original Beyond Burger 1.0 is difficult due to changes in formulation, sourcing and background data (see Table 7). Two unique natural flavor ingredients not present in the Original Beyond Burger 1.0 formulation demonstrate high impacts relative to their concentration in the formulation, but information on their production was also quite limited and therefore these contributions have higher uncertainty.

5.2 Assumptions and limitations

The choice to compare the Beyond Burger 3.0 with beef patties on a weight-based functional unit assumes that the two products provide equivalent functions. As mentioned in Section 2.2.2, since the Beyond Burger 3.0 is designed to mimic the flavor and texture profiles of beef patties, it is reasonable to assume qualitatively that the two products provide similar non-nutritional functions. Meat and meat analogues are commonly considered as dietary protein sources, and this key nutritional component is identical in the two products (see Table 1). The Beyond Burger 3.0 supplies about 18% fewer calories per serving than the 80/20 beef patty, largely due to a lower fat content (36% less fat than 80/20 beef patty), which would be considered a nutritional benefit to many Americans. In addition, saturated fat and cholesterol, which are linked to heart disease, are notably lower in the Beyond Burger 3.0 compared to the beef patty. While numerous nutrient profiling schemes exist that attempt to aggregate nutritional criteria into a composite index, there is little consensus as to the preferred approach or their accuracy (Santos et al. 2021; Cooper, Pelly, and Lowe 2016), and certainly no widely accepted method exists for incorporating such nutrient profiling into LCA (McAuliffe, Takahashi, and Lee 2020). Given the uncertainty introduced by such schemes, therefore, we consider comparison on a weight basis to be a conservative assumption with respect to the comparative assertions in environmental performance made here. In other words, incorporating a more complex nutrient profiling functional unit would most likely further favor the Beyond Burger 3.0 over the beef patty.

The boundary conditions employed in this study follow the products up to the point of delivery to retail distribution centers (or wholesale distributors), and therefore do not include retail and at-home use stages. In addition, the contribution from food waste at the retail and consumer level, as well as potential waste through distribution, are not included. Note, however, that product and packaging losses at the manufacturing stage were included in the Beyond Burger 3.0 life cycle. Excluding the retail and consumer stages is appropriate as there are unlikely to be major absolute differences between Beyond Burger 3.0 and beef patties through these stages. Beyond Burger 3.0 is distributed frozen, but is typically displayed in retail alongside fresh meat in a refrigerated counter. Cooking is similar to that of a beef patty. Waste rates are extremely difficult to estimate, but there is no indication that significant differences would exist between the two products. If anything, because the Beyond Burger 3.0 is distributed and stored frozen, there may be reduced retail-level waste compared to beef patties. Excluding the retail and consumption stages, however, can affect the relative differences between the products, as these stages would represent a larger percentage of the Beyond Burger 3.0 life cycle than the beef patty life cycle.

In the absence of specific data for North American distribution of beef patties, we have assumed the same distribution impacts for beef as the Beyond Burger 3.0. This may be an overestimate, as beef processing is likely more distributed across the US leading to a lower mean transportation distance to retail; still, the contribution from distribution is minor relative to overall life cycle impacts, and this assumption does not affect the overall conclusions of the study.

In alignment with the FAO Livestock Environmental Assessment and Performance Partnership (LEAP) guidelines (FAO LEAP 2016), the beef LCA considered all products edible by humans to receive equivalent environmental footprints. In other words, while the data used to represent the beef patty in this comparison does include some contribution from processing and packaging that is specific to ground beef, there is no differentiation between 'cuts' or quality grades of the harvested, human-edible beef; ground beef receives the same share of the impacts associated with raising and producing beef as does a high-end steak. While this is common practice in LCA, it is nonetheless an important assumption to appreciate when interpreting results.

The beef LCA excludes emissions associated with land use change. In addition, climate carbon feedback is excluded from the global warming potentials used to characterize the beef carbon footprint. While exclusion of climate carbon feedback has a small influence on the Beyond Burger 3.0 results, it will likely have a larger impact on beef results due to the large contribution from methane emissions within the beef production system. These limitations suggest that the beef environmental impacts may be an underestimate (i.e., a conservative comparison).

As with any LCA, the life cycle impact assessment results presented here are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks.

Additional limitations of Beyond Burger 3.0 LCA include the following:

- Life cycle assessment data provided by a pea protein isolate supplier were deemed incompatible with this study and generic pea protein isolate data from the Agri-footprint database, adapted for pea country of origin, were used instead.
- Electricity, natural gas and consumable inputs to the pea protein pre-treatment were derived from facility-level utility data and allocated to outputs from that facility by Beyond Meat based on production rates (mass allocation). Underlying data and the exact method of allocation were not made available and therefore calculations could not be corroborated.
- Electricity demand at co-manufacturers (manufacturing and packaging of Beyond Burger 3.0) was based on six months of facility-level utility records *at one co-manufacturer location* divided by the total product output over that period. Data were not available for other co-manufacturer locations and it was assumed that this electricity intensity (kWh / lb. Beyond Burger 3.0 produced) was applicable to other locations.
- Cold storage energy demand was estimated based on facility-level data provided by one warehouse and distributed across the 'total pallet positions' at this warehouse. This energy intensity was assumed applicable to all cold storage warehousing in the Beyond Burger 3.0 life cycle. Specific energy consumption reported in the literature shows wide variability. Data quality could be improved by gathering additional information from other warehouse partners.
- Minimal information was available on the composition and production methods for some minor ingredients, and these ingredients were represented in the LCA model by fairly coarse proxies. Based on these estimates, most contributions to system impacts of these minor ingredients are negligible. The exceptions are the proxies used for natural flavor #2 and #4 (both proxied with an average of amino acids), which demonstrate notable contributions across impact categories despite low concentrations in the Beyond Burger 3.0 formulation. Additional specification or data on production were not available for these ingredients; further investigation into their production is recommended in order to improve the reliability.

5.3 Sensitivity analyses

Sensitivity analyses can aid in resolving concerns regarding (for example) data quality, estimation or modeling approaches and modeling or methodological assumptions, by demonstrating the influence on environmental performance of perturbations in parameter values or model choices/assumptions.

5.3.1 Parameter sensitivity

This section considers a number of foreground parameters that are either based on limited data or could be expected to change through fairly routine business operations changes. Table 14 summarizes the effect on the Beyond Burger 3.0 environmental performance due to a *20% increase* in a number of parameters. Note that these effects are linear (tested by considering greater increases and decreases), meaning that a 60% increase in the noted parameter will result in three times the reported change in impact indicator, and a 20% decrease would result in the reported decrease. For reference, Table 14 also includes the baseline value for each parameter.

This analysis demonstrates that, for most parameters considered, a 20% increase would have less than a 1% effect on the final environmental performance results. Thus, while the electrical energy required to process the Beyond Burger 3.0 at co-manufacturing sites was based on an energy intensity from one location, we can expect even rather large deviations in this energy demand to have a minor influence on the environmental footprints. Similarly, the energy use intensity of cold storage was based on limited primary data from one site. Given the wide range of energy use intensity seen in cold storage facilities (standard deviations as high as 60%), this *could* introduce an uncertainty of 2-

3% to the Beyond Burger 3.0 carbon footprint and energy use footprint. The time that both WIP and the finished product spend in cold storage is likely to vary as inventory fluctuates; however, this analysis suggests that a 20% change from storage time estimated in the baseline will have less than 0.75% influence across all four indicators. Footprints are also only mildly sensitive to the distance that WIP travel to storage.

Transport distances of the finished product are the exception here, with 20% increases in distance to both cold storage and from cold storage to final customer (distribution) increasing global warming and fossil energy use by nearly 4%. These distances are weighted averages across multiple locations, and represent full national logistics. Reducing these average distances through shifts in co-manufacturing locations and improved logistics efficiencies *should* result in decreases to the carbon footprint, although other effects such as changes in electrical grid and inbound ingredient transport would also need to be considered.

TABLE 14. SENSITIVITY ANALYSIS CONSIDERING A 20% INCREASE IN VARIOUS MODEL PARAMETERS.

Influence of 20% increase in…	Global warming	Fossil resource scarcity	Land use	Water consumption	(Baseline value)
Beyond Burger 3.0 manufacturing energy use	0.10%	0.13%	0.01%	0.81%	0.06 kWh/lb patty
Finished product distance to cold storage	3.61%	3.89%	0.24%	0.31%	1338 miles
Finished product cold storage time	0.56%	0.73%	0.02%	0.01%	50 days
finished product distribution distance	3.61%	3.90%	0.24%	0.31%	1342 miles
WIP* distance to storage	0.14%	0.15%	0.01%	0.01%	231 miles
WIP* frozen storage time	0.17%	0.21%	0.00%	0.00%	35 days
cold storage energy use	0.72%	0.92%	0.02%	0.01%	0.65 kWh/pallet/day

*WIP = Work in Progress, and includes both pre-treated pea protein and another pre-assembled ingredient mix with intermediate shipping and storage.

5.3.2 Pea country of origin

Pea protein is the largest single contributor to the Beyond Burger 3.0 carbon footprint, fossil energy use, and land use. In the baseline model, half of the pea protein isolate (PPI) comes from China (but with peas cultivated in Canada), 40% from Canada, and 10% from France. In other words, 90% of the peas used to produce the PPI used in the Beyond Burger 3.0 (over the time window of this study) are grown in Canada.

Here, we consider extremes in these PPI sourcing percentages in order to demonstrate the influence of pea cultivation country of origin on Beyond Burger 3.0 environmental performance. Note that in these scenarios, the PPI processing remains the same (aside from electricity grid used); only the pea cultivation processes (based on Agri-Footprint datasets) and transport distances change.

TABLE 15. INFLUENCE OF PEA PROTEIN ISOLATE (PPI) SOURCING ON THE BEYOND BURGER 3.0 ENVIRONMENTAL PERFORMANCE

scenario	*percent change from baseline values*					
	Global warming	Global warming (LUC)	Global warming (total)	Fossil resource scarcity	Land use	Water consumption
All PPI from Canada	-2.8%	7.7%	-1.5%	-2.4%	1.3%	-0.5%
All PPI from France	-2.8%	-67.9%	-10.9%	-1.9%	-12.4%	18.4%
All PPI from China (Canada grown peas)	2.8%	7.4%	3.4%	2.3%	1.5%	-4.1%
Same sourcing as baseline, but assuming China PPI uses US grown peas	1.5%	-33.6%	-2.8%	1.1%	4.4%	21.9%

Table 15 demonstrates that extreme changes in PPI sourcing can have a notable influence on the overall environmental performance of the Beyond Burger 3.0. These are most prominent in land use change (LUC) emissions, direct land use (occupation), and water consumption. According to the LUC model implemented in Agri-footprint, Canadian grown peas have the greatest emission contribution from LUC among the regions analyzed here; therefore, shifts away from Canada grown peas reduce these emissions. However, since LUC is only 12.4% of the total global warming impact in the baseline, the effects are tempered somewhat when considering total global warming impact. The yield of peas grown in France is considerably higher than in Canada or the US, therefore leading to reduction in land use when shifting to PPI from France. Canada grown peas require no irrigation (according to the Agri-footprint dataset) whereas France and US require some irrigation; therefore shifts away from Canada grown peas increase water consumption. In the absence of additional information from the Chinese supplier, we assumed in the baseline that China supplied PPI utilized peas imported from Canada. Assuming instead that these peas are imported from the US leads to significant changes in Beyond Burger 3.0 impacts, especially water consumption. However, given the low water consumption in the Beyond Burger 3.0 baseline relative to beef, this does not affect the conclusions of this study.

5.3.3 Natural flavor proxies

Two natural flavor components (natural flavor #2 and #4) present in the Beyond Burger 3.0 recipe in relatively small quantities nonetheless have notable contributions to the overall LCA results. Little information was available from the supplier of natural flavor #2, other than it is prepared from the microbiological fermentation of plant-based source material. Thus, a conservative proxy assignment of an average of the five amino acids available in the Agri-footprint database – which are commonly produced via fermentation – was made. Natural flavor #4 was known to be an amino acid, but no direct match was available in accessible LCA databases, so the same amino acid average was used as a proxy. However, there is notable variance in impact values across the amino acids contained in the average: the coefficient of variation for global warming, land use, fossil resource use, and water consumption is 81%, 124%, 75%, and 81%, respectively. To provide indication of the sensitivity of the Beyond Burger 3.0 LCA results to these proxy assignments, we consider scenarios in which the lowest and highest carbon footprint amino acid is assigned as the proxy for both natural flavor #2 and #4, instead of the average. Table 16 summarizes the outcome of these sensitivity scenarios, and demonstrates that variance seen among amino acids in the average can have a sizable effect on the overall Beyond Burger 3.0 LCA results, especially for global warming and water consumption. Still, such variance is not large enough to change the overall conclusions of this study.

TABLE 16. CHANGE IN THE BEYOND BURGER 3.0 IMPACT ASSESSMENT RESULTS DUE TO CHANGING NATURAL FLAVOR #2 & #4 PROXY ASSIGNMENTS TO THE LOWEST OR HIGHEST CARBON FOOTPRINT (CF) AMINO ACID CONTAINED WITHIN THE BASELINE AVERAGE.

Indicator	% change from baseline values	
	Lowest CF amino acid	Highest CF amino acid
Global warming	-4%	+10%
Fossil resource scarcity	-2%	+9%
Land use	0%	0%
Water consumption	-13%	+48%

It is worth noting that availability of LCA data on amino acid production is limited, and as can be seen here, there is considerable variance in the impacts of production. This can be seen even between different datasets (different studies) for the same amino acid. Further accumulation and refinement of LCA data in the future could improve this variance, but it may also be that production methods and yields differ enough from one producer to another that such variance is characteristic for these purified amino acid products.

5.3.4 PET tray post-consumer recycled content

The baseline PET tray is modeled with 60.6% of the required resin weight recycled post-consumer. The remaining is post-industrial (pre-consumer) recycled, and conservatively modeled as virgin PET. Here, we consider the influence on Beyond Burger 3.0 environmental performance of varying these ratios at the extreme.

Table 17 demonstrates that the recycled content in the PET tray has a small but still noticeable effect on the Beyond Burger 3.0 environmental performance. Because virgin PET is derived from fossil resources, this indicator is most strongly influenced. These results also demonstrate the benefits of the current post-consumer content of the PET tray: without this recycled content, the carbon footprint (global warming impact) of Beyond Burger 3.0 would increase 3%, and fossil resource scarcity would increase 8%.

TABLE 17. SENSITIVITY ANALYSIS DEMONSTRATING THE EFFECT ON BEYOND BURGER 3.0 IMPACT ASSESSMENT RESULTS DUE TO CHANGES IN THE POST-CONSUMER RECYCLED CONTENT OF THE PET TRAY.

	Percent change from baseline	
	100% post-consumer	100% virgin
Global warming	-2%	3%
Fossil resource scarcity	-5%	8%
Land use	0%	0%
Water consumption	-2%	4%

5.4 Data quality assessment

As described in Section 2.6, data quality of primary data was qualitatively assessed using SimaPro's pedigree uncertainty calculator. These data quality ratings are reported in Appendix II. Overall, the foreground data quality for the Beyond Burger 3.0 LCA was very good as most primary data were based on measurements or records from Beyond Meat, and were temporally and geographically relevant. As described in limitations, proxy assignments were required for some minor ingredients, and these data are considered of lower quality.

No formal data quality evaluation was provided in the study used for the beef comparison. The authors acknowledge some limitations on data availability and a lack of detailed knowledge on the movement of beef animals during the life cycle (Putman, Rotz, and Thoma 2023). These were primarily considered as limitations in establishing representative supply chains at the *regional level*, and the aggregated national data were believed to provide a full accounting of the US beef industry.

5.5 Uncertainty analyses

A Monte Carlo uncertainty analysis was performed in SimaPro utilizing 500 iterations. Uncertainty distributions in background datasets were not modified and therefore rely on distributions reported by database developers. Foreground (primary inventory) data were assigned uncertainty distributions using the SimaPro pedigree uncertainty calculator tool, as described in Section 2.6 and reported in Appendix II. Overall, SimaPro indicated that 51% of values contained within the Beyond Burger 3.0 life cycle model contain uncertainty.

Table 18 provides the outcome of the Monte Carlo analysis, and suggests relatively small uncertainty within the Beyond Burger 3.0 life cycle model. The 95% confidence interval indicates that 95% of the results of the Monte Carlo iterations were within this range. It is important to note that this uncertainty estimate is dependent on the uncertainty distributions within the database and those estimated using the Pedigree approach (which is a fairly subjective and imprecise method). Still, this analysis suggests minimal uncertainty in the reported environmental performance values.

Uncertainty was not reported in the study used for the beef comparison, and because we do not possess that life cycle model, a paired Monte Carlo analysis was not possible.

TABLE 18. SUMMARY OF THE BEYOND BURGER 3.0 LCA UNCERTAINTY ANALYSIS

Indicator	**Unit (per ¼ lb patty)**	**Baseline**	**Coefficient of variation**	95% confidence interval	
Global warming	kg CO_2 eq	0.425	1.06%	0.418	0.435
Global warming (LUC)	kg CO_2 eq	0.060	1.35%	0.059	0.062

Fossil resource scarcity	kg oil eq	0.121	1.10%	0.119	0.125
Land use	m^2a crop eq	0.527	0.91%	0.518	0.537
Water consumption	liters	6.448	4.85%	5.93	7.20

5.6 Completeness and consistency check

The tables below provide a check on data completeness (Table 19) and consistency of the study (Table 20). The objective of the completeness check is to demonstrate that all relevant information and data needed for the interpretation are available and complete.

TABLE 19. COMPLETENESS CHECK

	Complete?	Included	Excluded
Beyond Burger 3.0			
Ingredient agricultural cultivation	Yes	• Upstream extraction and production of cultivation inputs • Direct emissions (e.g., N2O) • LUC emissions	n/a
Ingredient processing	Yes	• All material, water and energy inputs • Co-products and waste streams are considered	• Capital goods
Transport	Yes	• Mode of transport, transport distances	• Capital goods
Production step 1: pea pre-processing; WIP assembly	Yes	• All material and energy inputs • All water consumption (in recipe and for cleaning)	• Capital goods
WIP transport and storage	Yes	• Mode of transport, transport distance, cold chain • Energy consumption in cold storage	• Capital goods • Refrigerant emissions
Production step 2: patty manufacture	Yes	• All material and energy inputs • All water consumption (in recipe and for cleaning) • Manufacturing losses	• Capital goods
Packaging	Yes	• Packaging raw materials type and mass • Energy for forming packaging materials • Transport of packaging material • Recycled content of packaging material	• Capital goods
Finished product transport and storage		• Mode of transport, transport distance, cold chain • Energy consumption in cold storage	• Capital goods • Refrigerant emissions
Distribution	Yes	• Mode of transport, transport distance, cold chain	• Capital goods
Beef patty			
Feed cultivation	Yes	• Cultivation data for US feeds generated using IFSM • Upstream extraction and production of cultivation inputs • Direct emissions (e.g., N2O)	• Capital goods • Land use change
Feed processing	Yes	• All material (feed crops and other ingredients) and energy inputs for compound feed processing	• Capital goods
Transport	Yes	• Mode and load of transport, transport distances	• Capital goods • Movement of animals within production stage
beef and dairy farms	Yes	• Feed ration per animal type • Vitamins, minerals, feed additives • Housing system (energy, material and water inputs) • Manure management emissions • Emissions from enteric fermentation	• Capital goods
Harvest and processing	Yes	• Energy and material inputs for slaughter and meat processing • revenue for economic allocation at slaughter	• Capital goods
Packaging	Yes	• Packaging raw materials type and mass	• Capital goods
Distribution	Yes	• Assumed same as Beyond Burger 3.0	• Capital goods

The objective of the consistency check is to demonstrate whether the assumptions, methods and data are consistent with the goal and scope and between product systems.

TABLE 20. CONSISTENCY CHECK

Criteria	Beyond Burger 3.0	Beef patty
Data quality:	Very good	Good (sufficient for benchmarking national average production)
Geographical representativeness:	North American manufacturing and distribution	Benchmark for US beef industry
Temporal representativeness:	First half of 2022	circa 2017 (most recent and representative data available)
Allocation rules:	Economic allocation in background data; economic allocation at facility level	Economic allocation at harvest/slaughter; biophysical (metabolizable energy) allocation applied at dairy farms (per international guidelines)
System boundaries:	Cradle to distribution, including ingredient cultivation and processing, inbound transport, pre-processing, WIP transport and storage, manufacturing, packaging, final product transport and storage, distribution	Original study cradle to grave; adapted to cradle to distribution boundary with data from study author. Includes feed production, various beef operation stages, dairy operations (cull animals), transport, harvest, processing, packaging, distribution
Impact assessment methodology:	ReCiPe 2016 midpoint hierarchical	ReCiPe 2016 midpoint hierarchical (adapted to use GWP100 characterization factors without climate-carbon feedback)

6 Conclusions and recommendations

Beyond Meat's Beyond Burger 3.0 has evolved both in formulation and in its supply and production chain since initially examined by the life cycle assessment published in 2018. This study serves as an update to the 2018 LCA findings, although in many ways, it is more than simply an 'update' as the modeling approach has also evolved due to changes in the primary data available as well as changes in the underlying background databases. The main differences in modeling approaches are summarized above in Section 3.2.7. Therefore, comparisons with the 2018 LCA may offer valuable insights, but require careful interpretation and should not be construed simply as 'better' or 'worse' environmental performance.

The Beyond Burger 3.0 LCA reported here focuses on four impact indicators: global warming, fossil resource use, land use, and water consumption. Ingredient provision is an important contributor across all impact categories assessed, and ingredients are the dominant contributor to land use and water consumption. Pea protein isolate is the most contributing ingredient, except for water consumption. Refrigerated transport – both of intermediate components and final distribution – contributes 40% of the Beyond Burger 3.0 global warming impact and 42% of fossil resource use.

The Beyond Burger 3.0 LCA was compared with impacts associated with an average U.S. beef patty, based on a 2023 published study that serves as a current benchmark for the U.S. beef industry. The relative impacts (normalized such that Beyond Burger 3.0 = 1 for each impact category) between a Beyond Burger 3.0 and beef patty are shown in Figure 5. The resulting comparative statement from this study is as follows:

Based on a comparative assessment of the Beyond Burger 3.0 production system with a beef patty based on the 2023 beef LCA by Putman et al, the Beyond Burger 3.0 generates 90% less greenhouse gas emissions, and requires 37% less fossil resources, 97% less land use, and 97% less water consumption.

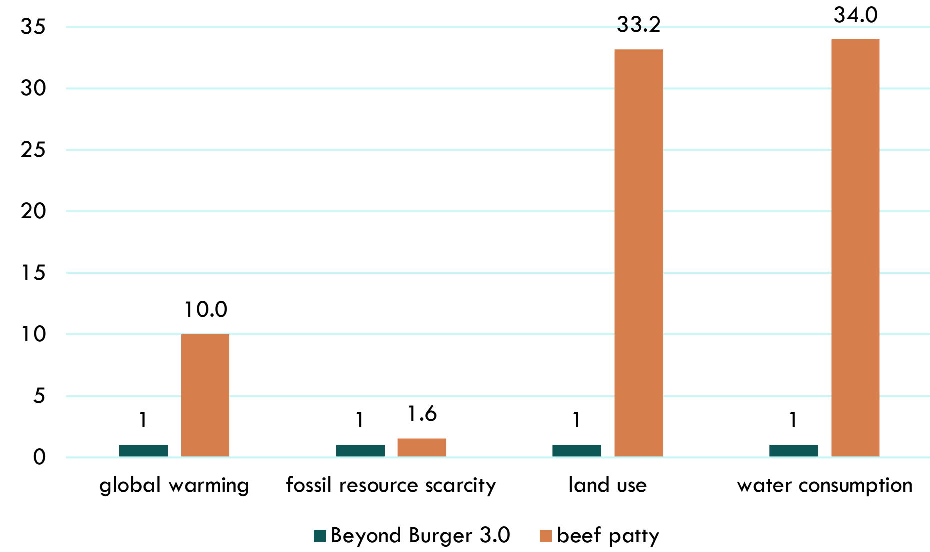

FIGURE 5. RELATIVE COMPARISON BETWEEN BEYOND BURGER 3.0 AND BEEF PATTY ACROSS FOUR IMPACT CATEGORIES. VALUES NORMALIZED SO THAT BEYOND BURGER 3.0 = 1 FOR EACH CATEGORY.

While uncertainty and sensitivity analysis suggest that the absolute values of these comparative numbers may vary somewhat, there is no indication that a situation or condition may arise in which the environmental performance, as indicated by the categories considered here, of the Beyond Burger 3.0 would be worse than that of a beef patty.

It is recommended that communication of the relative environmental benefits of Beyond Burger 3.0 over beef shall occur with acknowledgement of the specific environmental metrics used and the limitations and uncertainties present in this study. Additional recommendations that will support future LCA work include integrating LCA relevant data collection (material and energy inputs relative to product outputs) into routine business accounting and further engaging suppliers to provide LCA-based environmental impact data on the manufacture of their products.

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Appendix I Results based on impact assessment methods from Original Beyond Burger 1.0 LCA

To provide compatibility with the initial 2018 LCA, results are also presented using the impact assessment methods used there. These were selected to coordinate with the assessment methods used in the beef comparison as follows (with brief description of the method):

- GHGE: IPCC 2007 100a (IPCC 2007)
- Energy use: Cumulative energy demand (Frischknecht et al. 2007)

  Results reported are the sum of non-renewable fossil, nuclear and biomass energy as well as renewable biomass, wind, solar, geothermal and water energy. Gross calorific energy content of biomass materials (e.g., corrugated cardboard) has been excluded from the renewable biomass and reported cumulative energy demand. Energy values are based on higher heating value (HHV).

- Water use impact: (Pfister, Koehler, and Hellweg 2009)

  In this method, consumptive water use – the amount of water used that is not eventually returned to the system – is multiplied by a water scarcity indicator based on the ratio of withdrawn water to available water in a given region. The scarcity indicator is country specific. Water flows present in the life cycle inventory that were not present in the default method were added for completeness. Note that the AWARE water scarcity method is now preferred over this method within the LCA community.

- Land use impact: Ecosystem Damage Potential (Koellner and Scholz 2007)

This impact assessment method depends on the area and duration of occupation for specified land-cover types in order to calculate the total ecosystem damage. The amount of occupied land of a specific type and the length of time of the occupation is multiplied by a characterization factor between negative one (indicating a positive contribution to the ecosystem) and one, specific to each land-cover type. The result is a land use impact that is smaller than the total land area occupied, so it is important to note that these values are not simply the land use inventory, and do not include land transformation impacts. Land occupation flows present in the life cycle inventory that were not present in the default method were added for completeness.

Life Cycle Impact Assessment Results using methods compatible with the Original Beyond Burger 1.0 LCA

A different collection of impact assessment methods were used to evaluate environmental impact in the Original Beyond Burger 1.0 LCA (Heller and Keoleian 2018), primarily to allow compatibility with a published beef LCA used as a comparison. To support compatibility with the previous study, results using the same impact methods are presented here.

Table 15 summarizes the LCA results using these compatible methods. In addition to the characterized land and water use, absolute values (based on the life cycle inventory land occupation and water consumption balance) are provided. Note that the global warming method used in the previous study *includes* impacts of land use change. Results excluding LUC are provided in Table 15 to demonstrate alignment with the results from ReCiPe (Table 6) which uses updated (IPCC 2013) emission factors. However, it is recommended that the global warming values including LUC are used in comparisons Original Beyond Burger 1.0.

TABLE 21. CRADLE TO DISTRIBUTION LCA RESULTS FOR ¼ LB. BEYOND BURGER 3.0, USING THE IMPACT ASSESSMENT METHODS FROM THE ORIGINAL BEYOND BURGER 1.0 LCA STUDY.

indicator	Unit (per ¼ lb patty)	TOTAL	ingredients	ingredient inbound transport	production	packaging	cold storage	intermediate transport	final product distribution
Global warming	kg CO_2 eq	0.48	0.20	0.01	0.01	0.06	0.01	0.09	0.07
Global warming (excluding LUC)	kg CO_2 eq	0.42	0.14	0.01	0.01	0.06	0.01	0.09	0.07
Cumulative energy demand	MJ	6.16	1.83	0.23	0.29	1.16	0.26	1.34	1.05
characterized land use	m^2a-eq.	0.35	0.28	0.00	0.00	0.06	0.00	0.00	0.00
Absolute land use	m^2a	0.67	0.48	0.00	0.00	0.17	0.00	0.01	0.01
characterized water use	liter eq.	2.11	1.56	0.01	0.07	0.38	0.00	0.05	0.04
Absolute water use	liters	6.94	5.19	0.02	0.91	0.60	0.00	0.13	0.10

Appendix II Data quality and uncertainty (pedigree matrix evaluation)

The following table summarizes the data quality values used within SimaPro's pedigree uncertainty calculator in order to establish uncertainty distributions for primary data. See Section 2.6 and Table 2 for data quality matrix and definitions of pedigree values.

ingredient/process	modeled as	data quality (pedigree values)	SD^2	uncertainty applied to:
pea protein isolate	pea protein isolate	1,1,1,1,1	1.05	quantity in extrudate
coconut oil	coconut oil	1,1,1,1,1	1.05	quantity used
canola oil	rapeseed oil	3,1,1,4,4	1.53	quantity
sunflower oil	sunflower oil	3,1,1,4,4	1.53	quantity
rice protein	rice protein	1,1,1,1,1	1.05	quantity in extrudate
rice protein (production process)	from supplier	1,1,2,1,1	1.06	each flow included in process
dried yeast	yeast (RIVM)	1,1,1,3,4	1.51	quantity in recipe ingredient
methylcellulose	carboxymethyl cellulose powder	1,1,1,1,1	1.05	quantity in recipe ingredient
natural flavor #1	impact data from previous LCA (Heller and Keoleian, 2018)	3,4,1,2,4	1.54	each flow (water and CO2 emissions)
natural flavor #2	average of amino acids	3,1,1,3,4	1.52	quantity of amino acid
natural flavor #3	refined sunflower oil, refined rapeseed oil	3,1,1,4,4	1.53	each component
cocoa butter	cocoa butter (RIVM)	1,1,1,3,1	1.05	steam and electricity inputs
potato starch	potato starch	1,1,1,1,1	1.05	quantity used
natural flavor #4	average of amino acids	3,1,1,3,4	1.52	quantity used
sodium chloride	ecoinvent dataset	1,1,1,1,1	1.05	quantity in salt mix
potassium chloride	AFP5 dataset	1,1,1,1,1	1.05	quantity in salt mix
apple extract	apple concentrate (RIVM)	2,2,2,3,4	1.51	fresh apple input
vinegar	vinegar (RIVM)	2,1,2,3,4	1.51	quantity in recipe ingredient
lemon juice concentrate	lemon juice conc (RIVM)	1,1,2,3,4	1.51	quantity in recipe ingredient
beet juice extract	modeled as in Heller & Keoleian 2018	1,1,2,3,4	1.51	carrots and turnips input
		3,1,2,3,4	1.52	evaporation of milk
sunflower lecithin	byproduct of sunflower oil refining	2,1,1,1,4	1.51	each of four components in average
calcium chloride	calcium chloride	1,1,1,1,1	1.05	quantity in recipe ingredient
sodium bicarbonate		1,1,1,1,1	1.05	quantity in extrudate
water		1,1,1,1,1	1.05	quantity in extrudate
hydration WIP	numerous components (listed elsewhere)	1,1,1,1,1	1.05	each component
Marin paste	numerous components (listed elsewhere)	1,1,1,1,1	1.05	each component

fat blend	numerous components (listed elsewhere)	1,1,1,2,2	1.07	each component
liquid nitrogen	liquid nitrogen	1,1,1,1,1	1.05	quantity in extrudate
patty paper	tissue paper, paraffin	1,1,1,1,4	1.5	each component
octobin, liner, cover	materials required	3,1,1,1,2	1.12	each material component of bin
WIP packaging	extruded LLDPE	1,1,1,1,1	1.05	quantity used
pallet wrap film	extruded LLDPE	2,1,1,1,1	1.07	quantity used
cardboard sleeve	folding boxboard, printing ink	1,1,1,1,1	1.05	quantity used

Appendix III Review Statement

Critical Review of the Study "Beyond Burger 3.0 Life Cycle Assessment":

Commissioned by:	Beyond Meat, El Segundo, CA
Performed by:	Martin Heller, Blonk Consultants, Gouda, NL Iana Salim, Blonk Consultants, Gouda, NL
Critical Review Panel[1]:	Roland Geyer, Professor, UC Santa Barbara, CA (Chair) Alissa Kendall, Professor, UC Davis, CA Jasmina Burek, Professor, University of Massachusetts, Lowell, MA
Draft Date:	18 October 2023
Reference	ISO 14044: 2006. Environmental Management - Life Cycle Assessment – Requirements and Guidelines ISO/TS 14071: 2014. Environmental management — Life cycle assessment — Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006

The Scope of the Critical Review

The review panel had the task to assess whether

- the methods used to carry out the LCA are consistent with ISO 14044:2006 and ISO/TS 14071: 2014
- the methods used to carry out the LCA are scientifically and technically valid,
- the data used are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations identified and the goal of the study, and
- the study report is transparent and consistent.

The review was performed according to ISO 14044 and ISO/TS 14071 in their strictest sense as the results of the study are intended to be used for comparative assertions to be disclosed to the public.

The extent to which the unit process data are appropriate and representative, given the goal and scope of the study, was determined by a critical review of the available metadata, i.e. process descriptions, etc. Analysis and validation of the process inputs and outputs themselves was outside the scope of this review.

General evaluation

The defined scope for this LCA study was found to be appropriate to achieve the defined goals. The Life Cycle Inventory models are suitable for the purpose of the study and are thus capable to support the goal of the study. All primary and secondary data are adequate

[1] While the professional affiliations of the peer reviewers have been provided, their effort was personally compensated. Thus, their reviews do not represent any endorsements by their Universities.

in terms of quality, and technological, geographical and temporal coverage. The data quality is found to be mostly high for the most important processes and at least adequate for all others. Study results are reported using two impact categories and two inventory-level indicators. This selection was found to be appropriate and reasonable in relation to the goal of the study, which includes comparative assessment relative to previous studies with limited use of impact categories. As a result, the report is deemed to be representative and complete. The study is reported in a transparent manner. Various assumptions were addressed by uncertainty and sensitivity analyses of critical data and methodological choices. The interpretations of the results reflect the identified limitations of the study (and past literature) and are considered to be conservative.

The critical review process was open and constructive. The LCA commissioner and practitioner were cooperative and forthcoming and addressed all questions, comments, and requests of the review panel to its full satisfaction.

This Review Statement summarizes the review process and its outcome. The review process is documented in the Review Report, which is available as a separate document and contains all reviewer comments and practitioner responses.

Conclusion

The study has been carried out in compliance with ISO 14044 and ISO/TS 14071. The critical review panel found the overall quality of the report high, its methods scientifically and technically valid, and the used data appropriate and reasonable. The study report is transparent and consistent, and the interpretation of the results reflects the goal and the identified limitations of the study.

Roland Geyer   Alissa Kendall   Jasmina Burek

Blonk
CONSULTANTS

Groen van Prinsterersingel 45

2805 TD Gouda, The Netherlands

www.blonksustainability.nl