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Life Cycle Assessment of Soy Protein Isolate

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Abstract. Life cycle assessment (LCA) of food indicates that plant-based diets have lower impacts on the environment than those which include meat. However, such conclusions are based on a narrow representation of plant-based diets that excludes the growing number of meat substitutes available. These assessments therefore misrepresent the potential range of environmental impacts associated with plant-based diets, which depends in part on the foods people choose to fulfill their protein needs. Many realistic plant-based meat alternatives use soy protein isolate (SPI) to replicate the texture and nutritional profiles of a variety of meats. SPI uses soybean meal (soymeal) as a feedstock, which undergoes mechanical and chemical processing that in turn increases the environmental impact of the final product. The environmental impacts of SPI per kilogram are estimated here using LCA and expressed in terms of greenhouse gas emissions, freshwater eutrophication, land use, water depletion, fossil fuel use, and energy use. These results are compared to published values for soybeans, soymeal, tofu, chicken, pork and beef for reference. Publically available data, published literature and the ecoinvent database are used in SimaPro with the ReCiPe method to estimate environmental impacts associated with production of one kilogram of SPI. Results indicate that SPI has global warming potential higher than unprocessed chicken and pork, and similar to beef. Freshwater eutrophication associated with SPI is below impacts associated with chicken, pork and beef. Water depletion and fossil fuel depletion are higher in SPI than chicken, pork and beef. Energy use for SPI is lower than energy use for chicken, pork and beef. Land use associated with SPI is negative because of environmental credits from allocation to the byproduct of soymeal, soy oil and therefore represents a lower impact than chicken, pork, and beef. These findings demonstrate that this component of realistic fake meat may not be an environmentally preferable alternative to chicken, pork, or beef, depending on the impact categories considered.

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Introduction. Consumers can choose plant-based foods to promote better health, conform with ethical beliefs, and/or preserve the environment (Fox & Ward, 2008). Sustainability and LCA literature support the idea that plant-based diets are better for the environment (de Boer, Schösler, & Aiking, 2014; Pimentel & Pimentel, 2003; Westhoek et al., 2014). Therefore some consumers choose plant-based diets based on the belief that it is a more sustainable option.

Dietary LCA. LCAs of dietary choice typically assess the global warming potential of several diet types and find that the lower on the trophic scale a person eats (e.g. vegetarian or vegan), the lower their diet's associated environmental impacts are (Baroni, Cenci, Tettamanti, & Berati, 2007; Risku-Norja, Kurppa, & Helenius, 2009; Sanfilippo, Raimondi, Ruggeri, & Fino, 2012). These LCAs compare nutritionally equivalent foods and diets that meet the definition of vegetarian or vegan as the case may be and find that plant-based foods or diets are lower in every impact category considered than other options such as a nutritionally balanced omnivore diet or a typical diet for a given country. However, dietary LCA does not include highly processed plant-based animal product substitutes, at least in part because these items do not have existing LCA data published. This is an important omission to address because people transitioning to a plant-based diet or omnivores trying to reduce their environmental impacts are likely to include some of these substitutes. Some will continue to eat these products over a longer term as well. The impact of this choice is unclear until an investigation of the associated environmental impacts of these alternatives is performed.

Mapping the LCA Literature.

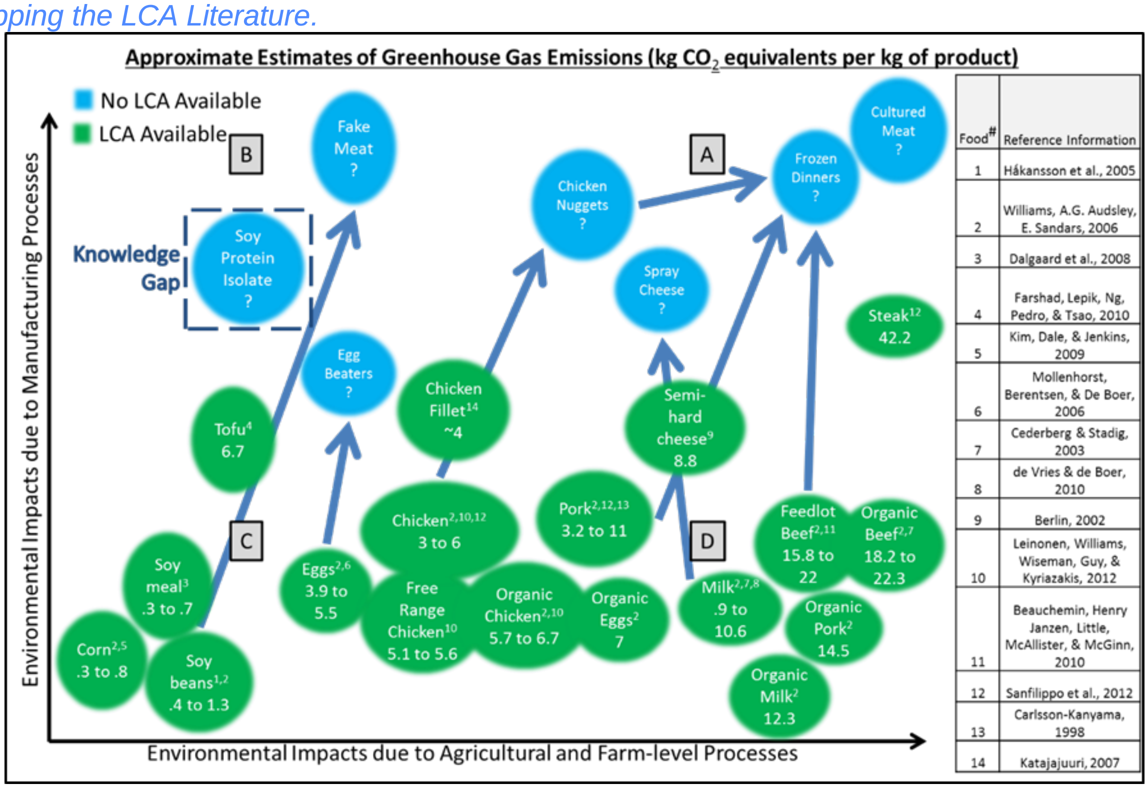

Figure 1. Conceptual Map of Food LCA Literature. Areas A-D are quadrants for later reference. Global warming potential is indicated within green circles, which are products for which LCA data exists. Blue circles are products without existing LCA data. Impacts from activities up to harvest are on the x-axis while impacts from post-harvest processing are on the y-axis. Positions on the map are estimations, not exact values.

Figure 1 shows the potential for tradeoffs that exists when consumers shift dietary choices from quadrant D to B, as in the case of a person replacing chicken with a fake meat. The X-axis represents environmental impacts that occur as a result of farm-level activities such as growing crops or raising livestock, while the Y-axis represents environmental impacts that occur as a result of manufacturing activities such as refining ingredients or preparing food from raw ingredients. Most dietary LCA comparisons are between quadrants C and D. There is potential for post-harvest processing and manufacturing to result in environmental impacts which are similar to those of products fake meats are intended to replace, negating environmental benefit consumers expect from these products. It should be noted that impacts from additional processing apply not only to plant-based foods, but also products for omnivores, such as ready-made meals and processed animal-based foods, which have higher environmental impacts than home-made meals (Schmidt Rivera, Espinoza Orias, & Azapagic, 2014). Consumers make difficult choices based on saving time, money, the environment or their health, so they deserve to be informed regarding the differences between products they consider.

Purpose and Hypothesis. Tradeoffs between farm-level and manufacturing based environmental impacts lead to skepticism regarding the environmental benefits of reducing meat consumption when the substitute is made with SPI or other highly processed ingredients. The purpose of this paper is to investigate the tradeoffs involved in shifting food choices from quadrant D to quadrant B of Figure 1. LCA of soy protein isolate (SPI) is used as a case study to demonstrate the potential impacts of fake meat. SPI is a common ingredient in fake meat and typically constitutes a large percentage of the final product (Thrane, Hansen, Fairs, Dalgaard, & Schmidt, 2014). Although the feedstock, soymeal, has relatively low impacts from agricultural processes, SPI has potential for high impacts due to manufacturing processes. It therefore serves as an appropriate representation of food in quadrant B of Figure 1.

Hypothesis. There is a positive correlation expected between processing required to create a food product and the environmental impacts associated with that food product. Further, it is possible that a plant-based food product may be so extensively processed that it is equivalent to or worse than an unprocessed animal product in terms of its environmental impacts.

Investigative Method. LCA is used to investigate the environmental impact characteristics of SPI. This attributional LCA relies on data from existing systems. Impact assessment is accomplished using the ReCiPe midpoint model with the hierarchist cultural perspective. The functional unit and reference flow are both set as 1 kg of soy protein isolate, which is compared to 1 kg of soybeans, soymeal, tofu, chicken, pork, and beef for reference. SPI has 90% protein and is considered a complete protein (Thrane et al., 2014). A weight based functional unit is selected because it allows simple conversion of impacts to any nutrient based on another functional unit such as protein or calories as nutritional data for these products is available. Data for SPI production practices (Processes 1-7 in Figure 2) comes from the Food and Agriculture Organization of the United Nations, a publication and Master's thesis by Zara Nazareth, and several other publications regarding the production of SPI (Berk, 1992; Cho, Shen, & Mooshegian, 2008; Joshi, Londhe, Bhosale, & Kale, 2011; Z. M. Nazareth, Deak, & Johnson, 2009; Z. Nazareth, 2009; "Soybean Protein Concentrates (SPC)," 1992). Data for ingredients comes from the Ecoinvent database where available, with all other data explained in the supplemental information section.

Product and System Boundaries. It is assumed SPI is made in the US with components grown or manufactured in the US. Soymeal is approximated using an LCA of soymeal grown in Argentina and delivered to the Netherlands, which is edited for this LCA in SimaPro to match transportation data for shipping within the US instead (Dalgaard et al., 2008).

System boundaries include life cycle stages from farming to production of SPI as shown in Figure 2. Data comes from LCAs that also have cradle to gate boundaries. Distribution, use and disposal are not considered due to substantial variation in potential uses for SPI. Data gaps result in the production of capital goods being left outside the system boundaries.

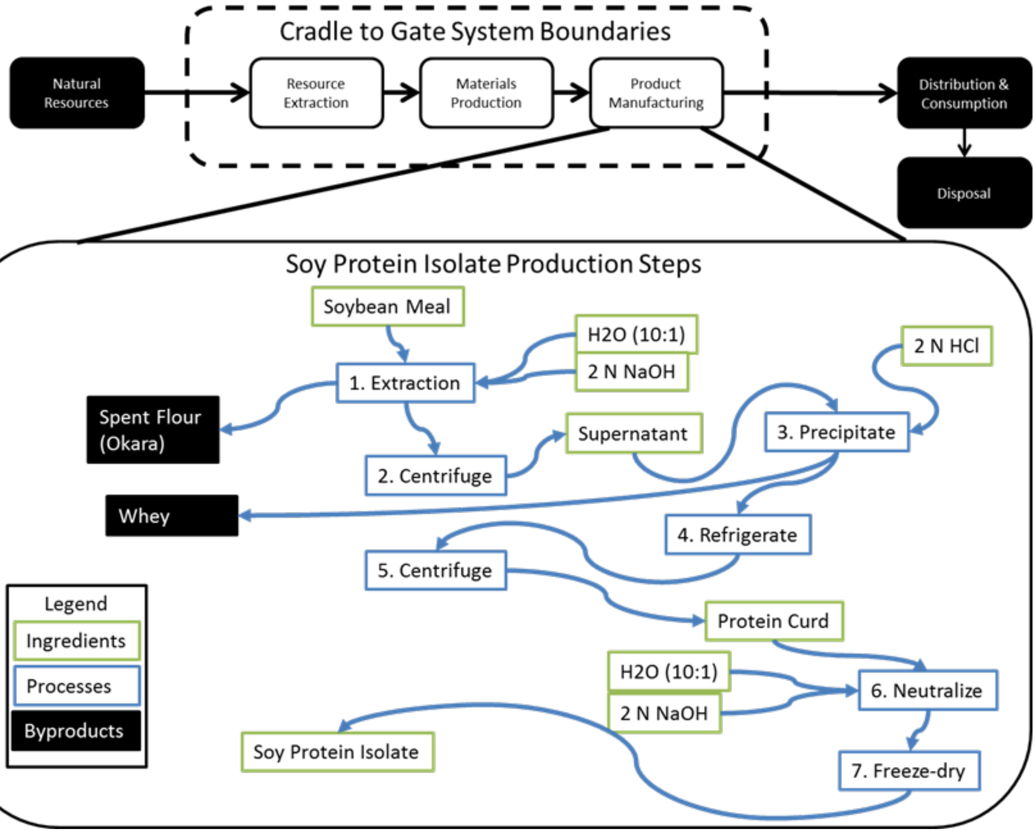

Figure 2. System Boundaries and Process Flow Diagram for SPI Manufacturing. This LCA is cradle to gate, and focuses on product manufacturing. The process of manufacturing SPI, starting with soymeal, is shown in the callout.

Production of SPI requires 7 primary steps shown in Figure 2 and the use of water, sodium hydroxide (NaOH) and hydrochloric acid (HCl). Twenty-five percent (%) of the original soymeal is lost as whey, a waste product not considered financially viable for use due to being diluted and toxic (Berk, 1992). SPI extraction residue (okara) is approximately 40% of the original soymeal, and is typically pressed, dried, and sold as a protein source for animal feed or dietary fiber in food products for humans (Berk, 1992). This study therefore assumes that okara replaces soy based animal protein feed, so 0.4 kg of soymeal for okara is credited against every kg of soymeal used in the production of 1 kg of SPI. The remaining material is SPI, which is about a third of the original material weight. Soymeal production is assumed to offset rapeseed and palm oil production with the byproduct soybean oil. This is accounted for in the data used for soymeal, which is from a paper using system expansion to avoid coproduct allocation (though it notes the soybean meal is 69% of the economic value while soybean oil is 31% of the economic value) (Dalgaard et al., 2008).

Results. Results are broken down by constituent processes so that hotspots in the life cycle are revealed. Impact categories reported include global warming potential, freshwater eutrophication, agricultural and urban land occupation, water depletion, fossil depletion, and energy use.

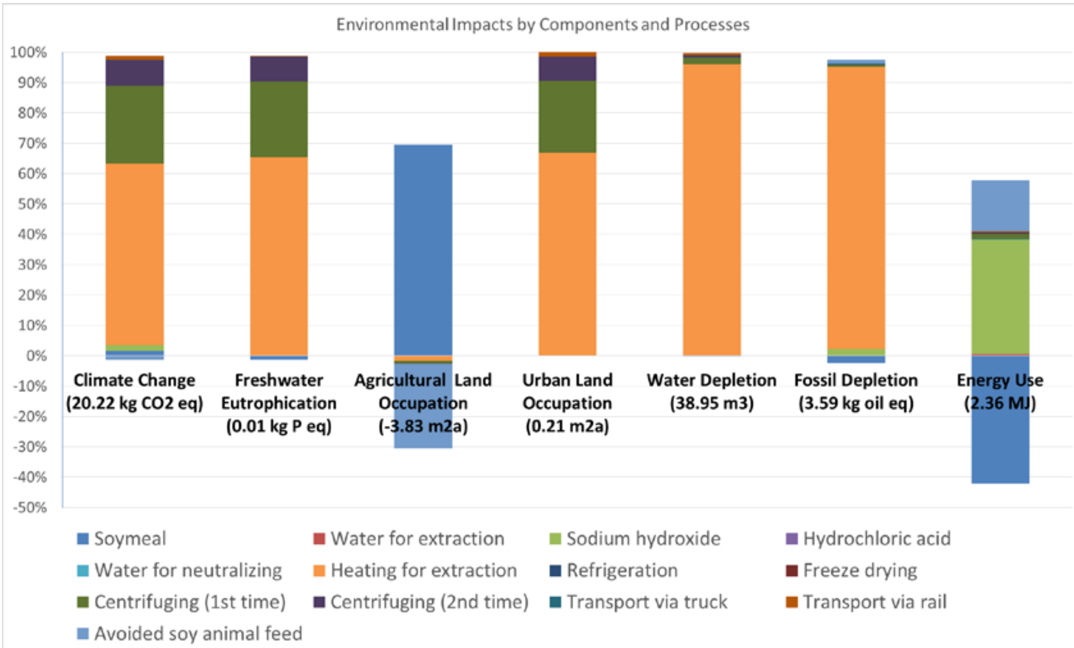

Figure 3. 100% stacked column chart showing contributions to total impacts associated with production of 1 kg of SPI by components and processes.

Figure 3 shows the environmental impacts as percentages of the total for every process across impact categories, and provides the total impact from 1 kg of SPI in each category in parentheses underneath the impact label. It is clear from this graph that the heating for extraction and centrifugation processes are responsible for the majority of impacts. Despite this, soymeal is the main driver of agricultural land use and sodium hydroxide accounts for the majority of energy use.

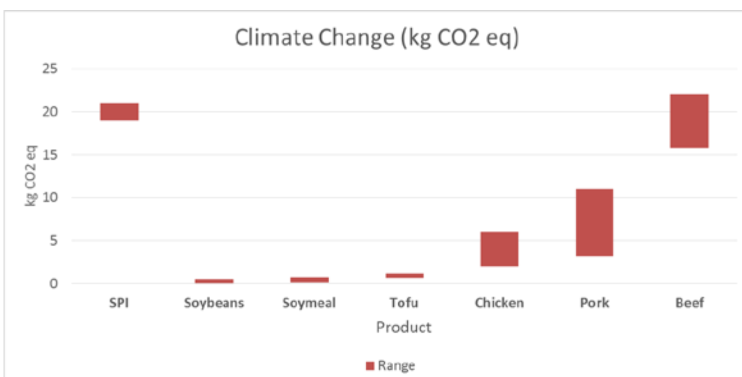

Figure 4. Floating column chart showing approximate ranges for climate change potential of 1 kg each of a variety of comparison products.

As seen in Figure 4, climate change potential of SPI is about 20.2 kg CO_2 equivalents per kg SPI. This can be compared to about 0.6 for soybeans, 0.7 for soymeal, 0.7 for tofu, between 2 and 6 for chicken, between 3 and 11 for pork, and between 16 and 22 for beef (Beauchemin, Henry Janzen, Little, McAllister, & McGinn, 2010; Dalgaard et al., 2008; Farshad, Lepik, Ng, Pedro, & Tsao, 2010; Nijdam, Rood, & Westhoek, 2012; Omni Tech International, 2010; Pelletier, Arsenault, & Tyedmers, 2008). References used are based on similar boundaries and assumptions to ensure a fair comparison.

Freshwater eutrophication has a similar distribution of impacts for SPI to those for climate change, and totals about 0.01 kg P equivalents per kg SPI. Soymeal is credited with negative impacts due to displacement of rapeseed or palm oil, resulting in -0.001 to -0.02 kg P per kg soymeal (Dalgaard et al., 2008). Soybeans contribute 0.003 kg P, chicken contributes between 0.01 and 0.02 kg P, pork contributes 0.07 kg P and beef contributes about 0.13 kg P per kg (de Vries & de Boer, 2010; Leinonen, Williams, Wiseman, Guy, & Kyriazakis, 2012). No data is available for tofu.

Water depletion is dominated by heating for extraction, totaling nearly 40 m^3 of water per kg of SPI produced. Displacement of other oil results in soymeal having a negative impact value of about 0.04 m^3 while soybeans use about 0.05 m^3 of water (Dalgaard et al., 2008; Omni Tech International, 2010). Tofu requires 0.7 m^3, chicken and pork both require about 4 m^3, and beef requires between 0.13 and 15.5 m^3 of water (Capper, 2012; Drastig, Prochnow, Kraatz, Klauss, & Plöchl, 2010; Hằkansson, Gavrilita, & Bengoa, 2005; Hoekstra & Förare, 2008; Ridoutt, Sanguansri, & Harper, 2011).

Fossil depletion is about 3.6 kg oil equivalents per kg SPI, which is again dominated by heating for extraction. No data is available for soybeans or chicken, but soymeal is between -0.03 and -0.09, tofu is between 0.09 and 0.11, pork is about 1 and beef is about 21 kg oil equivalents per kg (Boggia, Paolotti, & Castellini, 2010; Capper, 2012; Farshad et al., 2010; Hằkansson et al., 2005; Nguyen, Hermansen, & Mogensen, 2010).

Energy use of SPI is about 2.5 MJ per kg, which can be compared to -6.35 MJ for soymeal, 2.3 MJ for soybeans, between 0.8 and 43 MJ for tofu, 25 to 40 MJ for chicken, 16.7 to 22 MJ for pork, and 27.8 to 40 MJ for beef (Capper, 2012; de Vries & de Boer, 2010; Farshad et al., 2010; Hằkansson et al., 2005; Leinonen et al., 2012; Pelletier et al., 2008).

Land occupation is between -3.8 and 0.21 m^3 per year per kg SPI due to allocation with soy oil, while soybeans occupy 3.3 m^3 per year, soymeal is -2.3 to -6.8 m^3 per year, chicken is 5 to 25 m^3 per year, pork is 7.4 to 15 m^3 per year, and beef is 23 to 33 m^3 per year (Capper, 2012; Dalgaard et al., 2008; de Vries & de Boer, 2010; Leinonen et al., 2012; Nijdam et al., 2012).

Discussion. For most impact categories, heating is a significant driver. Waste heat recovery technology has the potential to reduce energy consumption by up to 50%, which could lower the environmental impacts of SPI (US Department of Energy, 2008). Results from this analysis indicate that SPI may match or exceed environmental impacts of unprocessed chicken, pork and beef in the categories of global warming potential, water depletion, fossil depletion, and energy use, though it performs better in freshwater eutrophication and land occupation. The hypothesis that there is a positive correlation between processing and environmental impacts is therefore supported by this evidence. It is also demonstrated that it is possible for a plant-based food product to be equivalent to or worse than an unprocessed animal product. Results from this work may be useful for informing decision makers in a variety of contexts, such as policy makers encouraging sustainable production and consumption, non-profit activist organizations promoting sustainable food, marketing specialists for fake meat using other less processed feedstocks such as tofu or seitan, and consumers seeking to lower their environmental impacts (Berardy, 2012). This work demonstrates that it should not be assumed that every plant-based food would be better than an equivalent animal-based food when comparing environmental impacts.

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Supplementary Information

Steps involved in the production of SPI as well as assumptions made for this LCA are described here.

Step 1: Extraction

Soymeal / Soybean Flour:

The amount of soymeal required is based on assumptions regarding byproducts and waste products. The amount of soymeal needed is based on the statement, "Nearly 3 tons of defatted soybean are needed to produce one ton of protein isolate," meaning that 1 kg of SPI would need 3 kg of soymeal to produce (Berk, 1992). This aligns well with the additional statements in this document that Okara is a by-product which is about 40% of the original raw material and that whey is a waste product that is about 25% of the original raw material. The soymeal input is converted into about 1/3 final product (SPI) and 2/3 waste material or by-product. A paper comparing methods for soy protein extraction found that SPI production resulted in solids yield percentages between 30.4% and 38% of the original material (Z. M. Nazareth, Deak, & Johnson, 2009). Finally, trials at lab scale for an extraction technique that minimized time in alkaline condition resulted in soy protein yield percentages between 24.3% and 32% of the original material (Joshi, Londhe, Bhosale, & Kale, 2011). Therefore, it is reasonable to assume that about 3 kg of soymeal are needed for production of 1 kg of SPI. This value is important because the other materials used in production of SPI are determined by ratios found in literature between soymeal and the other materials. Materials used also determine the characteristics of required processing. Therefore, all materials and processes are based on the assumption of using 3 kg of soymeal as the starting feedstock.

Life cycle data for US grown soymeal is not available. The data used for soymeal are from the LCA Food Database, which uses data from a previous study that avoided co-product allocation through system expansion, which ascribes inputs and outputs to soybean meal, but also expands the product system to include avoided production of palm oil and rapeseed oil due to the byproduct of soy oil (Dalgaard et al., 2008; Nielsen et al., 2003). System expansion includes consideration of palm oil and rapeseed oil as products displaced by the coproduct of soymeal, soy oil (Dalgaard et al., 2008). The geographic context for the data used is soymeal grown in Argentina and transported to Rotterdam Harbor in Netherlands (Dalgaard et al., 2008). Transportation values are changed to reflect transportation within the United States as described in the "Transportation" section, but growing processes are assumed to be representative and are not changed.

Transportation:

Transportation occurs via diesel truck and railway freight to get soymeal to the manufacturing facility for creating SPI. Typical transportation distances for soy are 20 to 40 miles on highway in a diesel truck and 900 miles on railway in a freight car (Soy Transportation Coalition, 2013). Translated to ton-kilometers, this means between 0.032 and 0.193 ton-kilometers of transportation are by diesel truck and between 1.448 and 4.345 ton-kilometers of transportation are by freight rail. Detailed calculations are in Appendix A.

Data for transportation via diesel powered truck in the US is taken from the US Life Cycle Inventory (USLCI) database, which does not model infrastructure processes as part of this inventory, but does account for diesel use and tailpipe emissions (National Renewable Energy Laboratory, 2012). Further details regarding modelling assumptions for this data are not available.

Transportation via railway is modeled after diesel powered European freight transport and includes production, maintenance and disposal of vehicles and railway tracks. Therefore the entire transportation life cycle is included and burdens are allocated based on gross ton per kilometer performance. US data for this process is extrapolated from the European data as part of the ecoinvent system process.

Water:

The amount of water used is based on a ratio with the soymeal used of 10:1 (Z. Nazareth, 2009). Therefore, between 30 kg of water is used. The RECIPE model used includes a mix of water use from lakes, rivers, wells and unspecified natural origins (Goedkoop et al., 2013).

Data for water is based on a cradle to gate inventory for drinking water from groundwater, including the purification processes. There are no assumed byproducts or coproducts. This data is from the European reference Life Cycle Database (ELCD).

Sodium hydroxide:

The amount of sodium hydroxide required to produce 1 kilogram of SPI is based on ratios used in a paper describing methods for reducing time the soy mixture has to be alkaline for processing. Three ratios of soy to 0.05 N NaOH are used (1:8, 1:40, and 1:5) (Joshi et al., 2011). For NaOH, 1 N is the same as 1 mol. The weight of 1 mol NaOH is 40 grams, to for every kg of water, 2 grams of NaOH is necessary to achieve a 0.05 N NaOH solution (Barrans & Bradburn, 2012). For 3 kg soymeal, 240 grams are necessary because 0.05 N NaOH is added in a 1:40 ratio to soymeal, so 120 liters of 0.05 N NaOH are required. 17 grams of NaOH is also used to raise the pH of water used, assuming that the pH is raised from 7 to 12 for 42.5 kg of water. Sodium hydroxide data is taken from the SimaPro Industry data 2.0 dataset, which does not provide system boundaries or allocation methodology. So, about 0.257 kg of NaOH per kg of SPI is necessary. More details are available in Appendix B.

Heating:

The extraction step requires the material to be at 60° C for 45 minutes. Calculations for heating are based on instructions in a paper intended to close data gaps of food LCA based on energy demand for food processing (Sanjuán, Stoessel, & Hellweg, 2014). The temperature is raised from room temperature, about 15.5° C to 60° C. The specific heat of soymeal is approximated by wheat flour which is 1.85 kJ/kg C, the specific heat of water is 4.186 J/gm K (Sanjuan, Stoessel, & Hellweg, 2014) and the specific heat of sodium hydroxide is 59.66 J/mol K. Therefore these calculations represent the thermodynamic minimum for energy required in this step.

The total energy required to raise the mixture from 15.5° C to 60° C is 11.47 kWh of energy. Detailed step by step calculations for this heating energy requirement are in Appendix B. Electricity is assumed to be used in Iowa, meaning that it comes from the Midwest Reliability Organization West (MROW) grid area. The MROW grid mix is about 65% coal, 14% nuclear, 10% wind, 6% hydroelectric, and the remaining 5% is divided between biomass, gas, oil, other fossil fuels, and other unknown or purchased fuel (Environmental Protection Agency, 2014).

Step 2: Centrifuge

The amount of material centrifuged is based on the assumption that the soymeal will hold its weight in water because SPI can hold 1.2 times its weight in water, so water is expected to double the weight of the soymeal to 6 kg (Z. M. Nazareth et al., 2009). The process of centrifuging results in a waste product of spent flour along with water. After this process the weight of the material should be 3 kg again.

Centrifuging data is based a paper with supporting information to close LCA data gaps which indicates that 2.69 MJ/kg product is used, which translates to 0.747 kWh of energy (Sanjuan et al., 2014). This data reflects energy used for centrifugation, but not upstream impacts.

Step 3: Precipitate

Hydrochloric acid:

The amount of hydrochloric acid is based on an experiment to reduce the time in alkalinity for SPI, which uses 0.1 N HCl in the amounts 22, 98, and 14 ml and 1 N HCl in the amounts of 2, 6, and 1 ml for 10 grams of soy in trials using 1:8, 1:40, and 1:5 ratios of soy to NaOH respectively (Joshi et al., 2011). The amount of HCl necessary is calculated based on the 1:40 ratio because this is used for NaOH. The HCl used needs to be multiplied by 30 to be appropriate for use in 3 kg of soymeal mixture because it is in reference to 10 grams of soy. There is 98 ml .1 N HCl and 6 ml 1 N HCl for the 1:40 ratio, which means for 3 kg soymeal, there is 2.94 L .1 N HCl and .180 L 1 N HCl used. HCl has a molecular weight of 36.46094 g/mol and 1 N is equivalent to 1 M HCl. Therefore, 2.94 L .1 N HCl uses 10.7195 grams HCl and 0.18 L 1 N HCl uses 6.563 grams HCl. The total amount of HCl required is 17.2825 grams, which is about 0.0172825 kg.

Hydrochloric acid data is taken from the ecoinvent database, which includes a cradle to gate inventory including raw materials and chemicals used for production, transport to manufacturing plant, emissions to air and water from production, and energy demand and infrastructure of the plant, with solid wastes omitted. The Mannheim process creates hydrochloric acid with the byproduct of sodium sulphate. Economic allocation is used for sodium sulphate and hydrochloric acid. Data is based on stoichiometry and therefore not associated with a certain geographic area.

Step 4: Refrigerate

The amount of material refrigerated is based on assumptions regarding additions and losses in previous processes and the material is refrigerated overnight (Z. Nazareth, 2009). Spent flour removed in centrifuge is about 40% of the total weight of the starting soymeal (3 kg of soymeal). With 60% of the starting weight left, this is 1.8 kg of material, but some water is left from the precipitation process, so this results in 2 liter days of refrigeration (equivalent to refrigerating 2 liters of mixture for 24 hours). Details regarding refrigeration are based on (Berk, 1992).

Refrigeration data is taken from the LCA Food database. This data reflects energy used for refrigeration, but not upstream impacts such as infrastructure or manufacturing. This data assumes the geographic location of Denmark and modern cooling technology for cold storage.

Step 5: Centrifuge

The amount of material centrifuged in this step is based on the calculations for the refrigeration step, so 2 kg of material is centrifuged.

Centrifuging data is based on a paper with supporting information to close LCA data gaps which indicates that 2.69 MJ is used to complete centrifuging of a kilogram of product (though time to do so is not discussed), which translates to 0.747 kWh of energy used per kilogram of product (Sanjuan et al., 2014). This data reflects energy used for centrifugation, but not upstream impacts.

Step 6: Neutralize

Neutralizing occurs by adding water in a 10:1 ratio and 2 N NaOH. The amount of water is based on a 10:1 ratio with 1.25 kg of material, which is assumed to be left after centrifuging based on a 25% loss subtracted from the weight after the first centrifuge. Therefore, 12.5 kg of water is added. The amount of NaOH added is discussed in more detail in Appendix B.

Step 7: Freeze-dry

Freeze drying is the process of freezing a material and reducing surrounding pressure, allowing frozen water to sublimate (Harris, n.d.). A study of vacuum cooling for vegetables found that between .16 and .26 kWh was necessary to cool between 23 and 27 kg of lettuce, which translates to between .006 and .011 kWh per kg to vacuum cool 1 kg of lettuce (Thompson, Chen, & Rumsey, 1987). Vacuum cooling reduces pressure to lower the boiling point of water, allowing for rapid cooling, which is similar to the steps in freeze drying, except in reverse, so the impacts from the processes are similar (Coldmax Europe, 2013; Harris, n.d.). Most of the energy was used for a compressor, rather than the vacuum pump, meaning that cooling used more energy than creating a vacuum (Thompson et al., 1987). The freeze-dry process is therefore approximated using the energy requirements of a freezer. The amount frozen material is based on the weight calculated for the neutralizing step. So, 1.25 liter days are required to freeze the material.

Freezing data is taken from the SimaPro ecoinvent database, which in this case contains data from lcafood.dk. Freezing detail is based on (Berk, 1992). This data reflects energy used for freezing, but not upstream impacts.

Steps 1 through 7 yield the final SPI product. SPI contains roughly 75% of the protein from the starting material (Berk, 1992).

Life Cycle Assessment of Soy Protein Isolate

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