Title:	A Comparative Life Cycle Assessment of Pork Meat and Non-Meat Alternative Patties **(NPB #19-226)**
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Industry Summary: The purpose of the industry summary is to provide producers with a quick reference to research results supported by Checkoff dollars. This summary is intended for non-technical audiences.

Increasing awareness of environmental issues related to food production, distribution, and consumption has led to studies focused on understanding the connection between nutritionally sound consumption and potential environmental impacts. Continued profitability of the swine production sector depends upon producers understanding how consumers may consider sustainability and nutrition when purchasing, preparing, and consuming pork. The main objective of this project is to perform a scan-level life cycle assessment (LCA) of greenhouse gas emissions (GHGEs), energy use, water use, and land use of pork products compared to recently emerging alternative meatless patties: Beyond Burger (BB), Impossible Burger (IB) and Veggie Burger (VB).

A review of the literature and industry reports has been performed to identify relevant lifecycle inventory information for environmental impacts and nutritional considerations. The literature review focused on life cycle inventories for typical ingredients and nutritional characteristics to calculate their nutrient density (Nutrient-rich Foods Indices, NRF9.3 and NRF15.3). The primary audience for this LCA is the pork industry (growers, processors, packaging companies and retailers). This LCA is a field-to-fork (or cradle-to-grave) assessment of the production, distribution, and consumption of pork meat and non-meat alternatives consumed in the U.S. Consideration was given to differential rates of cooking loss and other losses in the supply chain for each of the products.

These research results were submitted in fulfillment of checkoff-funded research projects. This report is published directly as submitted by the project's principal investigator. This report has not been peer-reviewed.

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The environmental indicators are greenhouse gas emissions (GHGEs; also referred to as the "carbon footprint" or global warming potential), cumulative energy demand (energy use), water use, and land use. The functional unit for the LCA is defined as consumption of 1 kg of each of the products. The system boundaries began with the production of raw materials, and end with purchase, preparation, consumption, and disposal of packaging and wasted food in a typical U.S. household. Environmental impacts embodied in the foreground infrastructure (buildings and equipment) are not included in the analysis; however, background processes such as electricity generation do include an accounting of infrastructure from the ecoinvent database. Where data are incomplete, proxy lifecycle inventory datasets were identified from databases available in SimaPro© 9. In determining whether to include specific inputs, a cut off criterion is established using a 1% cut off threshold of any input; however, if data were readily available, they were included. Where allocation of inputs is required, the allocation procedures follow the ISO 14044 hierarchy.

Global warming potential was evaluated using the IPCC 2013 (IPCC, 2017), which contains the climate change factors with a timeframe of 100 years. IMPACT World+ midpoint method (IMPACT World+, 2017) was used for energy and land use, and the ReCiPe 2016 (H) method was used for water use (Huijbregts et al., 2016). SimaPro© 9 was used to create computational impact assessment models. Monte Carlo Simulation (MCS) was conducted to quantify and characterize the effect of uncertainty of input data on the calculated impact estimates.

Differences in environmental impacts were observed between compared products. Pork consumption has the highest relative impacts in all categories. Feed production for swine at the farm was responsible for a significant fraction of impacts. For meatless alternatives, production of ingredients was the largest contributor to most of the impact categories. Unlike other plant-based patties, IB consumption had high intensity of energy demand, especially electricity consumption, during manufacturing stage for the processes of imitating meat-like taste. One somewhat noticeable result of this analysis is that the contribution at processing and packaging is relatively low and that retail refrigeration and energy use for in-home cooking are substantial contributors to the overall environmental impacts.

The nutrient profiles were constructed by accounting for the inclusion of 9 or 15 nutrients to be encouraged and 3 nutrients (saturated fat, added sugar, and salt) to be discouraged in diets. While pork had the highest environmental impacts, it was the second most nutrient dense option. According to the 9-nutrient profile, VB was most nutrient dense, while pork products were similar to IB and more nutrient dense than BB. This is primarily driven by the lower saturated fat content of IB. When B vitamins and Zinc were considered for the 15-nutrient profile, IB was the most nutrient dense, followed by pork, VB, and BB. The high nutrient density of IB was due to greater vitamin and mineral content. The greater amount of vitamin contents in pork products explain the conflicting results and highlights the importance of addressing micronutrient contributions in nutritional assessment. This study underlines the importance of understanding environmental impacts in complete lifecycle supply chain of products. At the same time, it is important to address different aspects of nutritional quality in pork and non-meat alternatives. This initial evaluation of nutrient quality in the context of environmental sustainability highlights the need for further research at the intersection of dietary health and environmental sustainability. In particular, the

role of micronutrients is important, as demonstrated by the deference of the NRF 9.3 and 15.3 results.

Key Findings:

- Pork had greater energy use, water use, land use, and global warming potential than the Beyond, Impossible, and Morningstar Black Bean burgers
- Pork was the most nutrient dense of the burgers when B vitamins and Zinc content were considered.
- Given the high levels of uncertainty associated with modeling emerging products such as non-meat alternatives, it is critical that more industrially relevant data is made available to the LCA community.

Keywords: environmental impact, carbon footprint, plant-based, sustainability, animal-source foods

Scientific Abstract: A cradle-to-grave life cycle assessment of carbon, energy, water, and land footprints was conducted to evaluate differences in potential environmental impacts of pork meat versus plant-based non-meat alternative patties such as Beyond Burger (BB), Impossible Burger (IB) and Veggie Burger (VB). Nutritional quality assessment was also performed using nutrient-rich food indices to compare the nutrient profiles of each product. Differences in environmental impacts were observed between products. Pork consumption was found to have the highest relative impact on global warming potential and land occupation. Feed production was the most significant contributor to the impact, whereas, for the non-meat alternative patties, production of ingredients was the largest contributor. Unlike to other plant-based patties, the IB consumption had high intensity of energy demand, especially electricity consumption, during the manufacturing stage. The contribution at processing and packaging stage was relatively low and that retail refrigeration and in-home cooking with loss were substantial contributors to the overall environmental impacts. A sensitivity analysis indicates that cooking loss clearly affects the results of GHGEs, but it does not affect the overall interpretation of the result. The average carbon footprint of BB, IB, VB, and pork were 8.07, 8.10, 5.43, and 12.2 kg CO2-eq per kg of products at consumption stage, respectively. Water use and land occupation impacts display a similar tread as carbon footprint. Nutritional profile analysis yielded conflicting results. Pork products indicated lower NRF9.3 scores compared to BB and VB, however, the NRF15.3 score indicated that pork products had higher nutritional value. This initial evaluation of nutrient quality in the context of environmental sustainability highlights the need for further research at the intersection of dietary health and environmental sustainability.

Introduction

Consumers increasingly express an interest in understanding the sustainability of the products they purchase. There is also an increasing willingness to make purchase decisions based on what they know about the environmental impacts of products that they purchase. The food-system in the United States is responsible for more than 25% of all greenhouse gas emissions (GHGEs) and is among the highest in the world per capita (Goldstein et al., 2017; Springmann et al., 2016). Increasing awareness of environmental issues related to food production, distribution, and consumption has led to studies focused on understanding the connection between nutritionally sound consumption and potential environmental impacts. In this study, life cycle assessment (LCA) has been used to compare the entire life cycle of pork meat versus non-meat alternative patties from production to consumption to evaluate differences in potential environmental impacts. We have included as an additional indicator a comparison of the nutrient profiles of each of the alternatives. The LCA enables the pork industry in the U.S. to position its products in the marketplace in terms of their sustainable and nutritional attributes and to provide basis for proactive response to consumer concerns. This scan-level cradle-to-grave LCA study focuses on quantifying embodied energy, emissions to air, water and land, and consumption of natural resources; there is a need to assess the impacts of these inventory flows on climate change (global warming potential), resource depletion, water use, and land occupation.

Dettling et al. (2016) studied whether switching to plant-based meals from meals containing meat decreased environmental impacts. The study reported that by shifting from a meal containing meat to a meatless meal, GHGEs would decrease by approximately 40%. The study covered multiple environmental impact categories, but the meat and meatless meals were compared on a mass basis, thereby ignoring differences in nutritional characteristics. Most studies evaluating the reduction of meat consumption conclude that potential environmental impacts will decrease (Aston et al., 2012; Baroni et al., 2007; Chen et al., 2016; Goldstein et al., 2016; Scarborough et al., 2014). However, not all studies reach that conclusion. For example, Tom et al. (2016) found that shifting from meat products like pork and chicken to a diet with large amounts of fruits, vegetables, and seafood increases impacts for most of the environmental categories. This was because fruits, vegetables, and seafood use significant quantities of natural resources and have higher emissions per calorie consumed. Therefore, there is an interest to conduct a cradle-to-grave LCA study of pork production and consumption compared to non-meat alternatives in the U.S.

The work reported here is a field-to-fork LCA of carbon, energy, water, and land footprints of pork products versus plant-based non-meat alternative patties including an assessment of nutrient-rich food (NRF) indices. The data used in this study are primarily from the scientific literature and academic reports as well as laboratory analysis. The comparative environmental assessment is performed using the SimaPro© 9 software platform.

Objectives

The objective of this project is to perform a scan-level life cycle assessment (LCA) of greenhouse gas emissions (GHGEs), energy use, water use, and land use of pork products compared to recently emerging alternative meatless patties: Beyond Burger (BB), Impossible Burger (IB) and Veggie Burger (VB).

Materials & Methods

This LCA is a scan-level analysis with a "field-to-fork" scope, also known as a cradle-to-grave assessment. The attributional modeling approach has been adopted since the objectives of the assessment are identification and comparison of environmental impacts and hotspots between products. Continued profitability of the pork production sector depends upon producers understanding how consumers may consider sustainability and nutrition when purchasing, preparing, and consuming food. This study quantifies and compares differences in the environmental footprints of the selected products.

Functional unit and system boundary

The functional unit for this scan-level LCA is defined as the consumption of 1 kg of each of the target products. The system boundaries begin with the production of the raw materials of food ingredients and encompass related transport, manufacturing processes, distribution to retailers, purchase, preparation, consumption of products, and disposal of packaging waste. Packaging materials subject to recycling in the end-of-life phase are also accounted. Environmental impacts associated with Infrastructure (buildings, machinery, etc.) are not included for foreground processes except when an existing database unit processes includes infrastructure. Where data are incomplete, proxy unit operations (inventory datasets) were identified (and adapted or modified, if needed) for the analysis from databases available in SimaPro© 9 (an LCA software platform). The life cycle stages included within the system boundaries are shown in Figure 1.

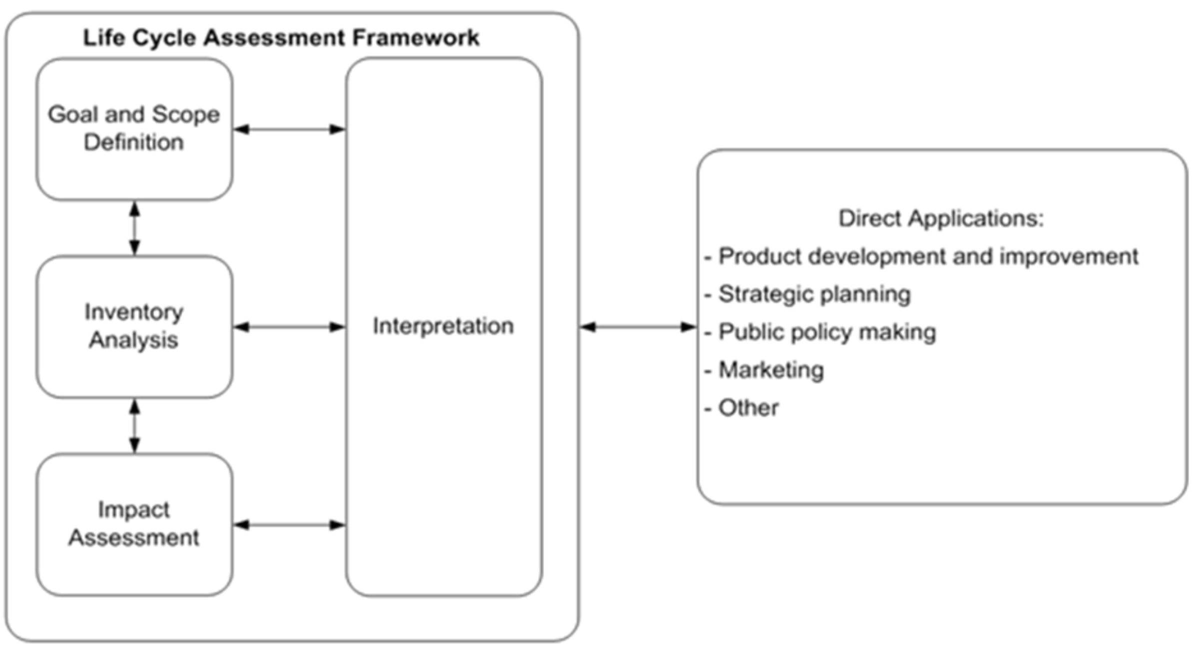

Figure 1. Stages of an LCA (ISO, 2006).

Cut-off criteria

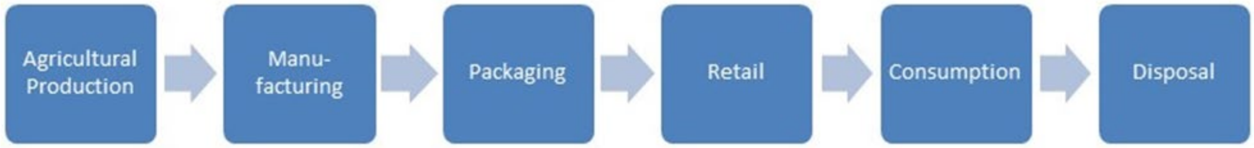

Figure 2. Lifecycle stages of pork and non-meat patties considered in the study.

In determining to include specific inputs, a cut off criterion was established using a 1% threshold. Any processes that contribute to the environmental impact that are estimated to be less than 1% were eligible for exclusion; nonetheless, if data could be readily obtained for an input or process, it is included. Figure 2 depicts the lifecycle stages of pork and non-meat patty products considered in this study.

Intended audience

This report is primarily intended for internal use by the National Pork Board (NPB). The NPB may choose to share the report with stakeholders from the pork industry including growers, processors, packaging companies, and retailers.

Allocation

Allocation is the process of attributing the environmental burdens and benefits of a system to primary and co-products of each process that produces multiple outputs (Gerber et al., 2010). Where allocation of inputs is required, the allocation procedures followed the ISO 14044 hierarchy. For pork production, there are three stages in the supply chain where allocation occurs; first for byproducts of feed processing (e.g., distiller's grains and soy meal); second at the processing gate where allocation between dressed carcass and rendering products occurs, and finally at retail and consumption where an allocation of refrigeration burdens and a fraction of consumer transport of groceries is necessary. We have adopted as a base case approach an economic value allocation. For allocation at retail and consumer phases, information of shelf space occupancy (refrigerated) was analyzed to determine burdens assigned for each product.

Life cycle inventory

The life cycle inventory (LCI) relies on data collected from multiple sources. Each ingredient in each product is represented by specific LCI data available in existing databases (Ecoinvent Centre, 2019) as part of the raw material production stage. (Table 7 through Table 9 in Appendix). We used the ecoinvent 3.6 (cut-off system model) database whenever a suitable proxy was available to quantify the impacts of raw materials. Where foreground LCI data is missing, a similar proxy food item was chosen as a substitute by modifying the LCI data for inputs from the Agri-footprint or LCA Food DK databases by replacing existing background processes from the ecoinvent 3.6 database. The purpose of this substitution is to ensure a consistent background system for comparative purposes.

The non-meat products in the study are composed of plant products as ingredients (e.g., wheat, potatoes, soybeans, peas, black beans, rice, etc.). LCI data for the production of wheat, soybeans, peas, and rice were derived from the ecoinvent database while fava bean unit process in ecoinvent was used as the proxy for black beans. In similar way, existing databases were used for the farm level production of other ingredients including flavorings (Table 10 in Appendix). Vitamin and mineral supplements were modeled using the best available proxy, modified to more closely represent the specific product based on available literature. Manufacturing of the non-meat products were simulated using existing literature to estimating energy requirements for basic operations (mixing, forming, separation, etc.). These were combined to represent each of the non-meat products manufacturing step. Typical packaging for each product is also included, as well as retail and consumer use (Table 11 to Table 13 in Appendix). The inventory flows in the processing and retail stages come primarily from facility energy use (machinery, refrigeration, etc.) and water use. Inventory flows associated with product packaging are related to the energy, land, and water needed to acquire, manufacture and distribute packaging materials. The transportation stage includes all transport modes necessary to deliver the food products to their retail destinations. Inventory flows in the consumption stage account for the consumer transport from retail, energy and water used for storing, cooking, cleaning, and consuming food. Disposal of packaging is also included for this stage but accounted at processing stage in the model.

Raw materials

The non-meat products have proprietary recipes. The composition was estimated based on publicly available information from a variety of sources including product labels and the USDA Foods Database. The ingredient list for each product was taken from public information available on the package label and/or the UDSA Branded Foods Database. The amount of each ingredient was determined using a linear programming process that combined the ingredients based on individual nutrient composition from the USDA database which provides macro- and micro-nutrient composition for standard reference foods. In addition, the optimization imposed the predominance order of ingredients based on the listed order on the package label. The objective function for the optimization was to minimize the sum of relative deviation from the nutrients in a serving and the total weight of the serving. The spreadsheet used for estimating the recipes is available on request, and a summary is presented in the Appendix. There is, of course, uncertainty in the recipe, and we provide a sensitivity assessment in the results section.

Beyond burger (BB)

Beyond Meat Inc. states on their website that the company wanted to make a burger that “looks, cooks, and tastes” like a beef burger but without the environmental and health problems that can come from red meat. The Beyond Burger (BB) is a vegetarian- and vegan-friendly plant-based product. The BB patties contain four main ingredients: water, pea protein isolate, canola oil, and refined coconut oil. These provide the nutrients including protein and moisture/juiciness of the burger. According to the product literature and USDA database, one patty of BB weighs 113 g and includes the following ingredients, in descending order of quantity: Water, pea protein isolate, expeller-pressed canola oil, refined coconut oil, contains 2% or less of the following: cellulose from bamboo, methylcellulose, potato starch, natural flavor, maltodextrin, yeast extract, salt, sunflower oil, vegetable glycerin, dried yeast, gum Arabic, citrus extract (to protect quality), ascorbic acid (to maintain color), beet juice extract (for color), acetic acid, succinic acid, modified food starch, annatto (for color). Beyond burger nutrient composition is close to beef. A four-ounce uncooked BB patty contains 270 calories, 20 g of fat with 5 g saturated fat, 380 mg of sodium, 5 g of carbohydrates, 3 g of fiber, and 20 g of protein. As well, BB provides 30% of daily iron requirement as well as phosphorus along with some vitamin C. In the manufacturing phase, ingredient mixing, patty forming, packaging, cleaning-in-place, and waste treatment processes are carried out consuming natural resources (electricity, natural gas and water).

Impossible burger (IB)

Impossible Foods Inc., the maker of the Impossible Burger (IB), says on their website that the company spent five years developing a product that recreates the taste, texture, and smell of a traditional beef burger made with no animal products. The main ingredients of IB include wheat protein, coconut oil, and potato protein. In a complete list, one patty of IB contains 112 g (data from CSU lab tests) of ingredients, in descending order of quantity are: Water, textured wheat protein, coconut oil, potato protein, natural flavors, 2% or less of: Leghemoglobin (soy), yeast extract, salt, konjac gum, xanthan gum, soy protein isolate, vitamin E, vitamin C, thiamin (vitamin B1), zinc, niacin, vitamin B6, riboflavin (vitamin B2), vitamin B12. The IB has roughly 29% more calories than a traditional beef patty. And even though it is plant-based, one three-ounce serving patty of IB represents 220 calories, 13 grams of fat (including 10 grams of saturated fat), 430 mg sodium, 20 grams of protein, 5 g carbohydrates, 0 g fiber, and less than 1 g sugar. One thing to note is that there is a high proportion of saturated fat per serving, likely from the coconut oil. In the manufacturing phase, fermentation, separation and concentration, ingredient mixing, burger forming, packaging, cleaning-in-place, and waste treatment processes are performed. They also manufacture a soy-based product which is intended to be a replacement for hemoglobin known as leghemoglobin.

Morningstar farms spicy black bean veggie burger (VB)

Morningstar Farms spicy black bean veggie burger (VB) comes in a box of four patties with two patties in each individually wrapped package within the box. One patty is 67 g (2.36 ounces) and 120 calories, and the recipe includes a large number of ingredients. There are obviously black beans, but the mix also includes corn, tomatoes, rice, onions, green chili peppers and jalapeno peppers. The complete ingredient list for one patty of spicy black bean veggie burger contains, in descending order of quantity: Water, cooked black beans (black beans, water), cooked brown rice (water, brown rice), onion, whole kernel corn, corn oil, soy protein concentrate, egg whites, diced tomatoes, wheat gluten, bulgur wheat, green chiles, onion powder, calcium caseinate (from milk), cornstarch, contains 2% or less of tomato juice, salt, yeast extract, spices, dextrose, tomato powder, hydrolyzed vegetable protein (corn gluten, wheat gluten, soy protein), garlic powder, jalapeno pepper, citric acid, natural and artificial flavors, paprika, modified corn starch, soy sauce (soybeans, wheat, salt), xanthan gum, disodium inosinate, disodium guanylate, vitamin B1 (thiamin hydrochloride), caramel color, lactic acid. In the manufacturing phase, ingredient mixing, burger forming, packaging, cleaning-in-place, and waste treatment processes are performed.

Ground pork and pork chop

Pork is the most commonly consumed meat in the world, accounting for about 38% of meat production worldwide even though consumption varies widely from country to country. According to the USDA's Foreign Agriculture Service, nearly 113 million tons of pork were consumed worldwide in 2018 (USDA, 2019). The USDA categorizes pork as a red meat and is very high in thiamin content. For the comparison purpose in this study, we adopt ground pork and pork chop for comparison. To compare environmental impacts between products, we adapted the recent study of pork production and consumption (Putman et al., 2018) by updating the background processes to ecoinvent 3.6 for compatibility with the models of the non-meat products, thus the numerical values reported in this document are not comparable to the previous report because of the changes in the background data required to ensure a valid comparison.

Nutrient content

Table 1 presents summary of nutrient contents for one serving of each product. These data were used to estimate nutrient-rich food (NRF) indices (Fulgoni et al., 2009; NRF9.3 and NRF15.3). These nutritional food indices are designed to measure nutrient quality of individual foods. The approach of ranking or classifying foods based on their nutrient composition is known as nutrient profiling (Drewnowski and Fulgoni, 2008). This study reports NRF9.3 and NRF15.3 indices of each product as nutritional quality indicators in results section.

Table 1. Nutrient contents for one serving of each product in this study.

Nutrient Content	Beyond burger (4 oz., 113 g)	Impossible burger (4 oz., 113 g)	Veggie burger (2.4 oz., 67 g)	Ground pork (4 oz., 112 g)	Pork chop (3.6 oz., 100 g)
Calories	260	240	110	190	202
Total fat (g)	18	14	4	11	11.1
Sat. fat (g)	5	8	0.5	4	3.3
Cholesterol (mg)	0	0	0	75	77
Sodium (mg)	350	370	330	55	58
Carbohydrate (g)	5	9	13	0	1
Fiber (g)	2	3	4	0	0
Sugars (g)	0	< 1	1	0	0
Protein (g)	20	19	10	22	24.7
Calcium (mg)	100	170	78	0	13
Iron (mg)	4	4.2	1.1	1.1	0.9
Magnesium (mg)	0	0	24.6	25.2	25.2
Potassium (mg)	280	610	260	470	416
Thiamin (mg)	0	28.2	0.07	0.84	0.48
Riboflavin (mg)	0	0.4	0.17	0.26	0.2
Niacin (mg)	0	5.3	0	0	0
Vitamin B_{12} (mcg)	0	3	0	0.24	0.29
Vitamin C (mg)	0	0	0	0	0
Vitamin E (mg)	0	0	1.1	0	0
Zinc (mg)	0	5.5	0.6	1.65	1.41

Manufacturing

Industrial energy use represents about 32% of total U.S. energy demand (U.S. Energy Information Administration, 2020). Manufacturing accounts for 76% of total industrial energy use, and food processing represents about 4% of that. There are more than 30,000 food processing plants and the number of plants has been increasing according to the comprehensive data available from the Census Bureau. According to the data available, the food industry consumes about 7% of the total electricity used by the manufacturing sectors.

Food manufacturing plants process raw agricultural materials and products to intermediate or final products for consumption. The raw material ingredients are mixed, formed, cooled, and packaged into the finished products of non-meat alternative patties; they are then frozen and transported to retail outlets for sale. Live swine are also processed into finished products in a manufacturing facility. The information relevant to the amount of electricity, natural gas, other fuels, chemicals, and water consumed at the processing facility is necessary to estimate environmental footprints.

Industrial environmental impact reporting is typically based on finished product leaving the facility and does not specifically account for rendering products which are co-products in pork processing facility; however, in life cycle assessment, when a system has multiple products, each of which have economic value, it is standard practice to assign some of the environmental impact burden from the overall process to each of the co-products. International standards recommend system division (which would require sub metering in the manufacturing facility), or system expansion where credit is applied for production of co-product that is equivalent to the environmental burdens from production of and equivalent product item from a different and independent system. An economic allocation among the co-products is often the most practical approach to this allocation of environmental burden and was adopted for this analysis. One approach to arrive at an economic allocation is to consider data from the U.S. economic census (U.S. Census Bureau, 2019). Although the North American Industry Classification System (NAICS) codes include meats other than pork, as the basis for an initial allocation ratio, in the absence of more granular data, these values were used. The allocation ratio calculated using this method assigns 89% of the burden to the meat processing and 11% assigned to the products from rendering operations. We have also included an export stream in the analysis; however, on a per serving (or kilogram) basis, this does not affect the result. There are differences in the cuts of exported meat as well as its packaging. However, differences in impacts associated with different cuts of meat are not available, and very likely to be extremely small. Packaging for exported meat is outside the system boundary for domestic consumption. The export volume does not affect the overall contribution per kg of domestic pork consumed in the U.S., as the burden of the exported pork can be considered to follow the meat to its point of consumption.

Since the circumstances of manufacturing and processing of non-meat alternatives are unique, we adopted previously published literature and reported data to estimate electricity, natural gas, and water usage (Dettling et al., 2016; Goldstein et al., 2017; Khan et al., 2019). Goldstein et al. (2017) study presents a detailed list of resource use for IB manufacturing, but other reports did not reveal detailed information related to manufacturing process of products because of confidentiality considerations. Thus, we estimated resource use at the manufacturing stage for BB based on Goldstein et al. (2017) and VB based on Dettling et al. (2016) study. Although these data may not affect the comprehensive results, energy usage at processing stages is required for a comprehensive evaluation of differences in the environmental impacts of these products.

Water consumption in manufacturing plants was also accounted. The food industry uses a large volume of water for various purposes. Water is used to clean floors, to sanitize processing equipment and vessels, and to rinse the raw food products before processing. Water is also required for cooling water, steam, and refrigeration systems (Kirby et al., 2003). Water use data exists for IB processing (Goldstein et al., 2017) and VB processing (Dettling et al., 2016). As for BB patty, we used industry-wide estimation. According to Maupin et al. (2014), total industrial water usage was approximately 15,900 million gallons per day in 2010. We assumed that 7% of the total industrial water usage to account for food industry sector same as electricity use as reported in U.S. Census Bureau (U.S. Census Bureau, 2012). We used this information as an average to estimate the water use for processing of BB. For pork processing, we used previously reported wastewater treatment volumes as representative of water used in clean-in-place processes. Because of the complexity of the system and lack of data, ancillary information including building infrastructure, employees' commutes, accounting, or legal services are not included in the inventory processes for this life cycle phase.

Packaging

Food packaging plays an important role to preserve food quality and safety. On the other hand, the production of packaging materials and disposal of packaging waste can contribute a significant portion of the environmental impact and depletion of non-renewable resources (Marsh and Bugusu, 2007). It was reported that about 33% of the total municipal solid waste (MSW) is packaging waste (Marsh and Bugusu, 2007). Food packaging waste has been reported to account for two thirds of packaging waste in the United States (Food Packaging Forum, 2017). In this study, we accounted for primary (tray, sealing film and cardboard), secondary (corrugated cardboard box) and tertiary (pallet and plastic film) packaging materials of each product relevant to the functional unit. For instance, the primary packaging of BB is composed by a plastic tray sealed with plastic film and wrapped in a color printed chipboard sleeve. Secondary packaging is a corrugated cardboard box and contains three units of primary packaging. We adopted the same assumption for all products analyzed in the study, tertiary packaging is composed by a wood pallet wrapped in polyethylene film. The composition and weight of packaging materials for each product are reported in Table 2 and Table 7 through Table 10 in the Appendix. The amount of packaging material recovered from

Table 2. Type of packaging materials used for each food item.

Products	Type of packaging materials used
Beyond burger	Thermoformed tray (PE), PE lid film, cardboard sleeve, patty paper, corrugated carton, Wood pallet, pallet wrap (LDPE)
Impossible burger	Flexible packaging (HDPE), patty paper, corrugated carton, wood pallet, pallet wrap (LDPE),
Veggie burger	Plastic packaging (PET), closure (PP), plastic film (HDPE), corrugated carton, Wood pallet, pallet wrap (LDPE)
Pork	Plastic packaging (PS), foaming (PU), plastic film (LDPE), corrugated carton, wood pallet, Pallet wrap (LDPE)

recycling is shown in Table 3. These values were incorporated in modelling for the recycling rate for each type of food packaging material.

Table 3. Amount of food packaging recycled.

Material	Percent of recycling
Paper and paperboards	34.1
Plastics	11.8

Transport

It has been reported that food transportation represents approximately 11% of food supply chain life cycle GHGEs (Weber and Matthews, 2008). According to a study, it was estimated that the total freight of food products from production to retail is about 12,000 t-km per U.S. household per year (Weber and Matthews, 2008). We assumed that both the pork products and non-meat alternatives follow equivalent distance from the point of manufacturing to retail center. We also assumed that the transport distance of ingredients for each product is same. The ingredients were delivered by freight lorry (16-32 metric tons, EURO6) and the packaged products were delivered by refrigerated truck (7.5-16 metric ton, EURO6). A transport of 1,000 km was assumed for both ingredient delivery and for product distribution.

Retail

Retail is a highly concentrated industry, which has substantial input flows (Scholz et al., 2015). Retail stores consume energy and resources that contribute to environmental impacts. The contributing streams are electricity for store operations (overhead) and refrigeration systems, loss of refrigerants due to leakage, natural gas consumption, and water usage (Aquacraft Inc., 2004; ASHRAE, 2012; FMI, 2014). The storage and sales of pork and not-meat alternatives to the retail consumer carries an environmental impact burden from energy use (electricity and natural gas), and fugitive emissions associated with refrigerant loss (U.S. EPA, 2005; U.S. EPA, 2008). Estimates of the space occupancy and energy demands per kg of each product sold were developed to determine the burden of this supply chain stage. Information from a proprietary study reports that approximately 215 square feet facing of refrigerated shelf space is devoted to pork products in a typical grocery configuration with a total of 4,668 refrigerated square feet facing and 42,415 square feet facing of total retail space (Bishop, 2013). This results in 4.61% of total refrigerated store space and 0.86% of total store space. These fractions were used as allocation fractions for refrigerated space for pork. The same study reported about 21.3 total square feet facing dedicated to meat and cheese alternatives, which corresponded to 0.46% of total refrigerated and 0.08% of total store space on a square foot facing basis. Due to a lack of specific sales data for each product, these retail burdens were applied equally to all three non-meat alternatives. An average annual loss of refrigerants was included (U.S. EPA, 2005). R22 and R404A were assumed to be used at 54% and 46%, respectively (U.S. EPA, 2005). We also accounted for retail loss in modeling. Buzby et al. (2009), in a study on the loss of perishables in supermarkets, reported average loss of pork is 4.4% (Buzby et al., 2009). We assumed same loss rate of pork in retail stage for all non-meat alternative products.

Consumption and end-of-life

Impacts accounted in this phase include transport from retail to home, refrigeration and cooking energy and product loss during cooking or waste. Consumer transportation related emissions were allocated using the same space-based allocation fractions (whole store allocation basis – 0.258% with an assumed 10 km round trip for grocery store purchases). The fundamental assumption in this allocation approach is that the composition (inventory) of the products on supermarket or grocery store shelves approximates the average U.S. household purchasing and storage. We also took the shelf space estimates from supermarket refrigerated space as the allocation fractions for in-home refrigeration electricity. Estimates of the consumer cooking energy for gas (~40% of households) and electric (~60% of households) ranges were made. Cooking energy requirements were estimated using information from the U.S. EPA Energy Star program. Both pre-heat and cooking times were included but assumed no additional idle time. The cooking loss for each product was measured from laboratory work performed at Colorado State University. As indicated in the table, there is a 12% to 31% weight loss due to cooking, and we have included this weight loss in the model calculations because the functional unit is one kg consumed, thus the reference flow for consumer purchase is the raw weight of each product necessary to deliver one kg of cooked product. There is a relatively small quantity of post-consumer waste generated, and it is modeled using an ecoinvent process for landfill disposal.

Life cycle impact assessment

The life cycle impact assessment (LCIA) was conducted using SimaPro© 9 and considered the environmental impact categories of global warming potential (GWP), cumulative energy demand, water use, and land use. We adopted the IPCC 2013 100a method (IPCC, 2017) for GWP, the IMPACT World+ method for the inventory items of cumulative energy demand and land occupation (IMPACT World+, 2017), and the ReCiPe 2016 (H) method for water use. Water use was determined as strictly an inventory of water consumed, which does not include water uses like that of hydroelectric power plants. Land use was also calculated as strictly an inventory item, thus does not include potential effects on ecosystem services. Unit processes associated with raw materials, energy inputs, transportation information, any activities in lifecycle supply chain of systems were linked in the LCA software and the impacts associated with the functional unit were compared.

Table 4. Cooking loss in percent of each product.

Product	Cooking loss (%)
Beyond burger (BB)	19.2
Impossible burger (IB)	11.5
Veggie burger (VB)	12.5
Ground pork	31.3
Pork chop	24.6

In addition to the environmental impact categories, we have also adapted the nutritional index as an additional midpoint indicator for comparison among the alternatives. As described elsewhere, the nutritional index is a metric used to characterize nutrient composition for food products and is an indicator of the healthiness of this food in a diet. A more complete assessment of nutritional quality in the context of LCA would include an end point indicator of human health that could be derived from risk factors published in the global burden of disease database following the recommendations of Fulgoni and Stylianou (Fulgoni et al., 2018; Stylianou et al., 2016).

Environmental impact categories

Climate change

There are several gaseous emissions that cause contribute to climate change such as, carbon dioxide, methane, nitrous oxide and refrigerants. The concentration of greenhouse gases is characterized as kg equivalents of CO_2 (kg CO_2-eq), i.e., the relative global warming potential of a gas as compared to CO_2 (IPCC, 2017). Then individual equivalents are added together to give the overall greenhouse gas indicator score that characterizes the total radiative forcing potential (or global warming potential) of all greenhouse gases released during the life cycle. To interpret this greenhouse gas indicator, the time horizon used (e.g., 50, 100, or 500 years) is an important consideration. Short horizons tend to emphasize gases with short residence times in the atmosphere, like methane. In addition, the indicator does not consider the effects of clouds and aerosols in reflecting the sun's heat and reduction the warming. For this study, we have adopted the 100-year time horizon for GHG emissions. Biogenic carbon, that is carbon which is part of the short-term (decades long) cycling of carbon through the bio-geosphere is not specifically accounted in this analysis. This follows the most recent IPCC guidelines in which the emission factor for biogenic carbon is set to zero. However, some biogenic carbon is converted to methane through anaerobic processes (including enteric fermentation and manure management as well as processes in wastewater treatment or landfills). The characterization factor for biogenic methane is 27.8 kg CO_2-eq per kg biogenic methane in the most recent IPCC guidance and this has been adopted for this study (IPCC, 2017).

Cumulative energy demand

The cumulative energy demand (CED) of a product, process or a service represents the direct and indirect energy inputs throughout the life cycle, including the energy consumed during the extraction, manufacturing, utilization and disposal of the raw materials. Direct energy use refers to primary energy input required for manufacture, use and end-of-life in life cycle. Indirect energy use represents all inputs that are used for other purposes than manufacturing product, such as infrastructure and equipment. As discussed in Hischier and Weidema (Hischier et al., 2010), CED is split up into eight categories based on extraction of energy materials from nature. For the purposes of this study, we are only considering one of the eight energy categories: non-renewable fossil fuel. The use of renewable fuels is out of the scope of this analysis.

Water use

The water depletion category quantifies the total water consumed by a product or process. We used the ReCiPe 2016 (H) method for water footprint (Huijbregts et al., 2017). Six of the elementary water flow types which are used in the ecoinvent data were selected as default (Goedkoop & Huijbregts, 2013). These are Water, fresh; Water, lake; Water, river; Water, well, in ground; Water, unspecified natural origin/kg; and Water, unspecified natural origin/m^3. A large quantity of water is used as cooling and process water in most supply chains. However, 99% or more of cooling and process water is returned to the source watershed, and therefore is not included in the inventory of water depletion. A similar situation exists for hydroelectric generation.

Land use

There are two types of land use interventions considered in life cycle impact assessments: land occupation and land transformation. Land occupation refers to how land is used and for the products in this study is dominated by crop production. It is essentially the inverse of yield. Land transformation accounts for conversion of one land use type to another (e.g., forest to pasture). Both are inventory items and are related to impacts on ecosystem quality and biodiversity. However, we report only land occupation (as inventory) and do not include land transformation as the majority of cropland has been under cultivation for decades. This tacitly assumes that the plant proteins are derived from US production. Data regarding the provenance of the ingredients for the plant protein alternates is not available. If this assumption is not valid and the sources are other countries, then the exclusion of land transformation could be important, depending on the country of origin.

Nutrient Rich Foods (NRF) Index

Nutrient quality assessment known as nutrient profiling is a method of ranking or classifying foods based on their nutrient composition. Each micro- and macro-nutrient in food is assigned a unique score that reflects its nutrient quality. We used the Nutrient-rich Foods indices (NRF9.3 and NRF15.3), which are science-based and consumer-driven guidance systems (Drewnowski & Fulgoni, 2008). These NRF indices were estimated per 100 kcal of each product as the sum of the recommended daily value (DV) of nutrients to encourage and subtracting the DV for nutrients (sodium, saturated fat, and added sugars) to limit in a healthy diet. We followed the procedures as described by (Fulgoni et al., 2009).

Uncertainty analysis

In LCA, there are sources of uncertainty (PRé Consultant Inc., 2018) that can influence the interpretation of the results and place limits on the conclusions:

- Data uncertainty: inexact or incomplete information of model input and design, for example, the electricity or natural gas consumption at a facility
- Uncertainties about the correctness (representativeness) of the model, allocation choices and methodological uncertainties
- Uncertainties related to systematic or random errors

- Uncertainty associated with the impact assessment framework

The uncertainty associated with the impact assessment framework, specifically the characterization factors, which define the impacts for emissions is not currently available. In this project, the uncertainty in the LCA results was evaluated using a statistical method, Monte Carlo Simulation (MCS), available in the SimaPro© 9 computational platform. This process is rules-based and incorporates probability distributions for uncertain or variable input data that reflect the associated knowledge and process uncertainty. This analysis is necessary for establishing defensible metrics for comparative evaluation of alternative products providing a given function. Briefly, MCS is a method of propagating uncertain knowledge regarding the input of the model to the outputs, in this case the environmental impacts. This technique is based on choosing one set of input values that are randomly selected from probability density functions that describe the expected range of allowable input values, followed by calculation of the system impacts, and then repeating this process many times, in this case, 1,000 runs. The result of the MCS provides a distribution of the model results, which can be used for calculation of the 95% confidence interval.

The ecoinvent pedigree matrix for quantifying uncertainty of inputs was applied to unit processes generated from primary data. An inherent uncertainty of ± 15% (σ_G^2 = 1.15), log normal distribution and the pedigree uncertainty score of (3,2,2,1,1,4) was assigned to all inventory data because multiple measures were not available to establish an empirical probability density function. Secondary or background data were taken, to the extent possible, from the ecoinvent v3.6 database (Ecoinvent Centre, 2019); the data quality pedigree provided by the ecoinvent center for these data was adopted without revision. Unit processes adapted from other LCI databases for which there was no uncertainty information provided, do not have uncertainty specifications added for this project. Therefore, it should be recognized that the confidence bands presented in this study represent a lower bound of the actual uncertainty in the reported impact.

Model validation

The LCA model was created using the SimaPro© 9 software system for life cycle engineering, developed by Pre-Consultants, The Netherlands. The ecoinvent database provides the life cycle inventory data for upstream burdens of most of the raw and process materials used as inputs. A complete listing of the life cycle inventory model can be provided in electronic form. Our goal was to provide a transparent model for calculating the environmental impacts of the non-meat alternatives and pork industry using a functional unit of 1 kg of product consumed. All computational modules were documented with reference citations to external sources. Spreadsheet computations were documented with the supporting logic. In order to prepare a defensible environmental impacts baseline and a transparent methodology that can be used to assess progress towards achieving a sustainable value chain, it is important to have a consensus regarding the sources and types of data used to develop the baseline, as well as general methodology.

Results

Life cycle impact assessment results

Climate change

Figure 3 presents comparative contribution analyses of GHGEs of the four alternative products. Each major supply chain stage has inputs and outputs that influence the overall GHGEs of the system. Veggie burger (VB) consumption has the lowest carbon footprint of 5.44 kg CO_2-eq/kg consumed, followed by BB of 8.03 kg CO_2-eq/kg consumed.

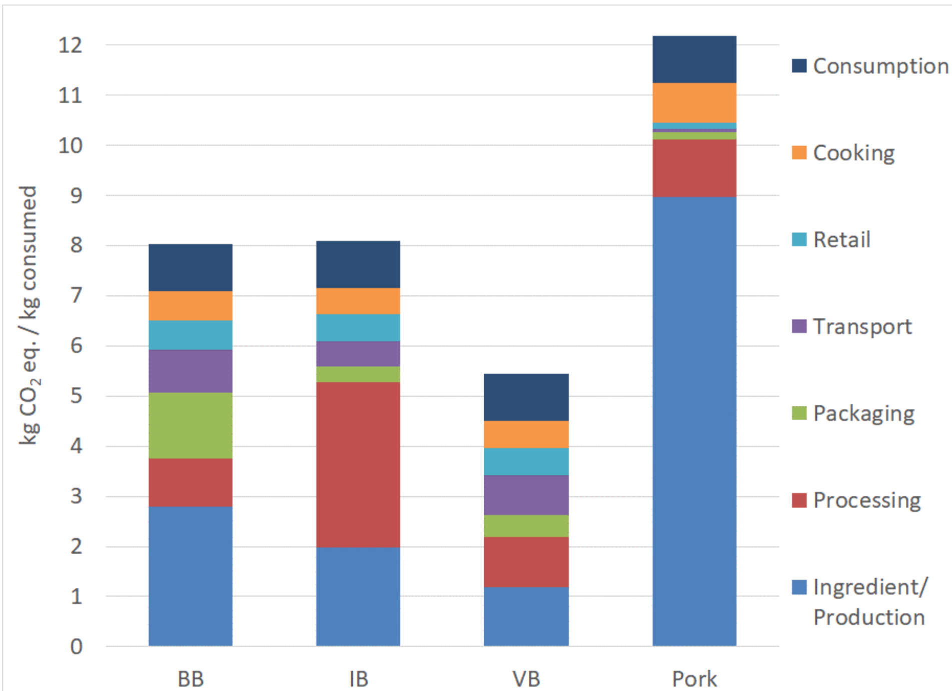

Figure 3. GHGEs of non-meat alternatives and pork meat consumption

In these two meatless alternatives, each life cycle stage contribution presents a similar trend except for the processing contribution to BB. In BB consumption, ingredient production contributes the most followed by the processing phase. The only difference in the order of process contributions is that BB packaging has a greater impact than IB and VB. This reflects a greater amount of packaging used in BB than in VB or IB. In the IB supply chain analysis, the processing stage is the largest contributor to GHGEs followed by ingredient production. Electricity use during manufacturing is the main driver of this result. Protein supplementation in the IB recipe is responsible for a large fraction of the ingredients' contribution.

Overall, pork consumption shows the largest GHGEs of 12.2 kg CO_2-eq per functional unit. Most of the GHGEs associated with pork consumption come from the production stage that represents 73.6% of the carbon footprint; Methane emission from manure management is 2.69 kg CO2-eq/kg consumed, about 22% of total (from cradle to grave analysis). 0.75 kg CO2-eq/kg live weight at farm gate. In general, except for the IB, the burger (ingredient production, processing, and packaging) was the single largest contributor to the lifecycle GHGEs associated with consumption of each product (**Figure 9** through Figure 11 in Appendix present GHGE contributions of each ingredient). The effect of cooking weight loss arises from the choice of functional unit as consumed (i.e., cooked) product. Because consumers purchase raw product, the amount purchased (and therefore quantities required in the upstream supply chain) is larger by the fractional weight loss. Retail, in-home cooking, and consumption phases also contribute to overall carbon footprints. The packaging materials in IB, VB, and pork add very small contributions to GHGEs, but those in BB add substantial contribution to GHGEs.

Fossil energy, water, and land use

Total fossil energy use ranged from 66.8 and 119 MJ deprived per functional unit. Unlike the results of GHGEs, pork consumption uses lower fossil energy than IB consumption (Figure 4). The energy requirement for IB processing is the dominant driver followed by raw ingredient production and cooking.

The magnitude of fossil energy use varies among products, however, there are similar GHGE trends are observed across lifecycle stages. In the pork supply chain, farm activities (production of the ration plus animal husbandry) are the dominant contributors of fossil energy demand. Processing is the second largest contributor followed by energy for in-home cooking. These results indicate that the mitigation potential in feed production as well as electricity and natural gas use in processing and in household food preparation represent opportunities for reducing the lifecycle impacts.

Water use ranged from 203 - 681 liters per kg of product consumed (Figure 5). Pork consumption has the largest water consumption, with 93.5% of the total attributed to crop production (to produce the ingredients). Water consumption per functional unit shows that crop production contributes most of the impact followed by water use incurred in the production of packaging materials.

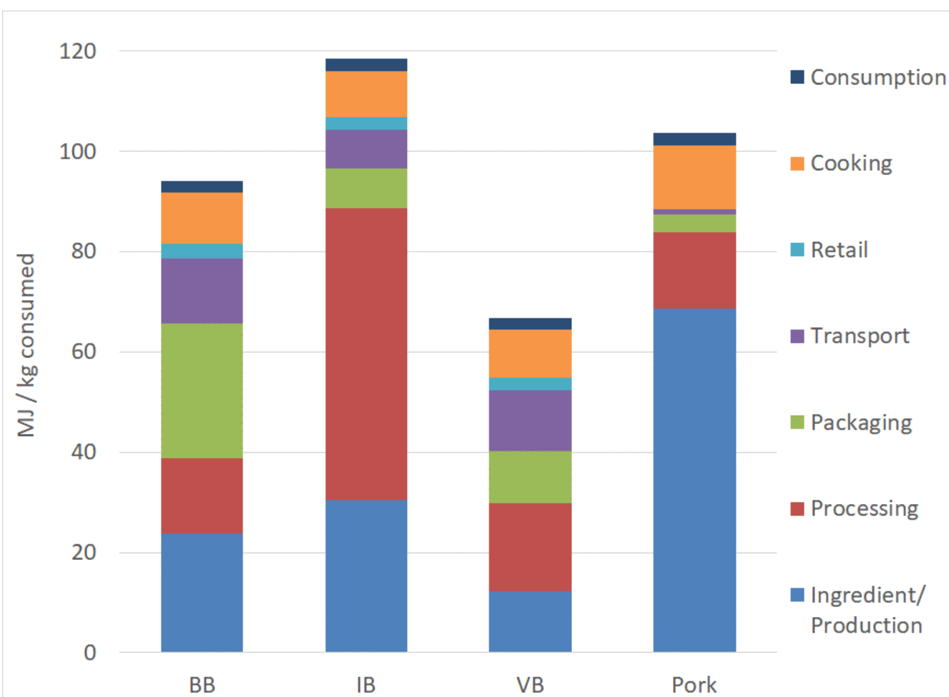

Figure 4. Energy use of non-meat alternatives and pork meat consumption**.**

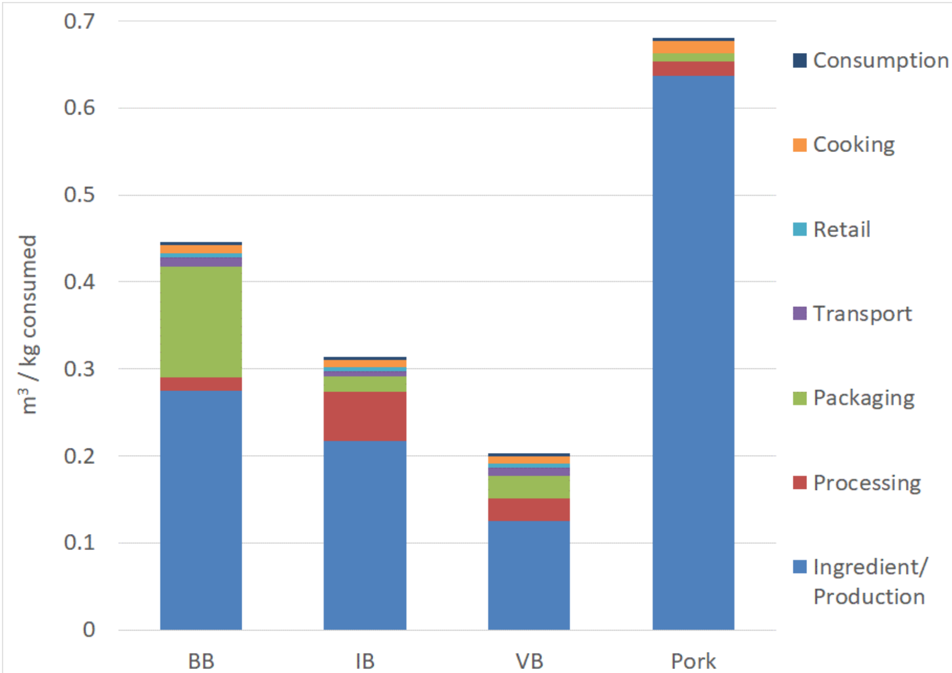

Figure 5. Water use of non-meat alternatives and pork meat consumption**.**

The result shows that the BB occupies 5.5 m² per year compared to 1.9 m² per year for the VB. Unlike to other products, packaging in BB contributes substantially to land occupation, 28% of total. For the pork, 99% of the impact comes from crop production for animal feed. Pork consumption is responsible for 19.4 m² per year of land occupation (Figure 6).

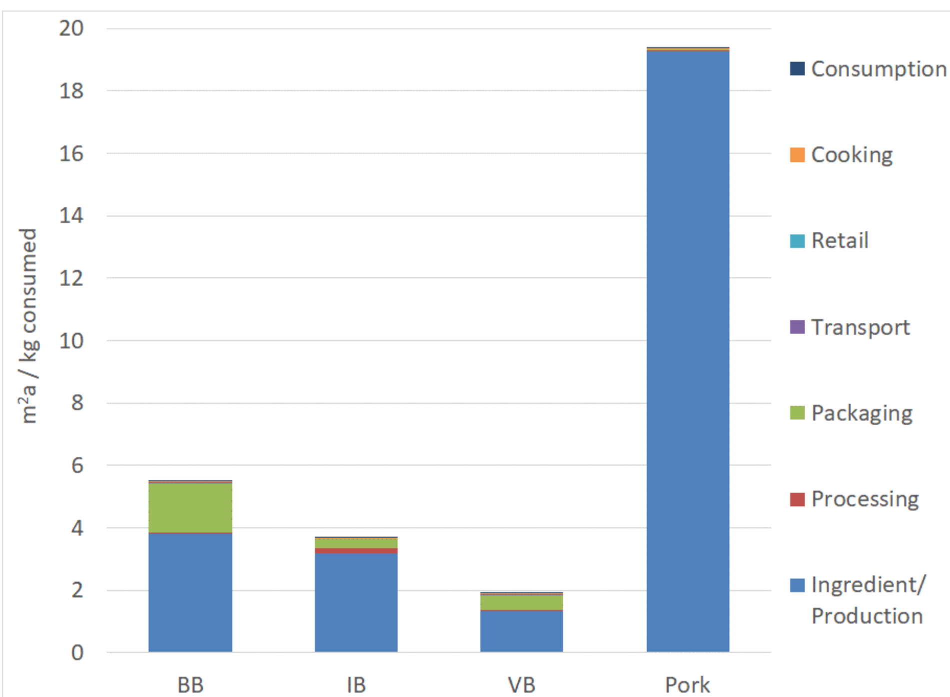

Figure 6. Land use of non-meat alternatives and pork meat consumption

Sensitivity analysis

No cooking loss model

Figure 7 presents a sensitivity result of GHGEs associated with a model including cooking loss (left column in each product) versus a scenario excluding cooking loss (right column in each product) by assuming same cooking loss rate for each product. Because the model simulated in this study had different cooking losses for each product, the lost weight at the consumption stage induces environmental impacts from the upstream lifecycle supply chains. Since the loss of nutrients is expected to be minimal during cooking and most of the weight loss during cooking is assumed to be moisture. A model scenario without cooking loss was performed. As the figure shows, cooking loss induces larger GHGEs in pork (25.8% reduction in GHGEs without weight change during cooking compared to a model with cooking loss) than other products due to the larger weight loss during cooking. Consumption of pork has 20% greater of climate change impact (GWP) than IB consumption based on the model without cooking loss. When cooking loss is included, pork consumption has 33.9% greater GHGEs than IB. GHGEs are quite sensitivity to changes in product loss rates. According to the GHG component contribution analysis, CO_2 emissions were the dominant contributor to total GHGEs in all the products followed by CH_4 emissions as the second largest driver. It is observed that N_2O (in the range of 2.5 – 6.7% of total) and refrigerants (in the range of 3.9 – 5.5% of total) contribute minor emissions in non-meat alternative production systems, but substantial N_2O emissions (20.7% of total) occur in pork consumption. In swine production systems, field emissions from N fertilizer and manure management are the main sources of N_2O emissions.

Sensitivity of electricity demand at processing facility

All forms of electricity generation have an environmental impact to air, water, and land. We analyzed the dependence and sensitivity of the electricity requirement at processing facility to environmental impacts. **Figure 7** presents the results of sensitivity analysis associated with changes in electricity demand (20% reduction) during processing stage of each compared product. These values indicate reduced environmental impacts, in percent, relative to the entire lifecycle impact of each product. As shown in Table 5 For IB production, a 20% decrease in electricity use at the processing facility reduces 7.4% of total GHGEs, 9.1% of total cumulative energy demand, 3.3% of water consumption, and 1.0% of land occupation. As the results demonstrate, reduced electricity use during pork processing step leads to minor changes in environmental impacts. According to the results shown in the table, non-meat alternative production systems are more energy intensive in processing step compared to pork. Overall, electricity consumption has more effect on GHGEs and cumulative energy demand than the impacts of water use and land occupation.

Table 5. Sensitivity of environmental impact change in percent associated with 20% decrease in electricity demand at processing facility.

	BB	IB	VB	Pork
GHGEs	-2.0%	-7.4%	-2.7%	-0.9%
Cumulative energy demand	-3.1%	-9.1%	-4.0%	-2.0%
Water use	-0.6%	-3.3%	-1.3%	-0.3%
Land occupation	-0.2%	-1.0%	-0.5%	0.0%

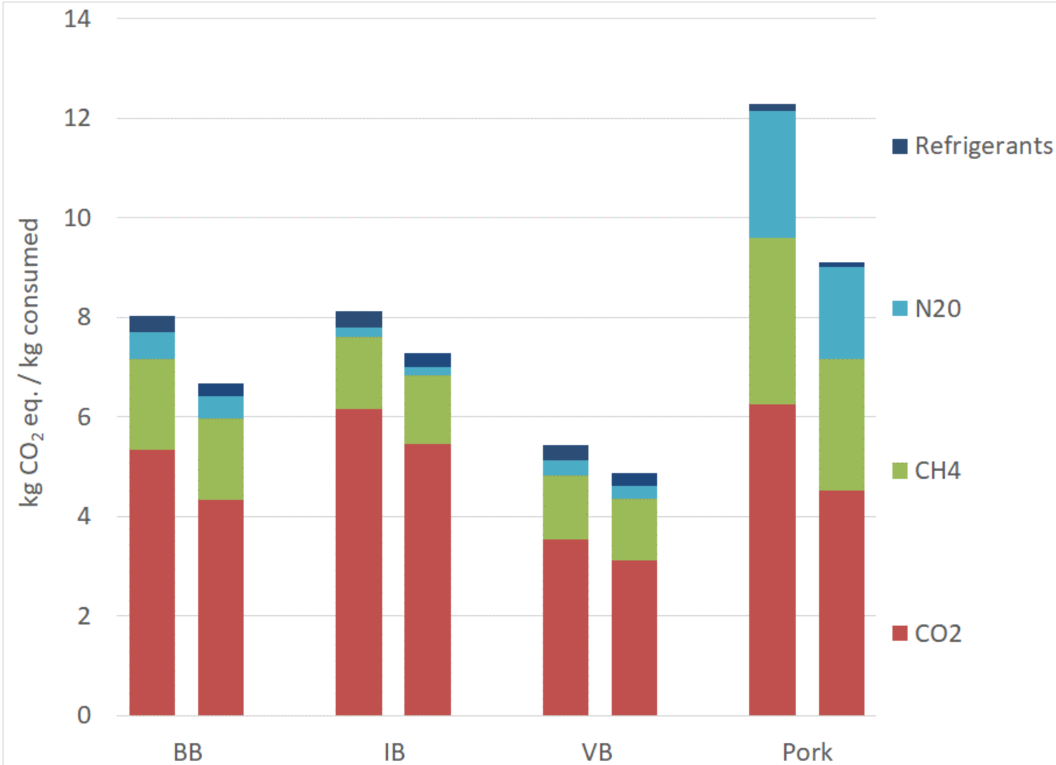

Figure 7. Sensitivity of GHGEs associated with cooking loss (left column in each product) versus non-cooking loss (right column in each product) models. The legend in right side represents contribution of GHG components.

Uncertainty analysis

Figure 8 presents uncertainty analyses of the non-meat alternatives and pork meat using Monte Carlo Simulations (MCS) with 95% confidence intervals for selected environmental impact profiles (global warming potential, cumulative energy demand, water use, and land occupation associated with 1 kg of products consumed). In the figure, the box represents the 25th percentile, 50th percentile, and 75th percentile, and the whiskers represent the 10th and 90th percentiles for the lower and upper whiskers, respectively. When there is little or no overlap of boxes between alternatives, we have a high confidence that the indicator for those alternatives is significantly different. The uncertainties of background unit processes embedded in the ecoinvent database were adopted without modification.

These figures display the mean differences between products. GHG emissions are of notable interest, and the average carbon footprint of BB, IB and VB are 8.07, 8.10 and 5.43 kg CO_2-eq per kg of products at consumption phase, respectively. The carbon footprints of BB and IB consumption display slightly greater than the carbon footprint of VB consumption. The 95% confidence bands for non-meat alternatives range 6.55 to 9.93 kg CO_2-eq per kg of BB consumed, 6.34 to 10.0 kg CO_2-eq per kg of IB consumed and 4.43 to 6.69 kg CO_2-eq per kg of VB consumed. For 1 kg of pork consumption, the carbon footprint is 12.2 kg CO_2-eq with a 95% confidence band of 9.31 to 15.6 kg CO_2-eq. Figure 3.6 shows that by comparing cumulative energy demand as opposed to climate change impact, IB impact (118 MJ/kg consumed) is the

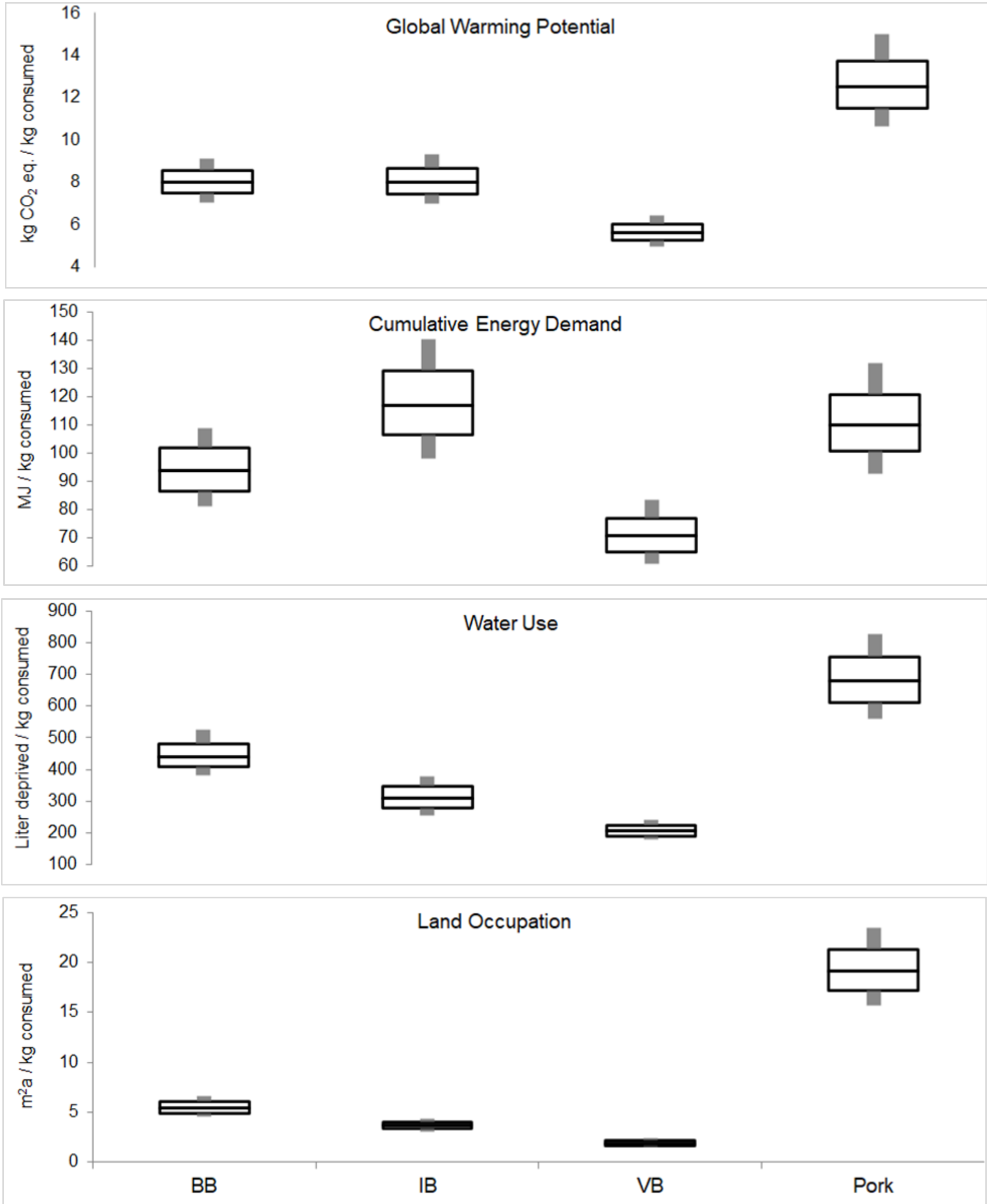

Figure 8. Results of 1,000 Monte-Carlo Simulations (MCS) for uncertainty analysis of greenhouse ga funny s emissions, energy use, water use, and land occupation for non-meat alternatives and pork meat at consumption phase.

highest among the products including pork. This is because manufacturing IB is more energy intensive, specifically electricity use, than processing of BB, VB, or pork.

Water use – defined as water removed during the production, but not returned to the same watershed – is 0.448 m^3 per kg of BB consumed with 95% confidence band of 0.342 to 0.586 m^3 of water consumed per kg of BB consumed. This is approximately 35% less water usage than pork, which is the highest water use impact among products. Water use and land occupation impacts show a similar trend as global warming potential in products comparison. Given the high levels of uncertainty associated with modelling emerging products such as non-meat alternatives, it is critical that more industrially relevant data is made available to the LCA community. Overall, the MCS results of non-meat alternatives and pork meat corroborate the environmental impact assessments described in the previous sections.

Nutrient-rich foods indices

Table 6 presents nutrient-rich food indices (NRF) evaluated for raw and cooked non-meat alternatives compared to pork products. Raw values were assessed using label information and cooked values were assessed using the nutrient analysis completed by CSU. Cooked results had greater NRF scores because the nutrient density increases as cooking evaporates moisture content. For NRF9.3, VB was considered the most nutrient dense due to a relatively low saturated fat content. However, for NRF15.3, the Impossible Burger was by far the most nutrient dense due to additional vitamin content not accounted for in the NRF9.3. Compared to non-meat alternatives, pork products show lower NRF9.3 scores, but display the second to highest NRF15.3 score. The greater amount of Thiamin and Riboflavin in pork products explain the different results.

Table 6. Nutrient-rich foods indices (NRF9.3 and NRF15.3) for raw and cooked non-meat alternatives compared to pork products.

	NRF Index	**NRF9.3**	**NRF15.3**
Beyond burger	Raw	18.7	31.3
	Cooked	33.5	50.2
Impossible burger	Raw	21.0	862.2
	Cooked	39.6	748.8
Veggie burger	Raw	43.9	66
	Cooked	51.8	73.9
Ground pork	Raw	22.3	82.9
	Cooked	24.5	73
Pork chop	Raw	25.3	70.1
	Cooked	27.3	62.9

Discussion.

This study presents a scan-level LCA of carbon, energy, water, and land footprints of pork meat versus plant-based non-meat alternative patties including an assessment of nutrient-rich food (NRF) indices. A combination of lifecycle inventory compilation, lifecycle impact assessment, and nutrient quality assessment of pork and non-meat alternatives were reported. Specific attention was paid to differential rates of cooking loss of each product at consumption stage. Differences in environmental impacts were observed between products: Beyond Burger, Impossible Burger, Veggie Burger, and Pork. Pork consumption had the highest relative impact in global warming potential and land occupation. Feed production for swine was responsible for a significant fraction of impacts. For meatless alternatives, production of ingredients was the largest contributor to most of the impact categories. Unlike to other plant-based patties, the IB consumption had high intensity of energy demand, especially electricity consumption, during the manufacturing stage. One notable result of this analysis is that the contribution at processing and packaging is relatively low and that retail refrigeration and in-home cooking with loss are not insignificant contributors to the overall environmental impacts.

We evaluated nutrient profiles as roughly equivalent to midpoint environmental impact scores. The nutrient profiles are constructed by accounting for the inclusion of 9 or 15 nutrients to be encouraged and 3 nutrients (saturated fat, added sugar, and sodium) to be discouraged in diets. According to nutrient profiling, pork products showed lower NRF9.3 scores compared to BB and VB (higher scores indicate a higher nutritional value). The IB has lower NRF9.3 score than pork products because the large amount of saturated fat, which is a discouraged nutrient. However, pork products show higher NRF15.3 scores. The larger amount of Thiamin and Riboflavin content in pork products explain the different results. It is important to address different aspects of nutritional quality in pork and non-meat alternatives. This initial evaluation of nutrient quality in the context of environmental sustainability highlights the need for further research at the intersection of dietary health and environmental sustainability. In particular, the role of micronutrients is important, as demonstrated by the difference of the NRF 9.3 and 15.3 results.

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Appendix

Table 7. Life cycle inventories for production of one-serving of Beyond Burger.

Output to Market	Amount	Unit	Ingredient
Beyond Burger	113	g	
Production Factors			
Resources	Amount	Unit	
Water, consumptive use, unspecified origin/m3	1.1411	l	
Occupation, industrial area, US	0.00005454	m2a	
Ingredients			
Tap water {GLO}| market group for | Cut-off, U	59.8	g	Water
Pea, protein-concentrate, at plant/US Economic	23	g	Pea protein isolate
Rape oil, crude {CH}| market for | Cut-off, U	10.7	g	Canola oil (expeller-pressed)
Coconut oil, crude {GLO}| market for | Cut-off, U	2.88	g	Coconut oil (refined)
Rice protein, protein extraction, at plant/GLO Economic	2.88	g	Rice protein
Flavorings	2.88	g	Natural flavor
Cocoa butter	2.88	g	Cocoa butter
Pea, protein-concentrate, at plant/US Economic	2.88	g	Mung bean protein
Carboxymethyl cellulose, powder {GLO}| market for | Cut-off, U	1.31	g	Methylcellulose
Potato starch {GLO}| market for | Cut-off, U	1.31	g	Potato starch
Apple {US}| apple production | Cut-off, U	0.3	g	Apple extract
Pomegranate {GLO}| market for pomegranate | Cut-off, U	0.3	g	Pomegranate extract
Sodium chloride, powder {GLO}| market for | Cut-off, U	0.3	g	Salt
Potassium chloride, as K2O {GLO}| market for | Cut-off, U	0.28	g	Potassium chloride
Acetic acid, without water, in 98% solution state {GLO}| market for | Cut-off, U	0.3	g	Vinegar
Lemon {GLO}| market for lemon | Cut-off, U	0.3	g	Lemon juice concentrate
Refined sunflower oil, from crushing (solvent) at plant/UA Economic	0.3	g	Sunflower lecithin
Sugar beet pulp {CH}| beet sugar production | Cut-off, U	0.3	g	Beet juice extract
Packaging Materials			
Polyurethane, rigid foam {RER}| market for polyurethane, rigid foam | Cut-off, U	12	g	
Kraft paper, bleached {GLO}| market for | Cut-off, U	1.36	g	
Polyethylene, high density, granulate {GLO}| market for | Cut-off, U	0.84	g	
Corrugated board box {RER}| market for corrugated board box | Cut-off, U	14.9375	g	
Solid unbleached board {GLO}| market for | Cut-off, U	13.7	g	
EUR-flat pallet {GLO}| market for | Cut-off, U	8.013E-06	p	
Packaging film, low density polyethylene {GLO}| market for | Cut-off, U	0.0001827	kg	
Energy Demand			
Electricity, low voltage {US}| market group for | Cut-off, U	0.10752	kWh	
Heat, district or industrial, natural gas {GLO}| market group for | Cut-off, U	0.0654948	MJ	

Transport			
Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, freezing {GLO}| market for | Cut-off, U	0.15255	tkm	
Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, U	0.1526	tkm	
Waste to Treatment			
Waste plastic, mixture {CH}| treatment of, sanitary landfill | Cut-off, U	12.84	g	
Municipal solid waste {CH}| treatment of, sanitary landfill | Cut-off, U	15.06	g	
Mixed plastics (waste treatment) {GLO}| recycling of mixed plastics | Cut-off, U	12.84	g	
Core board (waste treatment) {GLO}| recycling of core board | Cut-off, U	14.9375	g	

Table 8. Life cycle inventories for production of one-serving of Impossible Burger.

Output to Market	Amount	Unit	Ingredient
Impossible Burger	113	g	
Production Factors			
Resources	Amount	Unit	
Water, consumptive use, unspecified origin/m3	1.581	l	
Occupation, industrial area, US	0.00005406	m2a	
Ingredients			
Tap water {GLO}| market group for | Cut-off, U	65.22	g	Water
Soybean protein concentrate, from crushing (solvent, for protein concentrate), at plant//US EI3 U	28.3	g	Soy protein concentrate
Coconut oil, crude {GLO}| market for | Cut-off, U	7.1	g	Coconut oil
Refined sunflower oil, from crushing (pressing) at plant/UA Economic	7.1	g	Sunflower oil
Flavorings	2.26	g	Natural flavors
Potato protein, from wet milling, at plant/DE Economic	0.94	g	Potato protein
Carboxymethyl cellulose, powder {GLO}| market for | Cut-off, U	0.94	g	Methylcellulose
Fodder yeast {CH}| ethanol production from whey | Cut-off, U	0.94	g	Yeast extract
Maize starch, from wet milling (starch drying), at plant/US Economic	0.94	g	Cultured dextrose
Maize starch {GLO}| market for | Cut-off, U	0.94	g	Food starch modified
Soybean protein concentrate, from crushing (solvent, for protein concentrate), at plant//US EI3 U	0.91	g	Soy leghemoglobin
Sodium chloride, powder {GLO}| market for | Cut-off, U	0.91	g	Salt
Pea, protein-isolate, at plant/RER Economic	0.91	g	Soy protein isolate
Vitamin E, surrogate, at plant/US U EI3	0.9533	g	Vitamins
Ammonia, liquid {RER}| market for | Cut-off, U	1.7628	g	Ammonia, liquid
Ammonium sulfate, as N {GLO}| market for | Cut-off, U	0.61811	g	Ammonium sulfate
Chemical, organic {GLO}| market for | Cut-off, U	0.53347	g	Chemical, organic
Boric acid, anhydrous, powder {GLO}| market for | Cut-off, U	0.00000565	g	Boric acid
Sodium sulfate, anhydrite {RER}| market for | Cut-off, U	0.01695	g	Sodium sulfate
Acetic acid, without water, in 98% solution state {GLO}| market for | Cut-off, U	15.6322	g	Acetic acid

Chemical, inorganic {GLO}| market for chemicals, inorganic | Cut-off, U	0.000122	g	Chemical, inorganic
Copper sulfate {GLO}| market for | Cut-off, U	0.00147	g	Copper sulfate
Iron sulfate {RER}| market for iron sulfate | Cut-off, U	0.01582	g	Iron sulfate
Magnesium sulfate {GLO}| market for | Cut-off, U	0.461	g	Magnesium sulfate
Manganese sulfate {GLO}| market for | Cut-off, U	0.00073224	g	Manganese sulfate
Potassium carbonate {GLO}| market for | Cut-off, U	0.37064	g	Potassium carbonate
Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U	16.754	g	Sodium hydroxide
Sulfuric acid {RER}| market for sulfuric acid | Cut-off, U	0.00122	g	Sulfuric acid
Packaging Materials			
Kraft paper, bleached {GLO}| market for | Cut-off, U	2.5	g	
Polyethylene, high density, granulate {GLO}| market for | Cut-off, U	5.833	g	
Corrugated board box {RER}| market for corrugated board box | Cut-off, U	10.3	g	
EUR-flat pallet {GLO}| market for | Cut-off, U	3.561E-06	p	
Packaging film, low density polyethylene {GLO}| market for | Cut-off, U	0.0000812	kg	
Energy Demand			
Electricity, low voltage {US}| market group for | Cut-off, U	0.439025	kWh	
Heat, district or industrial, natural gas {GLO}| market group for | Cut-off, U	0.049266	MJ	
Transport			
Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, freezing {GLO}| market for | Cut-off, U	0.1508	tkm	
Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, U	0.1508	tkm	
Waste to Treatment			
Waste plastic, mixture {CH}| treatment of, sanitary landfill | Cut-off, U	5.833	g	
Municipal solid waste {CH}| treatment of, sanitary landfill | Cut-off, U	2.5	g	
Core board (waste treatment) {GLO}| recycling of core board | Cut-off, U	10.3	g	

Table 9. Life cycle inventories for production of one-serving of Veggie Burger.

Output to Market	Amount	Unit	
Veggie Burger	67	g	
Production factors			
Resources	Amount	Unit	
Water, consumptive use, unspecified origin/m3	0.9	l	
Occupation, industrial area, US	3.23E-05	m^2a	
Ingredients			
Tap water {GLO}| market group for | Cut-off, U	15.88	g	Water
Fava bean, organic {GLO}| market for | Cut-off, U	13.81	g	Black bean
Rice {GLO}| market for | Cut-off, U	2.62	g	Brown rice
Onion {GLO}| market for | Cut-off, U	2.62	g	Onion
corn grain; US national average; at regional storage/US U EI3	2.62	g	Corn

Crude maize germ oil, from wet milling (germ oil production, solvent), at Soybean protein concentrate, from crushing (solvent, for protein	2.62 2.62	g g	Corn oil Soy protein concentrate
Wheat grain {US}| wheat production | Cut-off, U	2.62	g	Wheat
Egg, spray-dried, at plant/US S	2.62	g	Egg whites
Tomato, processing grade {GLO}| market for tomato, processing grade |	2.62	g	Tomatoes
Wheat protein	2.62	g	Wheat gluten
Green bell pepper {GLO}| market for | Cut-off, U	1.34	g	Chiles, green
Soda, powder, at plant/US- US-EI U	1.34	g	Onion powder
Calcium carbonate, precipitated {GLO}| market for calcium carbonate,	1.34	g	Calcium caseinate
Maize starch {US}| market for | Cut-off, U	1.34	g	Starch, corn
Potato juice concentrated, from wet milling, at plant/DE Economic/US US-	1.34	g	Tomato juice
Fodder yeast {CH}| ethanol production from whey | Cut-off, U	1.34	g	Yeast extract
Sodium chloride, powder {GLO}| market for | Cut-off, U	0.7	g	Salt
Vitamin Premix, surrogate, at plant/US U	0.46	g	Spices
Glucose {GLO}| market for glucose | Cut-off, U	0.46	g	Dextrose
Strontium carbonate {GLO}| market for | Cut-off, U	0.46	g	Tomato powder
Wheat protein	0.46	g	Vegetable protein
Green bell pepper {GLO}| market for | Cut-off, U	0.46	g	Jalapeno pepper
Citric acid {GLO}| market for | Cut-off, U	0.46	g	Citric acid
Flavorings	1.3	g	Flavors
Green bell pepper {GLO}| market for | Cut-off, U	0.46	g	Paprika
Maize starch {GLO}| market for | Cut-off, U	0.46	g	Starch, modified corn
soybeans; US national average; at regional storage/US U EI3	0.46	g	Soy sauce
Chicory root, at farm/NL Economic	0.46	g	Xanthan gum
Vitamin Premix, surrogate, at plant/US U	0.05	g	Vitamins, Caramel color
Packaging materials			
Kraft paper, bleached {GLO}| market for | Cut-off, U	2.5	g	
Polyethylene, high density, granulate {GLO}| market for | Cut-off, U	3.475	g	
Polypropylene, granulate {GLO}| market for | Cut-off, U	0.55	g	
Corrugated board box {GLO}| market for corrugated board box | Cut-off, U	9.275	g	
EUR-flat pallet {GLO}| market for | Cut-off, U	4.01E-06	p	
Packaging film, low density polyethylene {GLO}| market for | Cut-off, U	9.1E-05	kg	
Energy demand			
Electricity, low voltage {US}| market group for | Cut-off, U	0.06375	kWh	
Heat, district or industrial, natural gas {GLO}| market group for | Cut-off, U	0.2894	MJ	
Transport			
Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, freezing {GLO}| market for | Cut-off, U	0.09045	tkm	
Transport, freight, lorry 16-32 metric ton, EURO6 {GLO}| market for | Cut-	0.09045	tkm	
Waste to treatment			
Waste plastic, mixture {CH}| treatment of, sanitary landfill | Cut-off, U	4.025	g	
Municipal solid waste {CH}| treatment of, sanitary landfill | Cut-off, U	2.5	g	
Core board (waste treatment) {GLO}| recycling of core board | Cut-off, U	9.275	g	

Table 10. Life cycle inventories for 1 kg of flavourings produced at manufacturing.

Reference flow	Amount	Unit
Flavorings	1	kg

Inventories		
Materials/fuels		
3-methyl-1-butyl acetate {GLO}| market for | Cut-off, U	0.2	kg
Pyridine {GLO}| market for | Cut-off, U	0.2	kg
Cyclohexanone {GLO}| market for | Cut-off, U	0.2	kg
Benzaldehyde {GLO}| market for | Cut-off, U	0.2	kg
Vanilla {GLO}| market for vanilla | Cut-off, U	0.2	kg

Table 11. Life cycle inventories for 1 kg of product displayed at retail.

Reference flow	Amount	Unit
Retail	1	kg
Inventories		
Resources	Amount	Unit
Occupation, urban	0.00009	m^2a
Materials/fuels		
Electricity, low voltage {US}| market group for | Cut-off, U	0.52116	kWh
R-404a, refrigerant EI3	4.89E-05	kg
Chlorodifluoromethane {GLO}| market for | Cut-off, U	5.74E-05	kg
Heat, district or industrial, natural gas {CA-QC}| heat production, natural gas, at industrial furnace >100kW | Cut-off, U CSU	0.286689	cuft
Tap water {CA-QC}| market for | Cut-off, U	1.658	kg
Emissions to air		
Methane, chlorodifluoro-, HCFC-22	1.046	kg
Waste to treatment		
Wastewater, average {CA-QC}| treatment of wastewater, average, capacity 1E9l/year | Cut-off, U	0.2639	l

Table 12. Life cycle inventories for 1 kg of product cooking in home.

Reference flow	Amount	Unit
Cooking in home	1	kg
Inventories		
Materials/fuels		
Electricity, low voltage {US}| market group for | Cut-off, U	0.556	kWh
Heat, central or small-scale, natural gas {RER}| market group for | Cut-off, U	1.33452	MJ

Table 13. Life cycle inventories for 1 kg of product at consumption stage.

Reference flow	Amount	Unit
Consumer	1	kg
Inventories		
Materials/fuels		
Electricity, low voltage {US}| market group for | Cut-off, U	0.1567	kWh
Transport, passenger car, small size, petrol, EURO 5 {GLO}| market for | Cut-off, U	0.0125	km
Dishwash EI3	0.9691	kg
Emissions to air		
Methane, biogenic	0.02872	kg

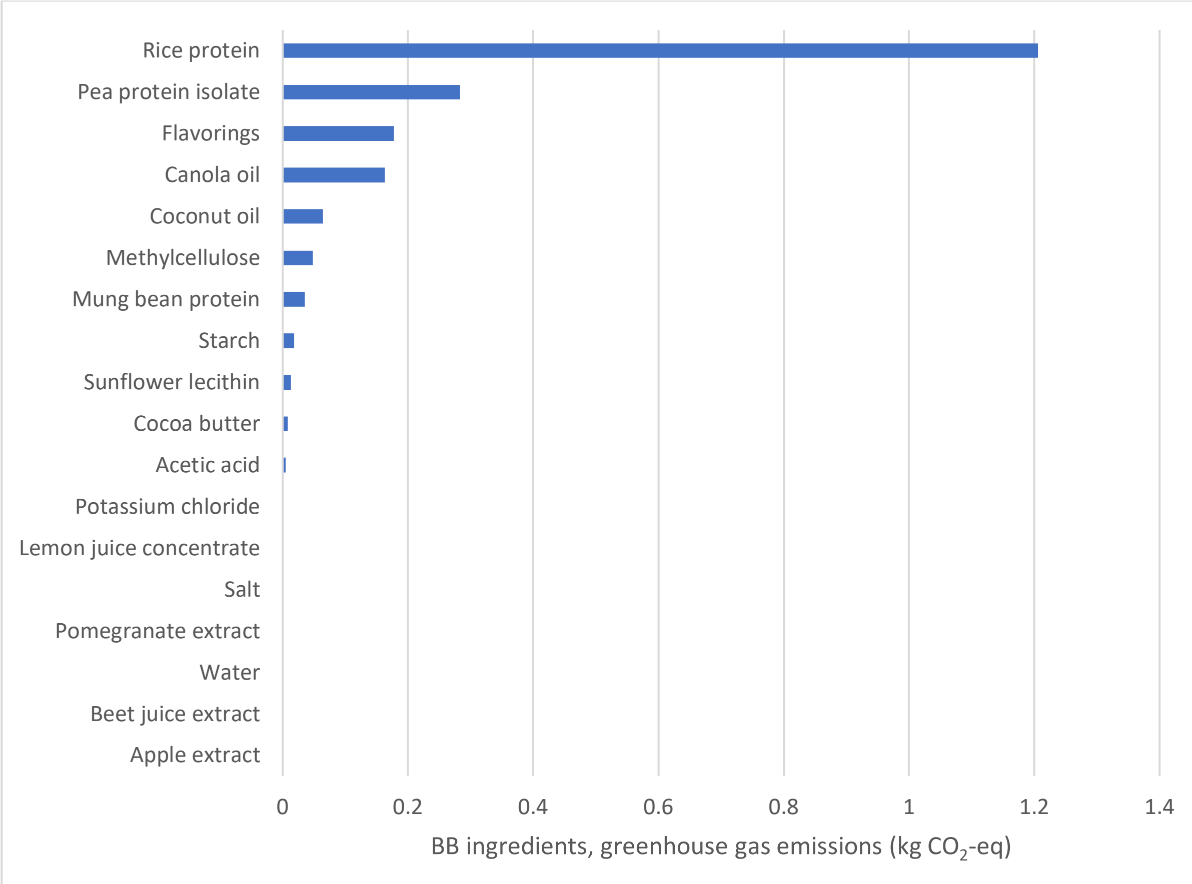

Figure 9. GHGE contributions of ingredients in BB.

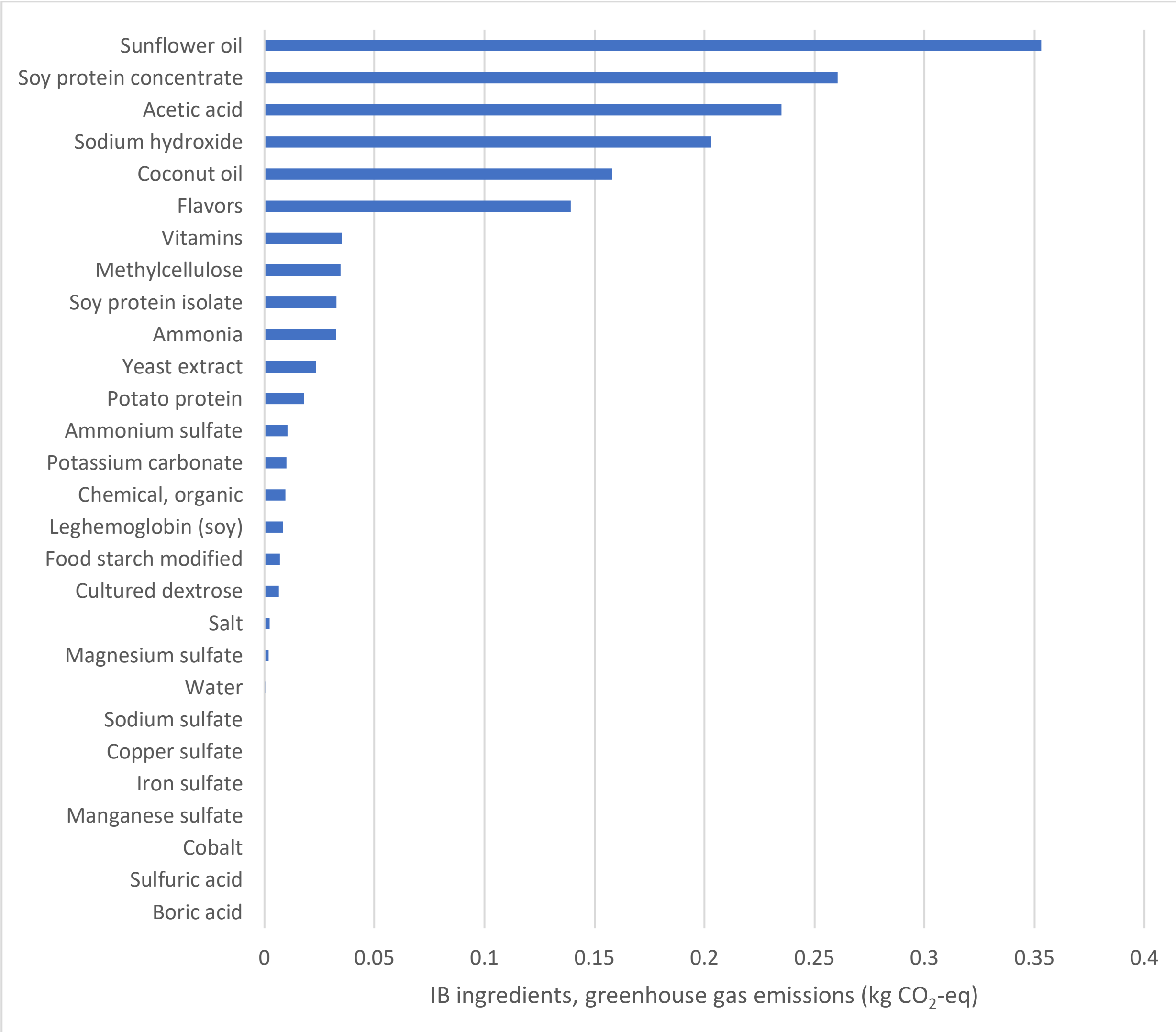

Figure 10. GHGE contributions of ingredients in IB.

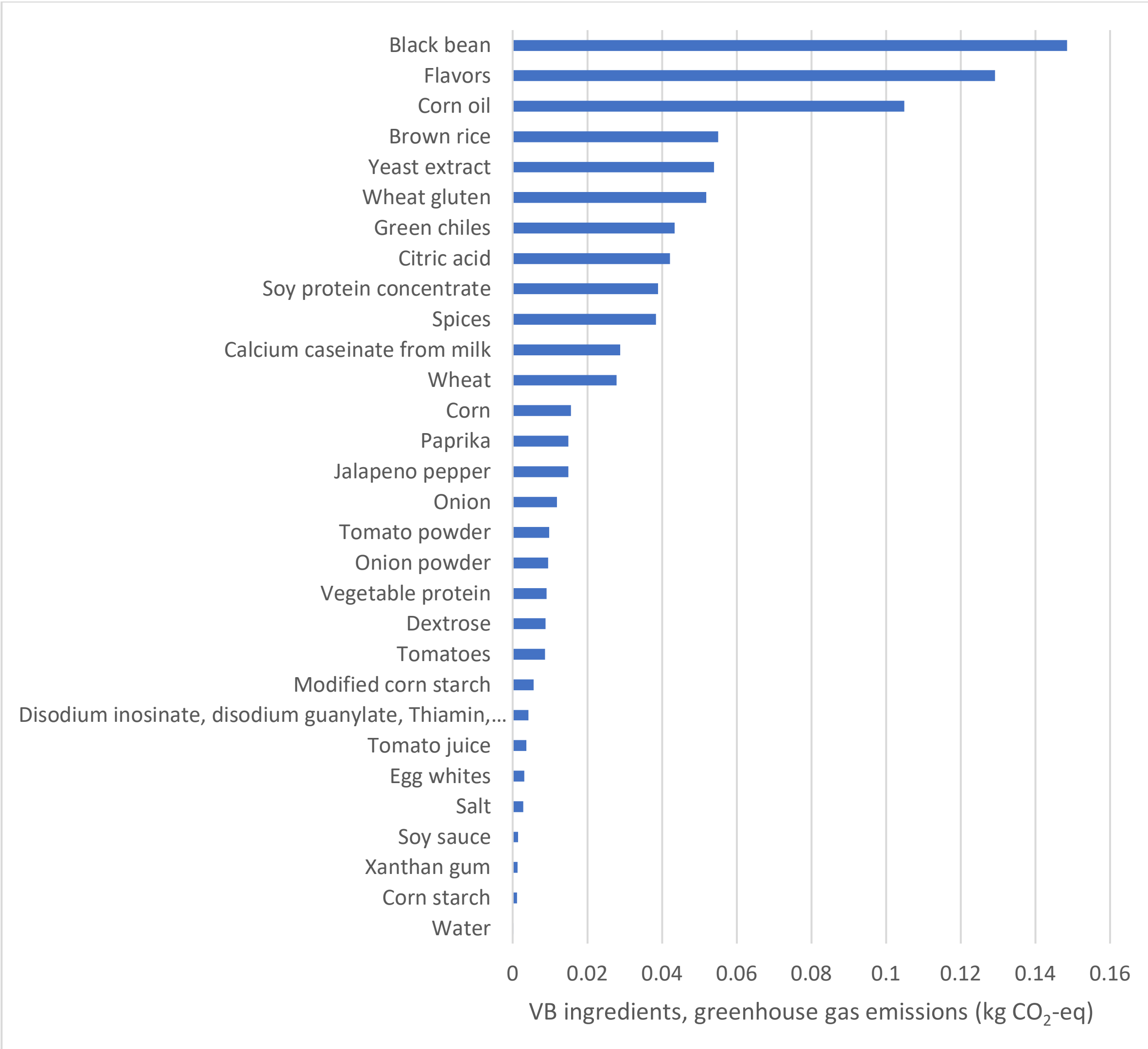

Figure 11. GHGE contributions of ingredients in VB.

Standard reference and brand nutrient composition data used for linear program recipe formulation											
Nutrient Proximate Per 100g	Water	Energy	Protein	Total lipid (fat)	Carbohydrate, by difference	Fiber, total dietary	Sugars, total	Calcium, Ca	Iron, Fe	Sodium, Na	Zinc, Zn
Unit	g	kcal	g	g	g	g	g	mg	mg	mg	mg
No data	0	0	0	0	0	0	0	0	0	0	0
Oil, canola	0	884	0	100	0	0	0	0	0	0	0
Oil, sunflower, linoleic, (partially hydrogenated)	0	884	0	100	0	0	0	0	0	0	0
Oil, coconut	0.03	892	0	99.06	0	0	0	1	0.05	0	0.02
Oil, corn, industrial and retail, all-purpose salad or cooking	0	900	0	100	0	0	0	0	0	0	0
Corn starch		375	0	0	87.5					0	
Spices, garlic powder	6.45	331	16.55	0.73	72.73	9	2.43	79	5.65	60	2.99
Tomato powder	3.06	302	12.91	0.44	74.68	16.5	43.9	166	4.56	134	1.71
Unsweetened pea protein powder		370	77.78	5.56	7.41	3.7	0	74	23.33	963	
pea protein isolate		400	84	8							
pea protein isolate		360.4	72.0		3.0			129.0	24.0	960.1	
Soy protein isolate	4.98	335	88.32	3.39	0	0	0	178	14.5	1005	4.03
Soy protein concentrate	5.8	328	63.63	0.46	25.41	5.5	20	363	10.78	3	4.4
Soy sauce made from soy (tamari)	66	60	10.51	0.1	5.57	0.8	1.7	20	2.38	5586	0.43
Potato flour	6.52	357	6.9	0.34	83.1	5.9	3.52	65	1.38	55	0.54
Bulgur, dry	9	342	12.29	1.33	75.87	12.5	0.41	35	2.46	17	1.93
Yeast extract dry	5.08	325	40.44	7.61	41.22	26.9	0	30	2.17	51	7.94
Tomato juice, canned, without salt added	94.24	17	0.85	0.29	3.53	0.4	2.58	10	0.39	10	0.11
Tomatoes, crushed, canned	89.44	32	1.64	0.28	7.29	1.9	4.4	34	1.3	186	0.27
Peppers, hot chili, green, raw	87.74	40	2	0.2	9.46	1.5	5.1	18	1.2	7	0.3

Onions, raw	89.11	40	1.1	0.1	9.34	1.7	4.24	23	0.21	4	0.17
Spices, onion powder	5.39	341	10.41	1.04	79.12	15.2	6.63	384	3.9	73	4.05
Vital wheat gluten	8.2	370	75.16	1.85	13.79	0.6	0	142	5.2	29	0.85
Corn grain, yellow	10.37	365	9.42	4.74	74.26	7.3	0.64	7	2.71	35	2.21
Beans, black, mature seeds, cooked, boiled, without salt	65.74	132	8.86	0.54	23.71	8.7	0.32	27	2.1	1	1.12
Rice, brown, long-grain, cooked	70.27	123	2.74	0.97	25.58	1.6	0.24	3	0.56	4	0.71
Egg, white, raw, fresh	87.57	52	10.9	0.17	0.73	0	0.71	7	0.08	166	0.03
Potato protein	5	166.7	41.7	0	0	0	0				
Potato starch		333	0	0	83.33	0	0				
Konjac/Xanthan Gum	5	50	0	0	0	95	0				
Bamboo shoots	91	27	2.6	0.3	5.2	2.2	3	13	0.5	4	1.1
Paprika	11.24	282	14.14	12.89	53.99	34.9	10.34	229	21.14	68	4.33
Salt										39400	
Dextrose							100				
Calcium Caseinate	4.8	364	60.61	3.03	24.24	3	18.18	909		424	
Tomato powder		293	14.63	3.66	68.29	7.3	43.9	98	6.59	122	
Bamboo shoots, 5% moisture basis	5	27	27.44	3.167	54.89	23.22	31.67	13	0.5	4	1.1
Glycerine		400			100						
Rice protein	0	400	80	0	13.33	6.7	6.67		13.33	67	
Mung bean protein	67.53	155	6.52	6.86	17.8	7.1	1.86	25	1.31	218	0.78
Cocoa butter	0	884		100							
Vinegar	93.81	21	0	0	0.93	0	0.4	7	0.2	5	0.04
Apple extract (juice)	88.24	46	0.1	0.13	11.3	0.2	9.62	8	0.12	4	0.02

Pomegranate extract (juice)	85.95	54	0.15	0.29	13.13	0.1	12.65	11	0.1	9	0.09
Beet juice	92.45	25	0.72	0.06	5.91	1.1	4.84	12	0.57	19	0.21
Soy protein concentrate, produced by acid wash	5.8	328	63.63	0.46	25.41	5.5	20	363	10.78	900	4.4
Source: USDA National Nutrient Database for Standard Reference 1 April 2018 Software v.3.9.5.2_2019-05-07											