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# Cradle-to-grave life cycle assessment of production and consumption of pulses in the United States

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ABSTRACT

Environmental impact associated with production and consumption of pulses in the United States was evaluated using life cycle assessment (LCA). The system boundary was set to cradle-to-grave with a functional unit of 60 g (dry basis) of pulses consumed in a US household. Varieties of pulses modeled in the study included field pea (Pisum sativum), lentil (Lens culinaris), chickpea (Cicer arietinum), and dry bean. Three methods of cooking pulses at the consumer stage tested in the study were cooking in open vessel on electric cooking range (OVC), cooking in stovetop pressure cooker on electric cooking range (SPC), and cooking in electric pressure cooker (EPC). OVC formed the base scenario against which all other scenarios were compared. The environmental impact of pulses varied with type of pulse crop, cooking method, and the batch size. Consumption of approximately 60 g of dry pulses resulted in the greatest environmental impact for OVC. The consumer stage contributed at least 83, 81, 76, 75, and 87 percent for global warming potential (GWP), fossil resource scarcity (FRS), water consumption (WC), freshwater eutrophication (FE), and marine eutrophication (ME), respectively for this scenario. EPC resulted in the greatest decrease in the environmental impact, compared to OVC, for GWP, FRS, FE, and ME for all pulse varieties, which was validated in the uncertainty analysis. SPC, on the other hand, decreased the impact across these categories only for chickpea and dry bean. The uncertainty analysis suggested that the differences associated with cooking methods in the mean land use and water consumption scores of pulses were statistically non-significant. The impact categories were also highly sensitive to the mass of pulses cooked in a batch. Increasing the reference flow in OVC to 1 kg decreased the environmental impact of pulses by 49–87 percent for all impact categories, excluding land use. Overall, the study identified the consumer stage as the hotspot for environmental impact in the supply chain of pulses in the United States. The large contribution of the consumer stage to the overall environmental impact of pulses was attributed to electricity consumption for cooking and associated upstream emissions.

## 1. Introduction

Growing population, dwindling resources, and changing climate have increased the pressure on agriculture to improve production and efficiency while maintaining or improving sustainability of the sector. The food sector contributes 19 to 29 percent of global anthropogenic greenhouse gas (GHG) emissions and agriculture is the largest contributor of $CH_4$ and $N_2O$ emissions (MacWilliam et al., 2018). A few major crops such as corn, rice, and wheat cover approximately 40 percent of global arable land and satisfy 50 percent of caloric demand of global population (Ebert, 2014). Overreliance on few major crops to meet the demands of growing population could be agronomically, environmentally, and economically perilous. These crops require substantial amount of synthetic nitrogen (N) fertilizers which results in increased GHG emissions from agriculture (MacWilliam et al., 2018). Monoculture also increases pesticide demand of the sector and results in pest-accumulation due to lack of crop diversity (MacWilliam et al., 2015). Therefore, diversification in crop production is important to improve pest and nutrient management, food production, and overall sustainability of the agriculture sector.

Pulses, which include leguminous crops such as dry beans, field peas, chickpeas, and lentils, when included in crop rotation, can play a major

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role in achieving these objectives by breaking disease and insect cycles and improving soil fertility (MacWilliam et al., 2015). Pulses have an ability to fix atmospheric nitrogen to meet most of their nitrogen demand. The synthetic N fertilizer demand of pulses ranges between 11 and 56 kg N/ha (Brouwer et al., 2015; Franzen, 1998; Kandel et al., 2018; Schatz and Endres, 2009) while that of corn ranges between 110 and 280 kg N/ha (Halvorson and Bartolo, 2014; Kim et al., 2009; Kim and Dale, 2008). This reduced reliance of pulses on synthetic N fertilizer offer various environmental and agronomic benefits. The production of synthetic N fertilizers is energy intensive and their application to soil results in GHG emissions, marine eutrophication, and atmospheric acidification. These impacts can be mitigated by including pulses in crop rotation, which also benefits following cereal crop in terms of improved yield and protein content (MacWilliam et al., 2015).

Pulses can be an excellent source of protein in human diets. Pulses contain 18 to 36 percent protein and are rich in nutrients, vitamins, and minerals (FAO, 2016). Furthermore, high levels of complex carbohydrates and fiber can help stabilizing blood sugar levels, while also providing a feeling of satiety. Chaudhary et al. (2018) reported that when refined wheat flour in pan bread, breakfast cereal, and pasta was partially replaced by Canadian yellow pea flour, the nutrient balance score of these products improved by 11, 70, and 18 percent and decreased GHG emission by 4, 11, and 13 percent, respectively. Consuming pulses such as dry beans and peas was found to increase fiber, protein, folate, zinc, iron, and magnesium intake in human diet while reducing intake of saturated fat and total fat (Mitchell et al., 2009).

However, evaluation of potential benefits and risks associated with any changes made to the existing cropping system is important before these changes are incorporated. Life cycle assessment (LCA), a measurable and quantifiable framework for such assessment, can be valuable for researchers, growers, and policy makers in making informed decisions (ISO, 2006a). While LCA studies of pulse production are available for Canada and a few other parts of the world (Kulshreshtha et al., 2013; MacWilliam et al., 2014a, 2015; Nemecek et al., 2008; Tidåker et al., 2021), only one study exists specific to the US, which exported 11% of global pulse exports in 2017 (Bond, 2019). Gustafson (2017) reported an LCA of US pulse production using survey data collected in six states and covering five pulse crops. The study estimated that GHG emissions associated with pulse crop production were 0.26 and 0.31 kg $CO_2$e/kg for non-irrigated and irrigated crops, respectively. The irrigation water use was 0.19 $m^3$/kg, lower than many other row crops. However, this study did not follow many of the commonly used and internationally standardized methods for performing life cycle assessment and included only two impact categories. The results for these two impact categories were aggregated for all types of pulse crops and differentiated only between irrigated and non-irrigated crops. Also, the underlying survey data excluded North Dakota, one of the largest pulse production states in the United States (USDA National Agricultural Statistics Services, 2017). Furthermore, the study was 'cradle to farmgate' and did not consider post-farmgate processes, which is necessary to provide a holistic sustainability picture of pulse crops. Assessment of impacts associated with both 'cradle to farmgate' and 'post-farmgate' supply chains, including consumption stage, could be important in evaluating and improving sustainability of agricultural sector in general and of pulse production sector specifically. The objective of this study was to perform a 'cradle to grave' attributional LCA of pulse crop production and consumption in the US using national average production and consumption practices for the most commonly grown peas, lentils, chickpeas, and dry beans.

## 2. Material and methods

Production and consumption of pulses was modeled in OpenLCA (GreenDelta). The background processes involved in production, processing, retail, and cooking of pulses were modeled using 'EcoInvent 3.4 – allocation, cut-off by classification' database (Wernet et al., 2016). The model was divided into four stages: crop production, processing, retail, and consumer stage. Process boundaries for each stage encompassed gate-to-gate activities, except for crop production. For example, the processing stage included all activities from transportation of harvested pulses to the processing facility to loading packaged pulses into tractor-trailer containers for distribution to retail. On the other hand, the boundary for crop production stage was set to cradle-to-farmgate.

### 2.1. Goal and scope of study

The primary goal of this study was to evaluate impacts associated with production and consumption of pulses in the United States using attributional LCA. The impacts of pulses were evaluated in terms of global warming potential (GWP) estimated over 100-year horizon, fossil resource scarcity (FRS), land use (LU), water consumption (WC), freshwater eutrophication (FE), and marine eutrophication (ME), using ReCiPe 2016 (H) midpoint life cycle impact assessment (LCIA) method (Huijbregts et al., 2017). These impact categories characterized sustainability of pulse supply chain in the United States.

#### 2.1.1. Functional unit

The functional unit (FU) quantifies the product studied and defines the reference flows for all the inputs and outputs. A functional unit of 60 g of pulses, cooked and consumed in the US household, was selected for this study. The functional unit represented current average weekly consumption of pulses in the United States (HHS and USDA, 2015). The cooking methods evaluated in the study include boiling or pressure-cooking pulses in water until they are cooked. Generally, cooked pulses are used as an ingredient in recipes such as soups, salads, spreads or can be consumed with rice. However, formulating and evaluating these recipes was out of scope for this study.

#### 2.1.2. System boundary

Defining system boundary is crucial in LCA (ISO, 2006a). The system boundary determines the processes in the product life cycle that are included or excluded from analysis. The system boundary for this study was cradle (production of seeds and other agronomic inputs and crop production) to grave (consumption of pulses at consumer's home). The processes included in the system boundary are illustrated in Fig. 1. Resource use and wastage at each stage were fully accounted for each process. Consumption of pulses away from home was excluded from the study. The system boundary also excluded processing and consumption of various finished products (hummus, canned beans, soups etc.) containing pulses. The consumer stage of the analysis was restricted to purchase, cooking, and consumption of dry pulses only. A cutoff criterion of 1% was established for mass flows and/or environmental impact categories. However, data were included regardless of cutoff criterion if they were readily available.

#### 2.1.3. Allocation methodology

Allocation of resources and burden is required for a process with multiple outputs. An ISO 14044 allocation hierarchy (ISO, 2006b) was followed in this study for allocation of inputs and emissions. The primary byproduct of harvesting at the farming stage is crop residue, which is often left on the soil (USA Dry Pea & Lentil Council, 2019). Although the crop residue may provide nutrients to the crops planted in the following season (Bedard-Haughn et al., 2013; Miller et al., 2015), the system boundary excluded recycling of soil nutrients and the burden of material, resources, and emissions was allocated to the harvested pulses. A single processing plant often processes several crops. Therefore, the system specific to the pulses was separated from processing of other crops at the processing facility. Processing pulses primarily produces seed coat and sometimes broken and powdered pulses. Due to lack of data regarding fate of these materials, they were treated as waste disposed in the municipal landfill. Therefore, inputs and emissions were allocated to the packaged pulses. For multifunctional activities such as

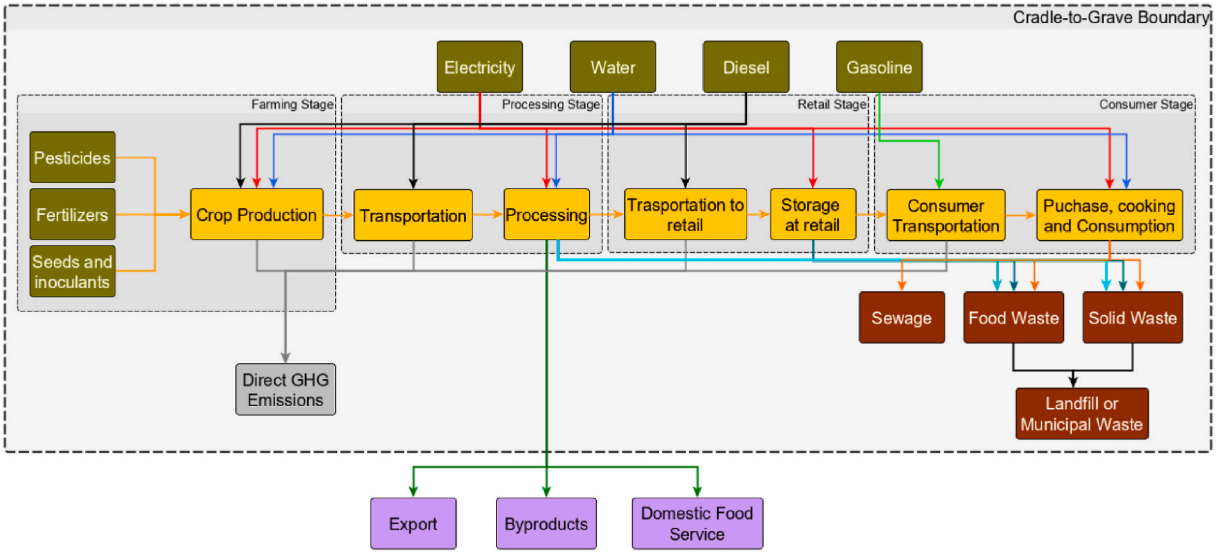


**Fig. 1.** Conceptual model with system boundaries and processes in production and consumption of pulses in the United States.

retail allocation based on shelf space occupied was adopted. A revenue-based approach was adopted at the consumer stage to attribute transportation associated with grocery purchase as well as refrigeration load and microwave usage to pulses when necessary.

## 2.2. Life cycle inventory

Data for life cycle inventory (LCI) was obtained from peer-reviewed manuscripts, crop budgets, extension documents published by the universities, technical specifications published by the manufacturers of crop processing machineries, and various publicly available data repositories and sources. We also consulted experts from the universities and the United States Department of Agriculture (USDA) for crop production data such as seeding rate, fertilizer application rates, and tillage practices.

### 2.2.1. Cradle-to-farmgate

Cradle-to-farmgate activities constitute the first stage in the cradle-to-grave system boundary. It includes seed production and transport, production and transport of fertilizers and pesticides, and all other on-farm activities associated with production of pulses.

*2.2.1.1. Crop production.* The pulse production methods and related data were obtained from expert opinion and from crop budgets and published extension documents. Crop yield was obtained from USDA-NASS survey data. Based on expert opinion, lentils, field peas, and chickpeas were modeled as no-till, dry land crops. This represented the general pulse production practices in Montana and North Dakota. Production practices could vary in other pulse production states. However, no state-specific data were available. Moreover, in 2018 Montana and North Dakota together produced 86 and 81 percent of total national production of field pea and lentil, respectively (USDA National Agricultural Statistics Services, 2017). Therefore, the production practices in these two states were assumed to represent national average. Data provided by experts included fertilizer application rates, seeding rates, and information about types of chemicals used (Miller et al., Personal Communication). Fertilizer application rates suggested by the experts were similar to those used by MacWilliam et al. (2014a, 2014b) for dry pea and lentil production. The dry bean production practices varied from other pulse crops (Miller et al., Personal Communication). However, in absence of specific data, the dry bean production was modeled as a conventionally tilled, dryland crop (Brouwer et al., 2015). Fertilizer application rates for dry beans were considered as an average of the upper and lower threshold provided by Brouwer et al. (2015). Production data for pulse production is provided in Table 1.

**Table 1**
Life cycle inventory for cradle-to-retail stage for variety of pulses. Data in the table are presented for the reference flow of each stage.

| Parameter | Chickpea | Dry bean | Field pea | Lentil |
|---|---|---|---|---|
| **Farming stage** | | | | |
| Seeding rate, kg/ha | 179.33 | 146.83 | 168.13 | 56.04 |
| Yield, kg/ha (Reference flow) | 1769.83 | 1922.60 | 2028.45 | 1342.20 |
| Nitrogen fertilizer, kg N/ha | 5.60 | 44.83 | 5.60 | 5.60 |
| Phosphorous fertilizer, kg P2O5/ha | 28.02 | 33.63 | 28.02 | 28.02 |
| Potassium fertilizer, kg K2O/ha | 8.41 | 8.41 | 8.41 | 8.41 |
| Pendimethalin, kg a.i./ha | 1.24 | – | 1.24 | 1.24 |
| Metolachlor, kg a.i./ha | 1.60 | – | 1.60 | 1.60 |
| Paraquat, kg a.i./ha | 0.54 | 0.54 | 0.54 | 0.54 |
| Glyphosate, kg a.i./ha | – | 1.68 | – | – |
| Dimethenamid, kg a.i./ha | – | 0.86 | – | – |
| **Processing stage** | | | | |
| Reference flow, kg | 1.00 | 1.00 | 1.00 | 1.00 |
| De-stoning electricity[a], kWh | 4.46 E−04 | 4.46 E−04 | 4.46 E−04 | 4.46 E−04 |
| Grading, electricity[b], kWh | 3.34 E−05 | 3.34 E−05 | 3.34 E−05 | 3.34 E−05 |
| Decorticating, electricity[b], kWh | 1.25 E−05 | 1.25 E−05 | 1.25 E−05 | 1.25 E−05 |
| Optical sorting, electricity[b], kWh | 1.79 E−04 | 1.79 E−04 | 1.79 E−04 | 1.79 E−04 |
| Splitting, electricity[b,c], kWh | 1.25 E−03 | 1.25 E−03 | 1.25 E−03 | 1.25 E−03 |
| LDPE film, kg | 6.06 E−03 | 6.06 E−03 | 6.06 E−03 | 6.06 E−03 |
| Water, kg | 0.13 | 0.13 | 0.13 | 0.13 |
| Transportation, tkm | 0.152 | 0.152 | 0.152 | 0.152 |
| Pulses hauled from the farm, kg | 1.52 | 1.52 | 1.52 | 1.52 |
| Pulses processed after de-stoning, kg | 1.33 | 1.33 | 1.33 | 1.33 |
| **Retail Stage** | | | | |
| Pulses, reference flow, kg | 1.00 | 1.00 | 1.00 | 1.00 |
| Electricity, kWh | 0.02 | 0.02 | 0.02 | 0.02 |
| Transportation, tkm | 0.48 | 0.48 | 0.48 | 0.48 |
| Packaged pulses purchased from processing plant | 1.06 | 1.06 | 1.06 | 1.06 |

[a] Electricity consumption estimated for 1.52 kg of pulses delivered from farm.
[b] Electricity consumption estimated for 1.33 kg of pulses processed.
[c] Electricity consumption was assumed equal to decorticating operation due to lack of data.

The pulse production includes herbicide and fungicide applications, and pre-harvest chemical desiccation using Paraquat (Miller et al., Personal Communication). Fungicide applications are particularly important for chickpea production. Herbicides, pesticides, and respective application rates were selected based on data reported by Brouwer et al. (2015), Kandel et al. (2013, 2018), and Schatz and Endres (2009) and available background data in the EcoInvent database. The application rate for Paraquat (a desiccant) was obtained from Syngenta's (2019) website. Application rates of all chemicals were modeled in OpenLCA as mass of active ingredient (a.i.) per hectare (Table 1).

Pulses require rhizobium bacteria to facilitate nitrogen fixation (Kandel et al., 2013). These bacteria are introduced to the soil through inoculants applied either directly to the soil or through seed treatment. The exact composition of inoculants was unavailable. However, MacWilliam et al. (2014b) reported that inoculants usually contain peat moss. Therefore, process for mining peat moss was used as a surrogate process for inoculants.

Field application of fertilizers often leads to nutrient loss in the form of denitrification, leaching, and ammonia volatilization. Considering their contribution to GWP, FE, and ME, accounting for these nutrient losses in LCA model is crucial for accurate analysis. Direct emissions from nitrogen fertilizer application were estimated using IPCC tier-2 method while IPCC tier-1 method was used to estimate indirect emissions (IPCC, 2006). The $N_2O$ emission factor of 0.21% estimated by Dusenbury et al. (2008) for wheat-pea cropping system in the semiarid northern Great Plains was used in the IPCC tier-2 method for direct emissions. This emission factor was less than the default emission factor of 1% suggested by IPCC (2006). Lower fertilizer induced $N_2O$ emissions in the semiarid regions were also confirmed by Sainju et al. (2020, 2012) and Thies et al. (2020). Phosphorus applications often result in loss of soluble phosphorus through leaching and runoff. These pathways were modeled using the method provided by Potter et al. (2006). Post-application fate of crop protection chemicals as well as desiccants used prior to harvest were modeled as emissions to soil.

*2.2.1.2. Seed production and fertilizer transportation.* In 1997, annual seed expenditure by farmers in the United States had reached $7 billion, making it the largest seed market in the world (Fernandez-Cornejo, 2004). This $6.5 billion increase in expenditure, compared to 1960, was largely attributed to increase in the share of seed purchased from commercial sources as a result of technological developments and plant breeding techniques. This makes seed production, processing, and transport a crucial process in terms of LCA.

Commercial seed production processes are proprietary and therefore, are not available in the public domain. In absence of these data, a seed production process 'Pea seed production, for sowing | pea seed, for sowing | Cutoff, U' available in EcoInvient 3.4 database was adapted for this study. The unit process included processes such as pre-cleaning, cleaning, drying, chemical dressing, bag filling, and storage. Four distinct seed production processes were created, each for a specific pulse crop modeled (dry beans, chickpeas, lentils, field peas). The source of seed production and electricity was replaced with relevant crop production processes modeled in OpenLCA and US electricity generation and distribution network, respectively. However, only the source of these processes was changed. We did not change the life cycle inventory data of any input processes.

The 2017 Commodity Flow Survey published by US Bureau of Transportation Statistics was used to determine average transportation distance and contribution from various modes of transportation. In the United States, single mode transportation dominated the sector contributing 92.1% of total mass moved and 81% of total value of shipment. However, about 71% of mass (73% of value of shipment) was moved by trucks in the United States. Therefore, transportation of seeds was modeled as freight transport by road. The average transportation distance of 196 km between seed production plants and the seed distributor was used (Bureau of Transportation Statistics, 2018).

Commercial, conventional agriculture depends heavily on fertilizer use. Production and application of fertilizers dominate the impacts associated with fertilizer use in agriculture (Hasler et al., 2015). To account for contribution of fertilizer production, unit processes in EcoInvent 3.4 database for nitrogen, phosphorus, and potassium fertilizers were used. These processes included production of ammonium nitrate phosphate, monoammonium phosphate, and production of potassium fertilizers from various sources. The transportation distances were modified to represent the United States transportation sector. The transportation of fertilizers from production plant to the distributor was modeled as freight by road to a distance of 214 km (Bureau of Transportation Statistics, 2018).

### 2.2.2. Processing stage

The processing stage in the LCA model included transportation of harvested crop to the processing plant, processing of pulses, and bagging. Harvested pulses may need to be cleaned, dried, sorted, split, milled, decorticated, and fractioned before they are bagged and shipped to the retail markets (USA Dry Pea & Lentil Council, 2019). The processing steps depend on intended use of pulses and sometimes, additional steps such as roasting, puffing, and grinding may be necessary.

The transportation distance between a farm and grain elevator varies depending on proximity to the pulse processing plant. Data specific to transportation distances of pulses are not available. However, O'Donnell (2008) reported that wheat is usually grown within 100 km from processing plants in northwest and central United States. Because pulses are grown in northwest United States and most of the machinery that processes pulses is also designed to handle wheat (Bühler, 2019a), a transportation distance of 100 km was adopted for this study.

The output of the processing stage in this study was raw, processed pulses, packed in 1 kg bags. Pulse processing steps included in the model involved destoning, grading, decorticating, sorting using optical sorter, and splitting (Wood and Malcomson, 2011). Electricity consumed for each processing step was calculated using technical specifications of machinery obtained from Bühler (2019a, 2019b, 2019c, 2019d) and the approach presented by Stössel (2018) was used, when necessary, to fill data gaps at processing stage. The resulting electricity consumption was first normalized for 1 kg of pulses processed using the throughput specified in technical specifications. When throughput was unavailable, an average of available data was used. Technical specifications were unavailable for splitting operations. Therefore, electricity consumption equal to decortication process was assumed for splitting because of similarities in the processes.

The pulse processing results in considerable losses in the form of husk, powder, broken, shriveled, and unprocessed pulses. These losses can amount to up to 25% of total pulses processed (Patras et al., 2011). However, stones and other debris collected during harvesting were not considered in the losses estimated by Patras et al. (2011). In absence of specific data, it was assumed that stones and debris accounted for 12.5% (half of losses) of harvested pulses hauled from the farm. Therefore, electricity consumption for destoning was estimated for 1.52 kg of pulses brought in for processing while that for other operations was adjusted to 1.33 kg of pulses processed (Table 1).

The decortication (also called dehulling) primarily removes seed coat; however, small broken pulses and powder is also removed during this process. Pulses can be decorticated using either wet or dry process. The wet process is primarily used to produce decorticated and split pulses, while dry decortication is used to produce both split and whole pulses (Wood and Malcomson, 2011). Because splitting was modeled as a separate process in the study, we assumed decortication by dry process. The dry decortication process requires prior conditioning with water or tempering with oil followed by drying to ease seed coat removal and to avoid breakage, especially for chickpea and field pea that are hard to decorticate (Wood and Malcomson, 2011). Lentil and dry bean varieties are easy to decorticate and are processed directly without conditioning or tempering.

For chickpea and field pea, conditioning prior to decortication was modeled assuming addition of water at the rate of approximately 10% (w:w), soaking for 4–8 h, and subsequent drying to 7–11% moisture content (Wood and Malcomson, 2011). For 1.33 kg of chickpea and field pea processed, 0.133 kg of water was added. It was assumed that the pulses were harvested at 12% moisture content (USA Dry Pea & Lentil Council, 2019) and all water added during conditioning was absorbed. The amount of water evaporated during drying (0.1613 kg) was estimated by mass balance. The output of the processing stage included 1 kg of pulses packed in a low-density polyethylene (LDPE) bag transported to retails stores. Weights of empty packaging bags of pulses were measured and modeled as 6.06 g of LDPE bag per kg of final product.

### 2.2.3. Retail stage

The processes in retail stage included transportation of packaged pulses from processing plants to retail stores, storage of these pulses at the stores, food losses at the retail, electricity consumption by the establishment, and land occupation. Input data used for the retail sector are presented in Table 1. The output of retail stage model was 1 kg of pulses stocked at the retail store. According to the USDA Economic Research Service (2019) on an average 5.88 percent of legumes are lost between and retail and consumer level. These losses were attributed to the retail stage and therefore, input to the processing stage was set to 1.0625 kg of pulses.

The transportation distance for processed and packaged pulses depends on locations of processing plants and retail stores, and regional consumer demand for pulses. Transportation data specific to pulses were not available. However, according to the Bureau of Transportation Statistics (2018) food manufacturing industry transported the food products to an average distance of 452 km. This transportation distance was adopted for processed and packaged pulses, with trucks as the primary mode of transportation.

Data for electricity consumption by retail stores were obtained from 2017 Annual Retail Trade Survey (ARTS) (U.S. Census Bureau, 2017). The total cost of electricity purchased by grocery stores was $5594 million in 2017. In the same year, average annual retail price of electricity for commercial sector was 10.66 cents per kWh (U.S. EIA, 2020a). These data were used to estimate electricity consumption by grocery stores in kWh in 2017. However, these estimates represented electricity consumption by all grocery stores in the United States. The electricity consumption was allocated to a kilogram of pulses stocked in the grocery store using allocation based on shelf space occupied by a product and per capita loss-adjusted availability of legumes at retail stores. Dry beans occupy about 0.06% of consumer facing shelf space area at a supermarket (Willard, 2016). In the absence of more granular data, this estimate was adopted to allocate retail stage burdens to all pulses. The total mass of pulses sold by the retail sector was estimated using per capita loss-adjusted availability of pulses at retail sector (5.40 kg/year) and 2018 estimate of US population (327 million) (U.S. Census Bureau, 2018; USDA Economic Research Service, 2019). The average of land occupation for superstore, neighborhood markets, and warehouse clubs was 11,179 $m^2$ (Walmart Inc., 2019), which was allocated to a kilogram of pulses using the same allocation factor estimated for electricity use.

### 2.2.4. Consumer stage

The consumer stage is the last stage in the cradle-to-grave LCA model. It included purchase of pulses from retail stores, transportation for grocery shopping, cooking, and consumption of pulses, and associated waste to landfill. The reference flow of the consumer stage on the dry basis was 56 g of dry bean, 58 g of chickpea, and 60 g each of field pea and lentil cooked and consumed at US household. The reference flow represented average weekly consumption of pulses in the United States (HHS and USDA, 2015). Accounting for an estimated 10% plate wastage (USDA Economic Research Service, 2019) in the form of uneaten cooked pulses, the quantity purchased from retail was 62, 54, 66, and 66 g for dry bean, chickpea, field pea, and lentil, respectively.

Transportation at the consumer stage involved passenger car transportation for grocery shopping. In the United States, the average distance to a grocery store in 2015 was 3.77 km (USDA Economic Research Service, 2015). This included distances for average US households (3.45 km), SNAP recipients (3.16 km), and food insecure and WIC households (4.70 km). However, it was reported in the same USDA study that consumers often travelled to their preferred grocery store, often farther than the closest one. Therefore, average distance of 5.52 km (average US household- 6.10 km, SNAP participants- 5.41 km, food insecure households and WIC 5.07 km) was used in the model for grocery shopping.

Consumption of pulses at the consumer stage varied by the pulse variety. The loss-adjusted per capita availability of dry beans and dry peas and lentils at consumer level was 2.90 and 1.65 kg per year respectively (USDA Economic Research Service, 2019). Per capita loss-adjusted availability of dry peas and lentils was disaggregated into chickpeas, lentils and field peas based on proportion of these varieties in total domestic availability of chickpea, lentil, and field pea (Tables S1–1). The burden of transportation was allocated to each pulse variety (Tables S1–1) using percentage of total household expenditure on chickpeas, lentils, field peas, and dry beans estimated using average 2017 national average retail price for dry beans and household consumption of each pulse variety (U.S. Bureau of Labor Statistics, 2018; U.S. Census Bureau, 2019; USDA Economic Research Service, 2019). The retail price was available only for dry bean, which was adopted for other three pulse varieties.

For the base case scenario, it was assumed that cooking pulses involved boiling and simmering pulses in an open vessel on electric stove (OVC). The electricity consumption and water requirements for cooking depend on pulse variety (USA Dry Pea & Lentil Council, 2019). Dry beans and chickpeas require soaking which reduces the cooking time and consequently electricity consumption. Pulses such as lentils and field peas can be cooked without soaking. The water requirement for soaking and cooking and cooking time are provided in Tables S1–2. Data provided by USA Dry Pea & Lentil Council (2019) included volumetric measurements of pulses and water. These were converted to mass measurements using density of pulses and water.

The base scenario in the study was open vessel cooking (section 2.2.4.1), which involved boiling and simmering pulses in an open vessel on an electric stove. Two other methods of cooking pulses were evaluated in this study, representing two alternative scenarios. These were cooking in stovetop pressure cooker and in electric pressure cooker (section 2.2.4.2). The LCI for the consumer stage, including the differences between study scenarios, is provided in Table 2.

#### 2.2.4.1. Open vessel cooking (OVC)

The total cooking time in OVC included time required to bring the water to boil and simmering time specific to the pulse variety. In OVC scenario, the energy required to bring the water to boiling point was estimated using Eq. (1). On an average the household electric stove draws between 1200 and 3000 W of power (Direct Energy, 2019). An average power of 2100 W (2100 J/s) was used to determine time required to bring the water to boiling from an initial temperature of 25 °C. Electricity consumption (kWh) to fully cook pulses was estimated assuming 20% of average cooking range power requirement (simmering setting) and simmering times provided in Tables S1–2. Cooking efficiency of 39% for electric coil, estimated as the ratio of energy transferred to water and energy input, was used to account for specific heat capacities of water and vessel and radiative energy losses (Karunanithy and Shafer, 2016).

Electricity and water consumption at the consumer stage also included dishwashing. A typical dishwasher in a US household consumed between 270 and 307 kWh of electricity per year and between 13 and 19 L of water per cycle (Appliance Standard Awareness Project, 2017). The dishwasher electricity consumption per cycle was estimated assuming one cycle per day. This electricity and water consumption

**Table 2**
Life cycle inventory for consumer stage for open vessel and pressure-cooking scenarios.

| Pulse variety | Inputs | | | | | | | Reference Flow, kg |
|---|---|---|---|---|---|---|---|---|
| | Mass of pulses, kg | Water (L) | | | Electricity, kWh | | Grocery Travel, km | |
| | | Cooking | Soaking | Dishwasher | Cooking | Dishwasher | | |
| **Open Vessel Cooking (OVC)** | | | | | | | | |
| Chickpea | 0.064 | 0.225 | 0.225 | 0.011 | 1.628 | 0.001 | 0.004 | 0.058 |
| Dry bean | 0.062 | 0.150 | 0.225 | 0.057 | 1.620 | 0.004 | 0.020 | 0.056 |
| Field pea | 0.066 | 0.150 | – | 0.014 | 0.685 | 0.001 | 0.005 | 0.060 |
| Lentil | 0.066 | 0.188 | – | 0.007 | 0.355 | 0.0004 | 0.002 | 0.060 |
| **Pressure Cooking, Stovetop Pressure Cooker (SPC)** | | | | | | | | |
| Chickpea | 0.064 | 0.225 | 0.225 | 0.011 | 0.588 | 0.001 | 0.004 | 0.058 |
| Dry bean | 0.062 | 0.225 | 0.225 | 0.057 | 0.303 | 0.004 | 0.020 | 0.056 |
| Field pea | 0.066 | 0.225 | – | 0.014 | 0.648 | 0.001 | 0.005 | 0.060 |
| Lentil | 0.066 | 0.225 | – | 0.007 | 0.327 | 0.0004 | 0.002 | 0.060 |
| **Pressure Cooking, Electric Pressure Cooker (EPC)** | | | | | | | | |
| Chickpea | 0.064 | 0.225 | 0.225 | 0.011 | 0.223 | 0.001 | 0.004 | 0.058 |
| Dry bean | 0.062 | 0.225 | 0.225 | 0.057 | 0.117 | 0.004 | 0.020 | 0.056 |
| Field pea | 0.066 | 0.225 | – | 0.014 | 0.366 | 0.001 | 0.005 | 0.060 |
| Lentil | 0.066 | 0.225 | – | 0.007 | 0.094 | 0.0004 | 0.002 | 0.060 |

were allocated to pulse varieties using the economic allocation provided in Tables S1–1.

$$Q = m \times c \times (T_f - T_i) \tag{1}$$

Where.

Q = energy required to raise temperature of water (J).
m = mass of water (g).
C = specific heat of water (J/g-°C).
$T_f$ = final temperature of water (°C).
$T_i$ = initial temperature of water (°C).

*2.2.4.2. Pressure cooking (Stovetop, SPC and Electric, EPC).* A pressure-cooking scenario was evaluated to estimate the impact of cooking method on sustainability metrics. Pressure cooking substantially reduces cooking time, consequently reducing cooking energy use. However, besides cooking time, energy savings also vary with the type of pressure cooker (stovetop or electric) and related energy losses. The heating components of electric pressure cookers are insulated making them more energy efficient than stovetop pressure cookers (Reynolds et al., 2018). These differences were captured by creating scenarios for stovetop (SPC) and electric (EPC) pressure cookers. It was assumed that temperature control on the cooking range was set to the medium heat setting (50% of average power requirement of electric cooking rage) for stovetop pressure cooker with the cooking efficiency similar to OVC. For electric pressure cooker, on the other hand, energy efficiency of 95% was assumed between heating element and wall power outlet with an average power consumption of 1071 W. The power consumption of electric pressure cooker was estimated from specifications provided by Instant Brands Inc (2020a). Data for cooking time of pulses were obtained from FastCooking (2019) and Hawkins Ventura (2003) for SPC (Tables S1–3) and from Instant Brands Inc (2020b) for EPC (Tables S1–4). It was assumed that the ratio between volume of cooking water and pulses reported by Hawkins Ventura (2003) was independent of pressure cooker type. The cooking time varied with pulse variety and is substantially reduced if pulses were soaked prior to cooking. Similar to OVC, it was assumed that only chickpea and dry bean were soaked prior to cooking, to ensure that only the influence of cooking method was evaluated. The amount of water required for soaking chickpeas and dry beans was adopted from the OVC scenario. Electricity consumption for the pressure-cooking scenario was estimated using the same method used in the OVC scenario. However, pressure cooking did not require bringing the water to a boil before adding the pulses. Therefore, cooking time in this scenario reflected time required to cook pulses that were started with room temperature water.

### 2.3. Uncertainty analysis

Data used for life cycle impact analysis is based on mean estimates of parameter values which carry uncertainty that could alter the conclusions. Therefore, an uncertainty analysis was performed using Monte Carlo Simulations (MCS) to increase confidence in the interpretation of results. Data for most parameters in the model included means and range. Therefore, uncertainty for these foreground model parameters was defined as a triangular distribution, with the exception of crop yield. A normal distribution was defined for the crop yield using standard deviation estimated using USDA-NASS data (USDA National Agricultural Statistics Services, 2017). Background processes from EcoInvent database were adopted in the model without changing their uncertainty characteristics. Uncertainty in impact characterization factors is not included in the evaluation, therefore this assessment represents a lower bound on uncertainty of the results.

### 2.4. Sensitivity to the reference flow

It was discovered during the initial runs of the cradle-to-grave model that the environmental impact categories were highly sensitive to the mass of pulses cooked in a batch. In OVC and both pressure cooking scenarios the reference flow of 60 g represented average weekly consumption of pulses. The influence of consumer stage reference flow on environmental impact categories was assessed by changing this reference flow to 1 kg of pulses while maintaining cooking method to open vessel cooking (OVC-RF1). This reference flow represented cooking one large batch of pulses to be consumed over approximately 4 months at current weekly consumption rate of 60 g. However, this required freezing cooked pulses and reheating them before consumption, most likely using a microwave. Annual household refrigerator and microwave electricity consumption obtained from U.S. EIA (2015) was attributed to each pulse variety using economic allocation factors used for passenger travel for grocery (Tables S1–1). Safe storage period of 2–3 months estimated for frozen soups and stews (FoodSafety.gov, 2021) was adopted for pulses to estimate increased food wastage. Assuming that four-month supply of cooked pulses can be safely stored only for maximum of 3 months, food wastage of pulses was increased to 25% for this scenario. However, it was assumed that pulses were stored for four months before they were discarded. Therefore, refrigerator and microwave electricity consumption were estimated assuming four-month refrigerator use and 12 instances of microwave use (Table 3).

## 3. Results and discussion

Cradle-to-grave environmental impact of pulses was assessed in this

**Table 3**
Electricity and water consumption at consumer stage for the reference flow of 1 kg.

| Pulse variety | Inputs | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Mass of pulse, kg | Water, kg | | | Electricity kWh | | | |
| | | Cooking | Soaking | Dishwasher | Cooking | Dishwasher | Refrigerator | Microwave |
| Chickpea | 1.333 | 4.662 | 4.662 | 0.132 | 2.129 | 0.008 | 0.069 | 0.001 |
| Dry bean | 1.333 | 3.231 | 4.847 | 0.686 | 1.968 | 0.042 | 0.358 | 0.006 |
| Field pea | 1.333 | 3.019 | – | 0.171 | 1.009 | 0.010 | 0.089 | 0.001 |
| Lentil | 1.333 | 3.773 | – | 0.087 | 0.760 | 0.005 | 0.046 | 0.001 |

study The base scenario, OVC, included cooking pulses on an electric stove in an open vessel. SPC and EPC scenarios evaluated the impact of cooking method while the OVC-RF1 scenario estimated the impact of mass of pulses cooked per batch on environmental impact of pulses. We also evaluated inter-varietal variability resulting from the differences in crop production practices and time required to cook the pulses.

### 3.1. Open vessel cooking

#### 3.1.1. Impact category scores

The GWP for 60 g (dry basis) of pulses consumed in a US household was 1.26, 1.34, 0.53, and 0.31 kg $CO_2$e for chickpeas, dry beans, field peas, and lentils, respectively (Fig. 2). Fossil fuel consumption in ReCiPe 2016 is reported as fossil fuel scarcity and expressed as kg oil eq. The FRS ranged between 0.08 and 0.34 kg oil eq per 60 g of pulse crop (chickpeas: 0.32, dry beans: 0.34, field peas: 0.14, lentils: 0.08 kg oil eq). The LU measured in $m^2$a crop eq was 0.69 for chickpeas, 0.63 for dry beans, 0.58 for field peas, and 0.82 for lentils. Throughout the cradle-to-grave processes, WC was estimated at 7.41, 7.75, 3.22, and 2.12 L for chickpeas, dry beans, field peas, and lentils, respectively. The FE, resulting primarily from phosphorus fertilizer application, was 1.37, 1.43, 0.59, and 0.36 g P eq for chickpea, dry bean, field pea, and lentil, respectively. ME ranged between 0.021 g N eq for lentil and 0.092 g N eq for dry bean. The ME for chickpea and field pea was 0.088 and 0.037 g N eq, respectively.

#### 3.1.2. Inter-varietal variability and contribution analysis

Inter-varietal variability within environmental impact categories was associated with factors such as crop management practices, fertilizer application rates, crop yield, and cooking time. With the exception of LU, the greatest contribution to all other impact categories resulted from the consumer stage, which involved purchasing and cooking pulses and plate waste. The consumer stage contributed at least 83, 81, 76, 75, and 87 percent of total impact for GWP, FRS, WC, FE, and ME, respectively.

*3.1.2.1. Global warming potential and fossil resource scarcity.* The contribution of the consumer stage to GWP and FRS varied with pulse variety. However, for both impact categories contribution from consumer stage was the greatest for chickpea and the least for lentil (Fig. 3). Greater contribution from the consumer stage to these impact categories as well as inter-varietal variability in impact category scores could be attributed to electricity consumed during cooking. Electricity was utilized at the consumer stage primarily for cooking and for running the dishwasher. However, cooking contributed to approximately 99% of total electricity consumption at the consumer stage for which, the driving factor was cooking time.

Cooking pulses in open vessels requires brining water to boil followed by simmering until pulses are cooked through. The time required to boil water (range: 57 s to 1 min 26 s) and consequently, associated electricity consumption did not vary substantially. This was because only small quantities of pulses were cooked, which required mass of water that ranged between 150 g and 225 g. On the contrary, post-boil simmering time varied between 19 min for lentil to 90 min for chickpea and dry bean. This difference in cooking times resulted in the proportional inter-varietal variability in electricity consumption, which was reflected in fossil fuel scarcity scores.

Electricity production in the United States relies heavily on fossil fuels, primarily natural gas, and coal. In fact, about 63% of total electricity generated in the US in 2019 was produced using fossil fuels (U.S. EIA, 2020b). Upstream emissions associated with electricity production were responsible for increasing overall GWP impact scores of pulses and contribution of consumer stage. For example, approximately 94% of total GWP of chickpea was associated with electricity production from all sources, while at least 78% of GWP resulted from electricity production that relied on coal and natural gas.

The GWP and FRS scores of pulses followed a general trend similar to electricity consumption at the consumer stage. However, a slight

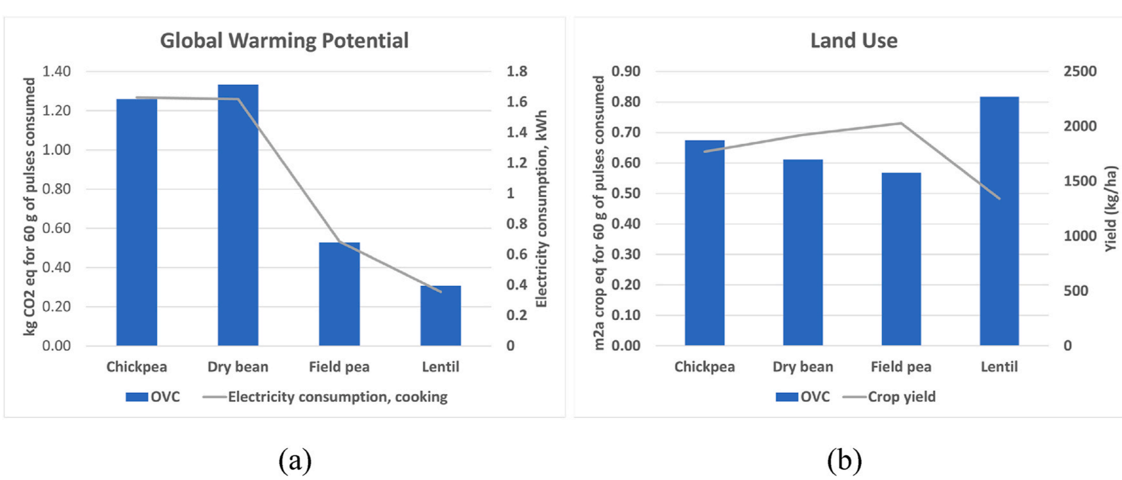


**Fig. 2.** Environmental impact of 60 g of pulses estimated for OVC scenario for following impact categories (a) GWP, (b) LU. Graphs for other impact categories are presented in Figs. S1–1 in the Supplementary Material.

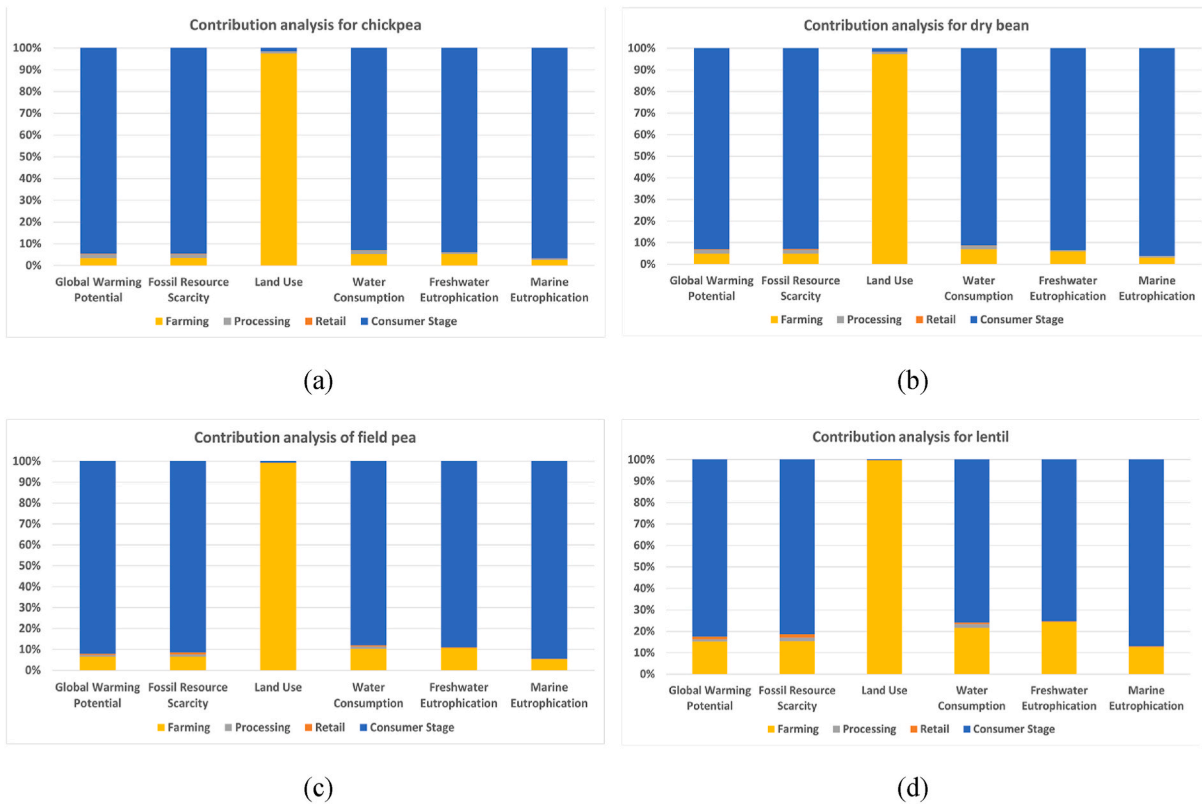


**Fig. 3.** Results of contribution analysis for (a) chickpea, (b) dry bean, (c) field pea, and (d) lentil, for OVC scenario.

anomaly was observed in GWP and FRS scores of chickpeas and dry bean. The GWP and FRS of dry bean was 6.4 and 6.3 percent greater compared to chickpea when the electricity consumption at the consumer stage for these were comparable. Greater GWP and FRS observed for dry bean was attributed to marginally greater contribution from the cradle-to-farm stage to these impact categories. Unlike other pulse varieties, dry beans were grown using conventional farming methods. Increased fossil fuel use required for conventional farming and related greenhouse gas emissions marginally increased the contribution of farming stage to these impact categories and overall impact scores.

*3.1.2.2. Land use.* In contrast to other impact categories, the primary contributor to the LU was crop production. The factor responsible for this contribution as well as for the inter-varietal variability in LU scores was crop yield. The LU score was inversely related to the yield because greater yield increased resource utilization efficiency at the farm. The crop yield varied with pulse variety ranging between 1342 kg $ha^{-1}$ for lentil and 2029 kg $ha^{-1}$ for field pea, respectively. Consequently, the LU was the greatest for lentil and the least for field pea (Fig. 2).

*3.1.2.3. Water consumption.* The greatest contribution to total WC came from the consumer stage, amounting to 76% of total WC for lentil and more than 88% of total WC for other pulse varieties. Similar to GWP and FRS, electricity consumption at the consumer stage and associated upstream water use were responsible for the greater contribution from consumer stage. For example, water use related to electricity consumption at the consumer stage accounted for approximately 85% of total water use. Only 7.3 and 7.7 percent of water use was associated with cooking and dishwashing, and other upstream processes, respectively. The electricity and water use at the consumer stage also influenced inter-varietal variability in WC scores. Chickpea and dry bean required longer cooking time and needed water for soaking which increased their WC compared to field pea and lentil.

*3.1.2.4. Freshwater and marine eutrophication.* The contribution of the consumer stage to the total impact category scores ranged between 75 and 94 percent for FE and between 87 and 97 percent for ME. For both impact categories, contribution from the consumer stage was the least for lentil and the largest for chickpea. A greater contribution of consumer stage was primarily because of electricity use at the consumer stage and associated upstream emissions of NOx and phosphate compounds.

However, phosphorus and nitrogen fertilizer application rates and crop yield at the farming stage influenced total eutrophication impact scores as well as contributions from the farming stage. Dry bean, for example, required more nitrogen fertilizers compared to other pulse varieties. This resulted in the largest contribution to ME (0.0029 g N eq per FU) scores for dry bean from the farming stage. In contrast, the ME scores of other three pulse varieties at the farmgate were lower than the dry bean because of lower nitrogen demand. However, despite identical phosphorus and nitrogen application rates, lower crop yield of lentil increased their FE (0.088 g P eq per FU) and ME (0.0026 g N eq per FU) scores compared to chickpea (FE: 0.073 g P eq per FU, ME: 0.0022 g N eq per FU) and field pea (FE: 0.063 g P eq per FU, ME: 0.0022 g N eq per FU) at the farmgate.

### 3.2. Pressure cooking

Switching cooking method from open vessel cooking to pressure cooking reduced GWP of pulse varieties by 5–86 percent. FRS by 5–85 percent, WC by 1–78 percent, FE by 5–86 percent, and ME by 5–88 (Table 4). The lower impact scores observed for pressure cooking scenarios were attributed to shorter cooking times and associated energy savings. However, shorter cooking times did not always result in proportional decrease in the electricity consumption, especially for SPC scenario. Despite 62% reduction in the cooking time for field peas in SPC (OVC- 39 min, SPC- 15 min), the electricity consumption decreased only by 5%. This discrepancy was primarily because of assumptions made

**Table 4**
Environmental impact for 60 g of pulses cooked in stove top and electric pressure cooker.

| Impact category | SPC | | | | EPC | | | |
|---|---|---|---|---|---|---|---|---|
| | Chickpea | Dry bean | Field pea | Lentil | Chickpea | Dry bean | Field pea | Lentil |
| Global warming potential, kg $CO_2$ eq | 0.50 | 0.33 | 0.50 | 0.29 | 0.23 | 0.19 | 0.30 | 0.12 |
| Fossil resource scarcity, kg oil eq | 0.13 | 0.09 | 0.13 | 0.07 | 0.06 | 0.05 | 0.08 | 0.03 |
| Land use, $m^2a$ | 0.69 | 0.62 | 0.59 | 0.82 | 0.69 | 0.62 | 0.58 | 0.82 |
| Water consumption, L | 3.31 | 2.44 | 3.18 | 2.06 | 1.86 | 1.68 | 2.09 | 1.16 |
| Freshwater eutrophication, g P eq | 0.55 | 0.35 | 0.56 | 0.34 | 0.26 | 0.20 | 0.35 | 0.16 |
| Marine Eutrophication, kg N eq | 0.034 | 0.022 | 0.035 | 0.019 | 0.016 | 0.012 | 0.021 | 0.008 |

regarding heat control setting on a cooking range, which was assumed to use 20% (low heat) and 50% (medium heat) of available energy for OVC and SPC, respectively. Therefore, more energy was required throughout the cooking period to achieve shorter cooking times in SPC, which decreased the magnitude of savings in electricity consumption. Nevertheless, SPC reduced the environmental impact scores of pulses by at least 5% across all impact categories, excluding LU.

The EPC resulted in the lowest impact scores among all cooking methods across all pulse varieties and impact categories, excluding LU. This was attributed to lower energy demand and improved energy efficiency of pressure cookers compared to OVC and SPC. The electric pressure cookers required an average 1071 W power compared to 2100 W required for stovetop cooking. Moreover, the energy efficiency of electric pressure cookers was at least 95% resulting in more efficient use of electricity. This lowered electricity consumption for cooking and associated upstream emissions. Electricity consumption for dry beans and chickpeas in EPC, for instance, was at least 61% lower compared to SPC, whereas cooking time remained identical (Tables S1–3).

Overall, the greatest reduction in impact category scores, compared to OVC, was observed for dry bean, followed by chickpea, lentil, and field pea. While the magnitude of this change was greater for EPC compared to SPC, an identical trend was observed for both scenarios. The magnitude of change in impact category scores compared to OVC depended on the decrease in electricity consumption required for cooking pulses. Compared to OVC, pressure cooking methods offered the greatest savings in electricity consumption for dry bean (SPC- 81%, EPC- 93%), followed by chickpea (SPC- 64%, EPC- 85%), lentil (SPC- 8%, EPC- 74%), and field pea (SPC- 5%, EPC- 47%), which was also reflected in their environmental impact score across all impact categories, excluding LU. The largest contributor to the LU was farming stage, where crop yield was the primary driving factor. Because cooking methods only influenced electricity consumption, only a small to no change in LU was observed for SPC and EPC (Table 4).

The pressure-cooking method expedited cooking of all varieties of pulses, reduced environmental impact of pulses, and marginally decreased the contribution of the consumer stage to the overall impact. However, the contribution of the consumer stage still remained high (Fig. S1-2 and S1-3). The consumer stage in pressure cooking scenario contributed between 52 (EPC, dry bean) and 92 (SPC, field pea) percent of total GWP (compared to 83 to 95 percent for OVC) and between 52 (EPC, dry bean) and 91 (SPC, field pea) percent of total FRS (compared to 81 and 94 percent for OVC). This was primarily because in spite of 5–93 percent reduction in total cooking-related electricity consumption, the upstream emissions associated with electricity production still dominated total emissions from the pulse supply chain, increasing the contribution of consumer stage for SPC and EPC.

### 3.3. Uncertainty analysis

Uncertainty analysis was performed to evaluate the robustness of conclusions regarding differences in the environmental impact category scores of pulse varieties and cooking methods. The results of MCS for GWP and FRS are presented in Fig. 4. Results for other impact categories are presented in (Figs. S1–4). Differences in GWP, FRS, FE, and ME scores of pulse varieties were more prominent for OVC, compared to SPC and EPC. For OVC scenario, there was more overlap of boxes and whiskers for chickpea and dry bean compared to other two pulse varieties suggesting a higher probability that impact scores of chickpea and dry bean for these four impact categories were comparable to each other but greater than field pea and lentil. Within SPC and EPC, the overlap of box and whiskers for chickpea, dry bean, and field pea indicated that only small to no differences in GWP, FRS, FE, and ME scores. This suggested that inter-varietal variability between chickpea, dry bean, and field pea observed within each pressure-cooking scenario was statistically non-significant. However, there existed a greater probability of lentil having the lowest impact scores across these four impact categories for all three cooking scenarios. The uncertainty analysis also suggested a probability that LU of chickpea, dry bean, and field pea was comparable to each other while that of lentil was marginally greater, and a probability that the differences in water use scores of these pulse

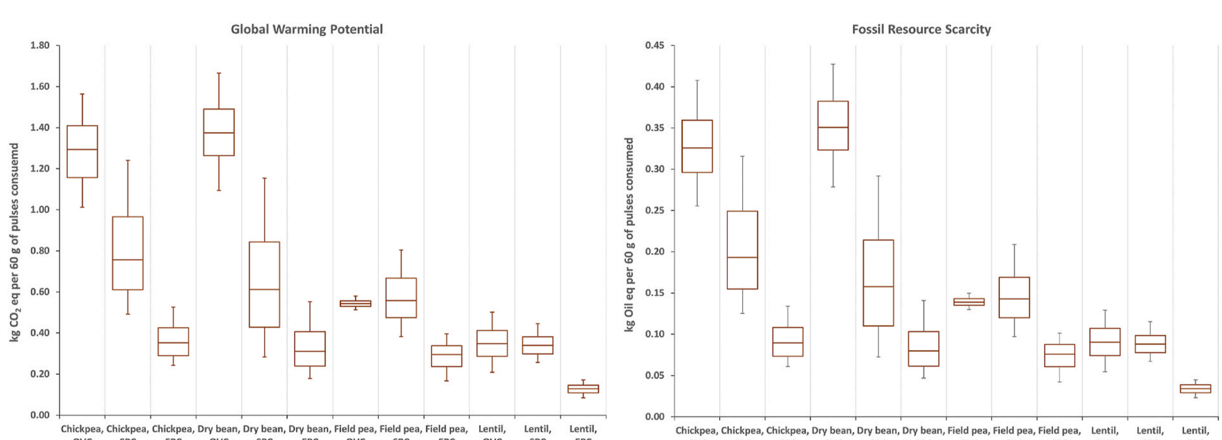


**Fig. 4.** Results of uncertainty analysis for (a) GWP and (b) fossil resource scarcity for OVC, SPC, and EPC. The results for other impact categories are presented in the supplementary material (Figs. S1–4).

varieties were statistically non-significant.

As expected, the absence of differences in LU in relation to cooking method was confirmed by the uncertainty analysis. Similarly, the uncertainty analysis indicated that the difference in mean WC scores in relation to cooking method were not statistically significant. For GWP, FRS, FE, and ME (impact categories discussed hereafter), the uncertainty analysis confirmed the mixed influence of cooking method on environmental impact. For chickpea and dry bean SPC decreased environmental impact scores across these four impact categories compared to OVC. However, the influence of pressure cooker type on impact categories was more pronounced for chickpea compared to dry bean. This suggested a greater probability for chickpea (and a lower probability for dry bean) that EPC significantly decreased impact category scores, when compared to SPC. The uncertainty analysis also indicated that for field pea and lentil, impact category scores of OVC and SPC scenarios were comparable, but a greater probability existed that EPC lowered environmental impact of these two pulse varieties.

### 3.4. Sensitivity to consumer stage reference flow (OVC-RF1)

Changing consumer stage reference flow to 1 kg of pulses substantially reduced environmental impact of pulses across all impact categories (excluding land use) even after accounting for increased food waste and electricity consumption. Estimated GWP in this scenario for 60 g of pulses was 0.18, 0.21, 0.10, and 0.10 kg $CO_2e$ for chickpea, dry bean, field pea, and lentil, respectively. The GWP in this scenario was approximately, 86 (chickpea), 84 (dry bean), 82 (field pea), and 68 (lentil) percent lower than OVC scenario (Fig. 5). Similar decrease in scores was also observed for FRS (67–86 percent), WC (49–77 percent), FE (60–85 percent), and ME (72–87 percent). The primary reason of this decrease in environmental impact of pulses was lower electricity consumption. Increasing the reference flow to 1 kg increased cooking electricity consumption as more energy was necessary to boil larger mass of water. However, the simmering time remained unaffected resulting in very small change in electricity consumption that ranged between 0.32 and 0.50 kWh. Moreover, because larger quantity of pulses was cooked in a single batch, total electricity consumption, normalized for mass of pulses cooked, remained between 0.61 and 1.78 kWh/kg of pulses for OVC-RF1 as opposed to 5.36 to 26.21 kWh/kg of pulses for the OVC. This reduction in total electricity consumption also reduced upstream emissions, resulting in lower environmental impact scores across all impact categories, excluding land use. The land use in OVC-RF increased by 18–20% compared to OVC. However, the Monte Carlo Simulations indicated that this change in land use was not statistically significant (Fig. 5, Figs. S1–5).

A trade-off between the contribution from consumer and farming stage was also observed for this scenario (Figs. S1–6). Cooking larger quantity of pulses in a single batch decreased the contribution from consumer stage to GWP by 42–48 percentage points compared to OVC. It also increased the contribution from the farming stage to overall GWP, which ranged between 28 and 57 percent for OVC-RF1 compared to 3 to 15 percent observed for OVC. A similar trend was also observed for FRS, WC, FE, and ME. A small increase, compared to OVC, in contribution from processing and retail stages to overall GWP (2–14 percentage points) and FRS (2–13 percentage points) scores was also observed.

Similar to pulses, the influence of batch size and cooking-related energy demand on GWP and FRS was also observed for potatoes and bread. Parajuli et al. (2021) reported that the contribution from the consumer stage for at-home consumption of 1 kg of fresh potatoes was 47% of total cradle-to-grave GWP, primarily because of frying in vegetable oil. For 1 kg of frozen potato fries this contribution was 38%. In case of bread, electricity consumption for refrigerated storage and toasting of bread at the consumer stage contributed as much as 25% of total GWP in a cradle-to-grave analysis (Espinoza-Orias et al., 2011). The most energy-intensive process in bread manufacturing was baking, which accounted for an average of 64% of total energy consumption in the bread supply chain (Braschkat et al., 2003). Moreover, the energy consumption was three times greater for home baking compared to industrial baking, which also increased the GWP of home-baked bread (Braschkat et al., 2003).

### 3.5. Cradle-to-farmgate impact analysis

The contribution of the farming stage to the most impact categories was lower compared to the consumer stage. However, cradle-to-farmgate impact assessment and contribution analysis can provide insights into influence of farming activities on sustainability of the pulses. It can also facilitate easy comparison between pulses and other crops in term of their environmental impact. The GWP of pulses at the farmgate ranged between 0.32 and 0.61 kg $CO_2e$ per kg of harvested pulses

**Table 5**
Environmental impact associated with production of pulses for 1 kg of harvested pulses at the farmgate.

| Impact Category | Chickpea | Dry bean | Field pea | Lentil |
|---|---|---|---|---|
| Global warming potential, kg $CO_2$ eq | 0.39 | 0.61 | 0.32 | 0.45 |
| Fossil resource scarcity, kg oil eq | 0.10 | 0.16 | 0.08 | 0.12 |
| Land use, $m^2a$ | 6.31 | 5.66 | 5.40 | 7.80 |
| Water consumption, L | 3.65 | 4.99 | 3.09 | 4.40 |
| Freshwater eutrophication, g P eq | 0.69 | 0.79 | 0.59 | 0.84 |
| Marine Eutrophication, g N eq | 0.021 | 0.027 | 0.018 | 0.025 |

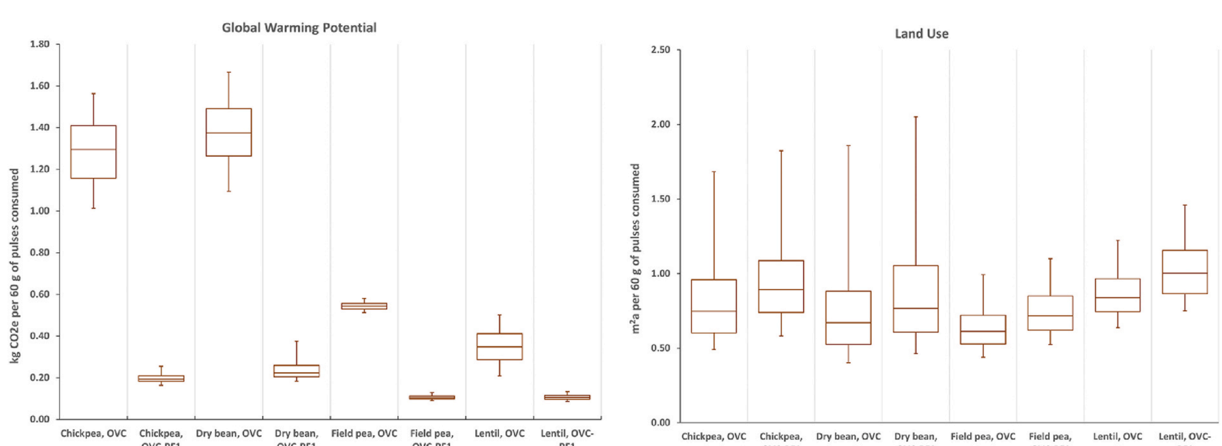


**Fig. 5.** Results of Monte Carlo Simulations indicating the influence of consumer stage reference flow on GWP and LU of pulses. The results for other impact categories are provided in Figs. S1–5.

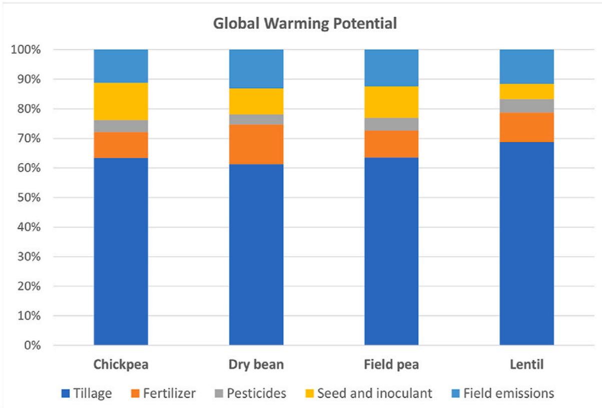


**Fig. 6.** Contribution from various farm activities to the GWP associated with production of pulses for 1 kg of pulses harvested at the farmgate. The graphs for other impact categories are provided in Figs. S1–7.

(Table 5), with the greatest GWP observed for dry beans, followed by lentil, chickpea, and field pea. A similar trend was also observed for FRS, WC, FE, and FE (Figs. S1–7). The trend for LU was slightly different. The greatest land use score was observed for lentil, followed by chickpea, dry bean, and field pea (Table 5). Primary contributors to the environmental impact of pulses (excluding LU) were tillage operations, emissions associated with fertilizer and pesticide manufacturing, production of seeds and inoculant, and field emissions related to fertilizer application (Fig. 6.).

The environmental impact scores of pulses as well as the inter-varietal variability were primarily influenced by crop yield, tillage practices, and fertilizer application rates. Conventional tillage and higher nitrogen demand of dry beans increased fossil fuel consumption as well as field emissions. These factors increased the environmental impact of dry bean even when the yield of dry bean was greater than chickpea and lentil. Contrarily, despite identical tillage operations and fertilizer and pesticide application rates, differences in yield resulted in the lowest environmental score for field pea compared to chickpea and lentil. The influence of crop yield was also evident in LU scores of pulses which carried inverse relationship with the yield.

The GWP of pulses estimated in this study was somewhat greater than the values reported by Gustafson (2017) for pulses grown in the United States. For 1 kg of harvested pulses Gustafson (2017) estimated the GWP of 0.31 and 0.26 kg $CO_2$e for irrigated and dryland pulses, respectively. Greater GWP observed in this study could be attributed to the differences in yield, tillage practices, and use of synthetic fertilizers. Crop yields used in this study ranged between 1,342 and 2,029 kg $ha^{-1}$ compared to 2,030 kg $ha^{-1}$ used by Gustafson (2017) for dryland pulses. While the mean fertilizer application rate was not reported by Gustafson (2017), an example data provided by the author reported that fertilizers were not applied to dryland pulses. On the contrary, we assumed used of nitrogen, phosphorus, and potassium fertilizers in the production of all varieties of pulses studied. We also modeled dry beans with conventional tillage practices and greater nitrogen fertilizer application rate compared to other pulse varieties. These differences in crop management practices between two studies may have contributed to the greater GWP observed in this study.

## 4. Conclusion

The GWP of pulses ranged between 0.12 and 1.34 kg $CO_2$e for 60 g of pulses produced and consumed in the United States. Impact category scores per functional unit for other impact categories was 0.03–0.34 kg oil eq for FRS, 0.58–0.82 $m^2$a for LU, 1.17–7.75 L for WC, 0.16–1.43 g P eq for FE, and 0.007–0.092 kg N eq for ME. Overall, the environmental impact of pulses varied with pulse variety, cooking method, and mass of pulses cooked per batch. However, the consumer stage dominated the environmental impacts of pulses for all pulse varieties and scenarios. Electricity consumed during cooking was the principal driving factor for cradle-to-grave impact of pulses and for contribution of consumer stage. Overall, the study identified cooking time and energy use efficiency as two parameters that influenced the electricity consumption at the consumer stage. The direct proportionality of electricity consumption with cooking time and inverse proportionality with energy use efficiency were evident from the results of three cooking method scenarios, where OVC (longer cooking time and lower energy use efficiency) resulted in the greatest environmental impact and EPC (shorter cooking time and greater energy use efficiency) resulted in the least. The benefits of shorter cooking time in SPC were offset by lower energy use efficiency resulting in statistically non-significant change in the environmental impacts for field pea and lentil as compared to OVC.

The study also identified the influence of cooking mass per batch on overall sustainability of the pulses. Even for the open vessel cooking method, increasing the batch size significantly decreased the environmental impact of pulses across all impact categories, excluding LU, despite increased food losses and added electricity demand for refrigeration and microwave use. This was primarily because larger batch size increased the resource utilization efficiency, as larger mass of pulses was cooked with only marginal increase in total cooking time. This substantially decreased electricity consumption per kilogram of pulses. However, the environmental impact of pulses in OVC-RF1 scenario was comparable to EPC for most impact categories.

Overall, the consumer stage, specifically electricity consumed during cooking, was identified as the hotspot in the production and consumption of pulses. Considering cooking pulses in electric pressure cooker or cooking larger mass of pulses per batch resulted in statistically significant reductions in environmental impact category scores, these methods can be adopted to ensure sustainable consumption of pulses.

## Author credit

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

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