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ARTICLE

Life Cycle Assessment of the peanut value chain in central Argentina

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ABSTRACT

This study presents a comprehensive Life Cycle Assessment (LCA) of seven peanut-derived products processed in central Argentina, quantifying their environmental impacts from agricultural production to end-of-life. The research is framed within the development of Environmental Product Declarations (EPD) in accordance with ISO 14025, 14040 and 14067 standards, using primary data from three farms and one industrial facility representative of the sector. Intergovernmental Panel on Climate Change (IPCC) Tier 2 methodology was applied, with emission factors specific for Argentina, enabling a precise and context-sensitive environmental evaluation. Results show that the agricultural stage is the main source of greenhouse gas emissions (40–66%), particularly due to soil and crop residue management. International distribution, mainly maritime, also represents a significant burden (16–24%). Compared to equivalent products from Brazil and the USA, Argentine peanut products show lower carbon footprint (CF, expressed as kg CO_2 eq kg^{-1}) values within the context of the available studies, with estimates indicating reductions of approximately 67% for peanut butter compared to the U.S. reference and 21% for blanched peanuts relative to Brazil, although these differences should be interpreted as indicative rather than as direct evidence of superior environmental performance. The assessment identified opportunities to improve precision agriculture, renewable energy use, and estimation of soil carbon changes, and to optimize packaging. This work provides novel data for the region, strengthens the international competitiveness of Argentina's peanut sector, and offers valuable inputs for public policy making and business strategies focused on sustainability.

INTRODUCTION

The peanut complex

The Argentine peanut (*Arachis hypogaea* L.), which is mostly concentrated in the province of Córdoba, has shown a notable capacity to adapt to adverse climatic conditions. With a total of 532,991 hectares planted nationally and an estimated production of 1.81 million tons, the 2024/25 season achieved historic records, positioning Argentina among the top peanut-exporting countries globally. At the provincial level, Córdoba stands out as the leading peanut-producing region, accounting for 70% of the cultivated area in the country, with over 374,000 hectares. It is followed by the province of Buenos Aires, which covers nearly 85,000 hectares (16% of the national total), and La Pampa with 37,000 hectares (7%). This growth not only reflects improved yields (4.13 t ha^{-1} in Córdoba), but also a strategic decision by producers to diversify in response to the declining profitability of crops such as soybean and corn (Bolsa de Comercio de Rosario, 2025).

According to recent data from the Argentine Peanut Chamber (CAM) and USDA-FAS, Argentina reached record peanut production levels of approximately 1.8 million tons in the 2024/25 season and remains the world's leading peanut exporter, with minor differences among sources explained by reporting scope and timing. India holds second place, with 0.98 million tons of projected exports, and China ranks third, with 0.65 million tons. Exported products from Argentina included shelled peanuts (USD 527 million), roasted peanuts and peanut butter (USD 81 million), peanut oil (USD 64 million) and pellet/expeller (USD 5.1 million). The European Union is the main importer from Argentina, accounting for 60% of the total Argentine exports (Ferrari *et al.*, 2025).

The peanut industry in Argentina has become a significant regional economic driver, providing more than 12,000 jobs and with exports exceeding USD 1 billion annually. The industrial sector has state-of-the-art processing plants, with many of them having installed production capacity higher than the actual production, enabling an increase in processing volume (Cámara Argentina del Maní, 2022).

Global context and sustainability challenges in peanut production

The growing global awareness about climate change and sustainability has exerted unprecedented pressure on agri-food supply chains. International markets, regulators and consumers demand transparency of the environmental impact of products; in this context, quantification tools have turned into a strategic imperative. Thus, the Life Cycle Assessment (LCA) has become the principal method to evaluate the environmental impacts of a product along its entire value chain.

Environmental Product Declarations (EPDs) emerged as a standardized and independently verifiable mechanism to communicate Life Cycle Assessment (LCA) results, based on internationally recognized and voluntary standards such as ISO 14025 (2006), ISO 14040 (2006) and ISO 14067 (2018). These standards do not constitute mandatory regulations, but provide harmonized methodological frameworks that are widely referenced in environmental policies, green procurement schemes and market-based sustainability requirements. A Type III EPD represents a transparent and comparable disclosure of the environmental performance of a product and serves as a strategic tool for product differentiation in highly competitive international markets and for addressing the sustainability demands of global value chains.

The LCA has been the focus of studies in the agricultural sector in diverse geographic regions. However, no complete LCA has been conducted for peanuts in the world. Argentina, one of the world's leading peanut producers and exporters, lacks a thorough "cradle-to-grave" study. There is no accurate knowledge about the complete environmental profile of a vertically integrated supply chain, one that simultaneously evaluates agricultural production and industrialization of several byproducts, from raw peanut to the most complex processed products. The lack of regional data of life cycle inventory and emission factors for Argentina is a critical gap in scientific knowledge, especially regarding the influence of soil management practices (e.g., conventional tillage and its impact on carbon emissions) as these studies often focus on geographical areas where energy matrices and agricultural practices differ significantly from the local ones. Conversely, there are some reference studies of peanut products that have quantified environmental footprints in highly productive areas and that have provided valuable reference information for industry and academia. In the United States, the American Peanut Council (2022), based on the *Sustainable U.S. Peanuts Initiative*, reports field-level greenhouse gas emissions for the 2021 growing season averaging 0.167 kilograms of CO_2 equivalents per kilogram of product (kg CO_2 eq kg^{-1}) of raw peanuts at the farm gate. This value is derived from grower-reported data and represents the first pilot-year results of the program.

For context, these results are compared against the Field to Market national benchmark of approximately 0.300 kg CO_2 eq kg^{-1} of peanuts, which is not specific to a single year but reflects a broader reference value developed from national datasets and modeling frameworks. Therefore, the difference between 0.300 and 0.167 kg CO_2 eq kg^{-1} should not be interpreted as a year-to-year reduction, but rather as a comparison between a benchmark reference and recent measured performance, indicating that most participating fields (approximately 90%) performed below the national benchmark.

On the other hand, a mean carbon footprint of 2.88 kg CO_2 eq kg^{-1} of peanut butter consumed was reported by McCarty *et al.* (2014). This value corresponds to a cradle-to-grave life cycle assessment, in which the system boundary extends from agricultural production through processing, retail, consumer use (including household activities), and final disposal of packaging (McCarty *et al.,* 2014, McCarty *et al.*, 2016a, McCarty *et al.*, 2016b). Likewise, an impact of 0.670 kg CO_2 eq kg^{-1} was calculated for blanched peanuts in Brazil (Ramos *et al*, 2023; Embrapa Meio Ambiente, 2021). These values provide useful contextual reference points, since peanut cropping practices in both countries are similar (Table 1).

It is important to note that most published studies on peanuts quantify carbon footprint (CF, or Global Warming Potential, GWP) rather than performing a complete LCA covering multiple environmental impact categories. Therefore, the international comparison presented here refers exclusively to carbon footprint values expressed as kg CO_2 eq kg^{-1} of product, under comparable system boundaries. Full LCA-based comparisons remain largely unavailable in the literature.

Results of a cradle-to-grave analysis for peanuts in Argentina would make a great contribution as quantifying environmental footprints results in a roadmap for continuous improvement. Identifying the stages of greatest impact (i.e., hotspots), allows producers or industries to direct their investments to cleaner technologies, optimize processes and reduce costs, thereby strengthening their competitiveness in international markets. Knowledge of the environmental profile of local products boosts transparency for consumers and validates the commitment of the peanut sector to sustainability; thus, this knowledge becomes a differentiating factor and an added value, both crucial aspects in international trade.

Table 1. Comparative Carbon Footprint of Peanut Products

Product Category	Carbon Footprint	Scope of Study	Region / Source
	kg CO_2 eq kg^{-1}		
Farmgate (In-shell/Pods)	0.167	Cradle-to-farm gate	USA National Benchmark (American Peanut Council, 2022)
Farmgate (In-shell/Pods)	0.300		
Farmgate (In-shell/Pods)	0.087	Cradle-to-farm gate.	Argentina (2016) (Bongiovanni et al, 2016)
Blanched Peanuts	0.237	Cradle-to-gate (industrial blanching).	
Farmgate (Historical/2013)	< 0.60	Cradle-to-farm gate (40% decrease since 1980).	USA (2016) (McCarty et al, 2016)
Blanched Peanuts	0.670	Cradle-to-gate (industrial blanching).	Brazil (Ramos et al, 2023)
Peanut Butter	2.880	Cradle-to-grave (national average).	USA (2014)

The aim of this study was to determine the environmental impacts along the value chain of seven peanut products originating from the central region of Argentina, from agricultural production to the end-of-life. An LCA was performed, which can inform EPD and support continuous improvement and sustainability validation. This work follows the authors' research line (Bongiovanni *et al.*, 2016), using the LCA method to evaluate the entire value chain, from cradle-to-grave of peanut products, but also including the environmental impact categories required by EPD as well as the carbon footprint.

MATERIALS AND METHODS

Life Cycle Assessment.

LCA is a methodological frame standardized by ISO 14040 (2006) and ISO 14044 (2006), which allows one to account for the environmental burden generated by a product or service along its life cycle. Its theoretical basis lies in a systematic approach that goes beyond the emission measurements at a specific point in the production process, encompassing the extraction of raw materials (cradle) to a product's end-of-life (grave). This comprehensive approach contrasts sharply with the partial environmental impact assessments, such as a simple measurement of emissions at the farm gate or factory gate, offering a holistic and objective view of environmental externalities. The products evaluated in this study are commercialized under a Business-to-Business (B2B) model.

The LCA's robustness lies in its capacity to identify the transfer of environmental burdens along the value chain, a phenomenon that specific measurements fail to detect. For example, an analysis of the emissions at the processing plant might detect a low impact but would ignore the high impacts generated during agricultural production or long-distance transportation. The LCA's cradle-to-grave approach allows an accurate diagnosis of the environmental hotspots, providing a roadmap for continuous improvement.

Declared Units.

The declared units followed the Central Product Classification (CPC), including CPC 21421 (1 kg of shelled peanuts and 1 kg of blanched peanuts) and CPC 21495 (1 kg of roasted peanuts, peanut granules, fried peanuts, peanut paste, and peanut butter). In all cases, the declared unit refers to 1 kg of product excluding packaging. The CPC provides a comprehensive and internationally harmonized framework for classifying goods and services (United Nations, 2015).

Geographical and temporal scope.

Data were obtained from three farms representative of peanut production in Argentina: two in the province of Córdoba (Tercero Arriba and General Roca departments) and one in Buenos Aires province (Lincoln district). The industrial complex is located in Hernando, Córdoba province, and products produced are mostly exported to Europe. The analysis covers the 2023/2024 peanut crop season and the calendar year 2024 for industrial data. The temporal representativeness of the study corresponds to current production conditions, with primary data reflecting the most recent complete production cycle available.

Primary peanut production on the farm

The following factors were included: production and use of agricultural inputs (agrochemicals, fertilizers, fuel, seeds), production of their packaging, emissions from the use of fuels for transport and agricultural activities (planting, spraying, digging and harvesting), emissions from the application of nitrogen fertilizers, and those from above- and below-ground residue decomposition. Data of use of fuels and inputs were taken from the records of each farm.

Weighted averages of the results obtained from the farms were calculated so that the input to the industry represents output from the field.

For the agricultural stage, direct emissions from the application of nitrogen fertilizers -which were used only in low rates as foliar feeding- as well as from decomposition of above- and below-ground crop residues, were considered. These emissions were calculated using Intergovernmental Panel on Climate Change (IPCC) tier 2 methodology, with default equations and emission factors specific for Argentina, taken from the Biennial Update Reports of the Ministry of Environment and Sustainable Development (MAyDS, 2023). This approach improves accuracy, since it uses disaggregated activity data.

On the farm located in Tercero Arriba department, Córdoba, yield was 4000 kg ha^{-1} of in-shell peanut. Fungicide/insecticide-treated seeds were planted at a density of 175 kg ha^{-1} using a paratill, weeder, double action disc harrow and conventional planter. Crop fertilization consisted of 1.57 kg ha^{-1} of compound fertilizer and 0.63 kg ha^{-1} of micronutrients (i.e., a total rate of 2.2 kg ha^{-1}). Crop protection included the application of herbicides (4.88 kg ha^{-1} of active ingredient, ai), insecticides (0.091 kg ha^{-1} ai) and fungicides (3.95 kg ha^{-1} ai). The amount of agrochemical packaging waste was 0.54 kg ha^{-1} of plastic material, which was destined for recycling. Fuel consumption was 67.67 L ha^{-1} of diesel; for technical assistance, a pick-up truck travelled 2 km per cultivated ha. Input transport to the field required 8 km by truck (3.5 to 7.5 t load capacity). Transport of in-shell peanuts from the farm to the processing plant was also 8 km by truck (16 to 32 t load capacity). Transport of agrochemical packaging waste covered 115 km by truck (3.5 to 7.5 t load capacity). Crop residues were left on the soil surface as cover and no cover crops were used.

On the farm in General Roca department, Córdoba, yield was 6200 kg ha^{-1} of in-shell peanut. Treated seeds were planted at a density of 175 kg ha^{-1}, using weeder and no-till planter. No fertilization was applied in the cases studied. Crop protection included herbicides (7.09 kg ha^{-1} ai), insecticides (0.088 kg ha^{-1} ai) and fungicides (3.12 kg ha^{-1} ai). The amount of agrochemical packaging waste was 0.62 kg ha^{-1} of plastic material, which was destined for recycling. Gas oil consumed amounted to 48.99 L ha^{-1}, and 12.47 km were travelled by pick-up truck for technical assistance per cultivated ha. Input transport covered 6 km by truck (3.5 to 7.5 t load capacity). Transport of in-shell peanuts from the farm to the processing plant covered 300 km by truck (16 to 32 t load capacity). Transport of packaging waste covered 82 km by truck (3.5 to 7.5 t load capacity). Crop residues were left on the surface as cover and no cover crops were used.

On the farm in Lincoln district, Buenos Aires, yield was 5,700 kg ha^{-1} of in-shell peanuts. Fungicide/insecticide-treated seeds were planted at a density of 175 kg ha^{-1}, using a double action disc harrow, and conventional tillage. No fertilization was applied to the crop. Crop protection consisted of the application of herbicides (6.14 kg ha^{-1} ai), insecticides (0.10 kg ha^{-1} ai) and fungicides (3.39 kg ha^{-1} ai). The amount of agrochemical packaging waste was 0.58 kg ha^{-1} of plastic material, which was destined for recycling. Fuel consumed amounted to 58.23 L ha^{-1} of gas oil; for technical assistance, a pick-up truck travelled 23.34 km per cultivated ha. Transport of inputs covered 28.75 km by truck (3.5 to 7.5 t load capacity). Transport of in-shell peanuts from the farm to the processing plant covered 505 km by truck (16 to 32 t load capacity). Transport of agrochemical packaging waste covered 65 km by truck (3.5 to 7.5 t load capacity). Crop residues were left on the soil surface as cover and no cover crops were used.

Peanut processing industry

Peanut processing primary data was obtained for products, like shelled peanuts, blanched peanuts and their byproducts, from a company representative of the sector, located in Hernando, Córdoba. For each product, the company identified the use of inputs, fuel and energy, the suppliers involved, the process losses and the byproducts obtained.

Regarding logistics, all types of packaging materials used for the commercialization of each product were included; they were calculated according to the percentage of participation in the total volume exported. The analysis considers the terrestrial transportation by truck to the port and the marine transportation to the final destination. Lastly, final disposal of packaging materials was considered, thereby completing the product's life cycle.

Figure 1 shows the stages included in the study, with the division between upstream, core and downstream processes, as requested by the Product Category Rules (PCR). All the declared units and their relationships are shown.

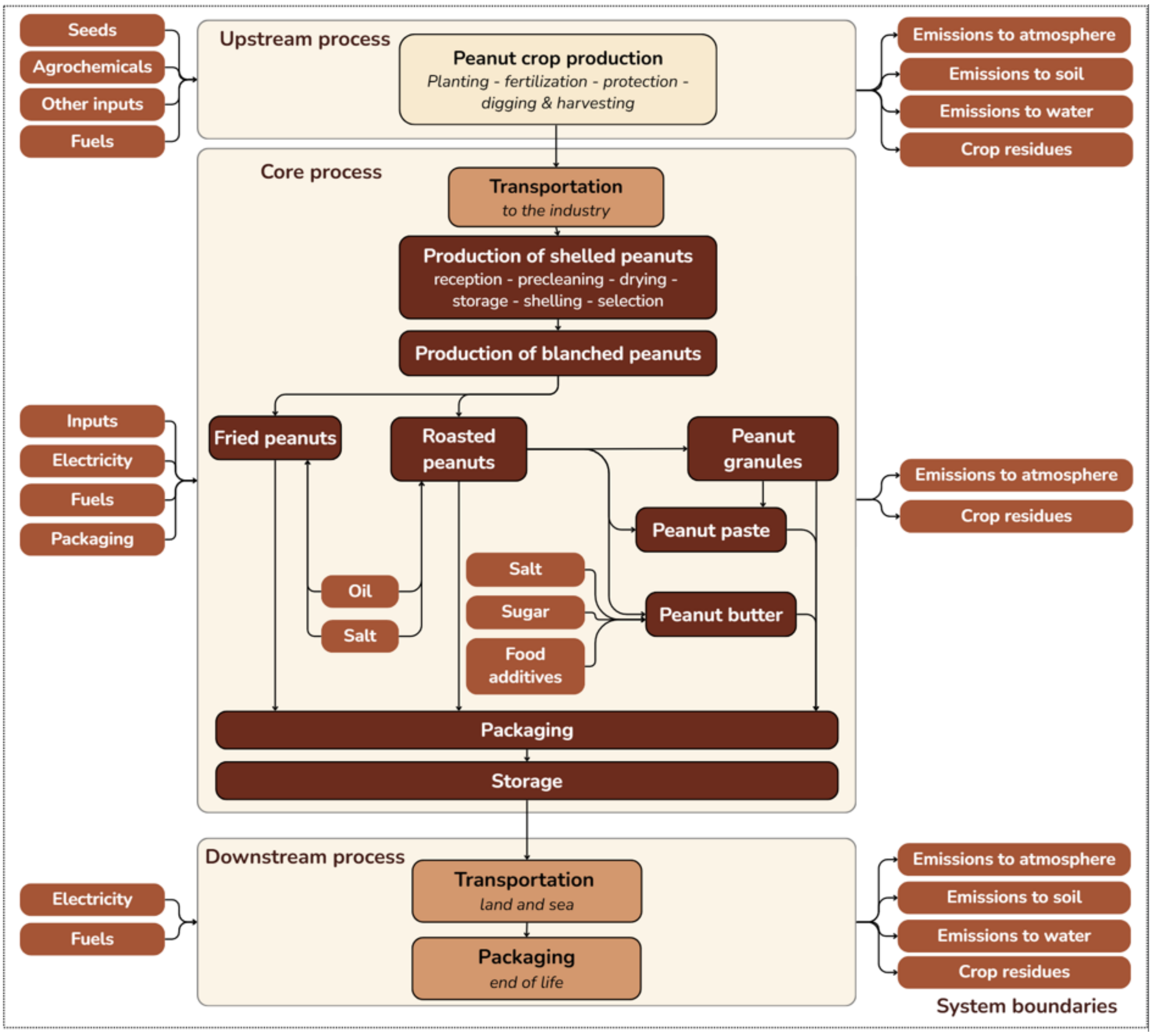

Figure 1. Stages of the production system and system boundaries, including upstream, core and downstream processes.

The industrial process starts with the reception of in-shell peanuts, which are dirty and moist, in bulk in trucks. Upon arrival at the plant, each truck is weighed, and samples are collected for further laboratory analysis, following quality rules. If peanuts comply with the requirements, they are received at the plant. Once unloaded, peanuts are subjected to mechanical pre-cleaning using aspiration and screening procedures to remove large foreign materials (i.e., stones, stems, leaves and other visible debris). Then, to avoid fungal development, peanuts are dried, if necessary, to reach less than 10% moisture. This process is conducted in double-floor drying wagons, through which air at ambient or high temperature –depending on the environmental humidity– is blown. Once dried, peanuts are stored in bins until processing. These processes entail losses due to dirt, foreign materials and moisture.

At the cleaning stage, in-shell peanuts pass through a series of devices that remove heavy elements (i.e., stones, dust and leaves) through aspiration. After this process, the in-shell peanuts are introduced into the shelling machine, where the shell is removed by some rollers and the shell remains are separated from the grain. Then the grains undergo a two-type sorting process: sorting by size and color. At this initial stage, the shelled peanuts are obtained, which are stored in industry standard (APC, 2023) one-ton flexible intermediate bulk containers (big-bags) until the next stage of commercialization. In addition, shells obtained as a byproduct are sold for energy generation; peanuts rejected during processing are sold to the oil industry, and there are losses due to dirt or foreign materials. In accordance with the applicable Product Category Rule (PCR) and the General Program Instructions (GPI) of the EPD system, the environmental burdens of the shared processes were allocated among the main product and the valorized byproducts (e.g. shells used for energy generation and rejected peanuts sold to the oil industry), and no environmental credits were assigned.

Shelled peanut kernels are first subjected to a dry thermal treatment in an oven, followed by controlled cooling to promote differential contraction between the kernel and the testa, thereby loosening the skin. The kernels then pass through abrasive rollers with rough surfaces that mechanically rub and detach the skin, while an air aspiration system removes the released skin particles. Subsequently, the kernels are conveyed over vibrating screens, where remaining skin fragments and fines are separated. A final sorting stage separates whole kernels from splits and classifies them by size. Byproducts recovered from the sorter are obtained and diverted to other lines; the skin is sold for energy generation, and discolored sorter rejects are used in the oil industry. There are also losses due to moisture. Blanched peanuts are stored in big-bags.

Roasted peanuts can be produced using both blanched and unblanched peanuts, with the former being the most used. Roasting involves putting the peanuts in an oven at a controlled temperature (160 to 180 C). After this process, peanuts are rapidly cooled with air to stop the roasting process. Besides roasted peanuts with or without skin, salted peanuts can also be obtained; in this case, oil is added before roasting. Once the products are cooled, they are packed and stored.

Fried peanuts can also be produced using both shelled and blanched peanuts, most commonly using peanuts without skin. Unlike roasted peanuts, peanuts are fried in oil at about 160 C, then placed on a mesh conveyor where they are cooled, and the excess oil is drained. Finally, peanuts are salted in a rotating cylinder. At the end of the process, fried peanuts pass along a belt for packaging and further storage.

Peanut butter is produced with roasted peanuts without skin. Peanut grains are ground with rollers, until a creamy consistency is obtained. Then salt, sugar and stabilizer are added, and the butter is homogenized. Finally, the product is packaged using the different packaging options offered by the company.

Peanut paste is produced in a similar way to that of peanut butter, but no ingredients are added. Once the desired consistency is obtained by grinding, it can be packed as a finished product, or granules can be added to obtain a crunchier paste.

Finally, peanut granules are produced by partially grinding roasted peanuts without skin; then they are packaged and stored.

Production Seasonality And Emissions

Industrial processes depend on the peanut harvest time. Peanut reception at the industrial level starts between March and April and ends in July. Peak electricity consumption occurs in the transformers feeding the shelling plant, blanching and unloading in bins. Peak natural gas consumption occurs in the drying process, immediately after reception at the plant.

Transportation And Logistics

Transport at the primary production stage includes the supply of agricultural inputs, raw materials, and fuel for peanut production, as well as the transport to (loaded) and from (empty) the processing plant (203 km) in Hernando. For the processing stage, the transportation of inputs, fuel and associated packaging was included. In addition, waste similar to urban waste, which is disposed of at the dump site of Hernando, 5 km away from the plant, and hazardous waste, which is disposed of in Córdoba city, 150 km away, were considered.

All the finished products analyzed are mainly destined for export. The distance covered by truck from the plant to the Buenos Aires port (620 km) was accounted for, as well as the marine transportation (11,928 km) to Europe, as reported by the company.

All packaging materials required, including plastic containers, cardboard boxes, polythene bags, multilayered bags, big-bags, metal drums, and pallets, among other elements, were assumed to be disposed of in a sanitary landfill at the end of their useful life. For modelling consistency and to avoid underestimation of impacts, all packaging and logistics items were conservatively assumed to be single-use, due to the lack of reliable data on reuse rates across different markets and logistics systems.

Models for the characterization of environmental impact

Selection of models for the characterization of environmental impact used are in line with the scientific principles that describe the environmental phenomena evaluated. The impact categories recommended by the PCR of the EPD system (https://www.environdec.com/pcr/env-perf-indic/gpi5) applied in this study are detailed in Table 2.

Climate change (total), expressed as Global Warming Potential (GWP), quantifies the cumulative radiative forcing of greenhouse gas emissions over a 100-year time horizon, aggregating contributions from fossil, biogenic, and land-use-related CO_2, as well as other greenhouse gases, and expressing them as kilograms of CO_2 equivalents (kg CO_2 eq) according to the IPCC baseline characterization model.

Eutrophication potential describes the contribution of nutrient emissions, mainly nitrogen and phosphorus compounds, to excessive enrichment of aquatic and terrestrial ecosystems, which may result in algal blooms, oxygen depletion and loss of ecological balance.

Ozone depletion potential (ODP) quantifies the contribution of emissions to the destruction of stratospheric ozone, by accounting for substances that reduce ozone concentrations relative to a reference compound and is expressed as kilograms of CFC-11 equivalents (kg CFC-11 eq).

Acidification potential (AP) quantifies the contribution of emissions to the increase of acidity in soils and water bodies through the release of acidifying substances, such as sulfur dioxide, nitrogen oxides and ammonia, which lead to proton formation (acid rain), and is expressed as moles of H^+ equivalents (mol H^+ eq).

Photochemical ozone creation potential (POCP) quantifies the contribution of emissions, mainly nitrogen oxides (NO_x) and volatile organic compounds (VOCs), to the formation of tropospheric (ground-level) ozone through photochemical reactions in the presence of sunlight and is expressed as kilograms of NMVOC equivalents (kg NMVOC eq).

Depletion of abiotic resources quantifies the consumption of nonrenewable natural resources, including minerals, metals, and fossil fuels, by accounting for the extraction of finite stocks and their potential scarcity. This impact reflects the reduction of resource availability for future use and is expressed using antimony equivalents (kg Sb eq) for minerals and metals, and energy content (MJ, net calorific value) for fossil fuels, following the CML characterization method.

Water deprivation potential quantifies the potential impact of freshwater consumption on water availability by accounting for the reduction of locally available water resources relative to demand. It reflects the risk of water scarcity induced by water use and is expressed as cubic meters of worldequivalent deprived water (m^3 world eq), based on the AWARE (Available Water Remaining) method in accordance with ISO 14046.

Table 2. Categories of environmental impact, parameters evaluated and models applied.

Environmental impact category	Parameter	Model
Climate change– total	kg CO_2 eq	IPCC's baseline model of GHG emissions for a 100-year timescale (IPCC, 2021)
Ozone depletion potential	kg CFC-11 eq	Ozone destruction exceeds ozone creation (EU-ILCD, 2010; WMO, 2014)
Acidification	mol H^+ eq	Proton release or acid rain (Seppälä et al, 2006; Posch et al, 2008).
Eutrophication - freshwater	kg P eq	Excessive nutrients in freshwater, ReCiPe (Struijs et al, 2009; Huijbregts et al, 2017; Eutrend, 2021)
Eutrophication – aquatic marine	kg N eq	Excessive nutrients in marine environment, ReCiPe (Struijs et al, 2009; Huijbregts et al, 2017; Eutrend, 2021).
Eutrophication - terrestrial	mol N eq	Excessive nutrients in soils (Seppälä et al, 2006; Posch et al, 2008)
Photochemical ozone creation	kg NMVOC eq	Degradation (NOx, VOCs) in the presence of sunlight. ReCiPe Method. (Struijs et al, 2009; van Zelm and Hollander, 2008).
Depletion of abiotic resources – minerals and metals	kg Sb eq	kg Sb eq/MJ, CML Method (van Oers and Guinée, 2016; Guinée et al, 2002).
Depletion of abiotic resources – fossil fuels	MJ, net calorific value	kg Sb eq kg^{-1} of extracted resource, CML Method (van Oers and Guinée, 2016; Guinée et al, 2002).
Water deprivation	m^3 world eq of deprived water	AWARE (Available Water Remaining) method + ISO 14046 2014 (Boulay et al, 2018).

Allocation Of Environmental Burdens

Within the framework of the LCA, allocation of environmental burdens is a crucial theoretical challenge in modelling production of processed peanuts to avoid over- or underestimating impacts. Allocation theory determines that environmental burdens generated during a shared process should be distributed among the different co-products and byproducts that have economic value. In this study, the allocation method was based on a biophysical criterion, specifically by mass of products and byproducts (e.g., shell, skin), following the guidelines of the PCR for "Food and Beverage Products" (International EPD System, 2025). The selected method ensures an equal distribution of environmental burdens, reflecting the actual material burden of the production system.

Figure 2 shows the processes of allocation. Since all the products share some part of the production chain, all the declared units are affected by at least one allocation. Table 3 presents the allocation of environmental burden to the products and byproducts.

For peanut butter and paste, environmental burdens were also allocated based on mass because they generate byproducts for the oil industry. However, they were not included in the table because the amount was lower than 0.1%.

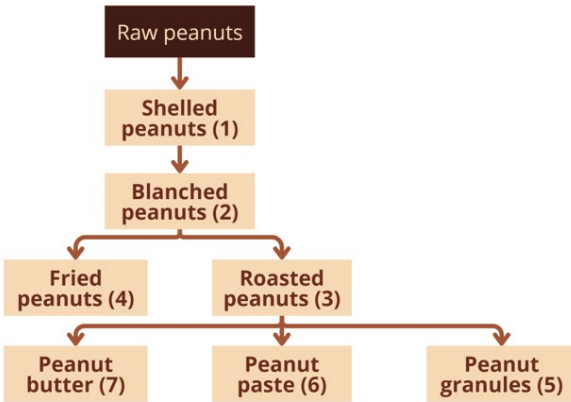

Figure 2. Diagram of product integration with identification of allocation points. Numbers in parenthesis correspond to numbers of products in Table 3.

After the input and output inventories of each operation and stage were generated, the unit emissions associated with each input were obtained: inputs, raw materials and energy referring to the corresponding declared unit. Then, the amounts used of each input were associated with their unit emissions to obtain the environmental impact for each inventory element.

Table 3: Percentage of environmental burden allocated based on mass in the industry.

Allocation of environmental burdens	Percent allocated based on mass (%)
Production of shelled peanuts (1)	
Shelled peanuts	64.3%
Byproduct- Peanuts recovered from sorter: peanuts rejected by sorter, which can be recovered through reprocessing or use as raw material in other lines.	3.8%
Byproduct – Peanut shell: sold for generation of energy	23.5%
Production of blanched peanuts (2)	
Blanched peanuts	80.5%
Byproduct- Peanuts recovered from sorter: peanuts rejected by sorter, which can be recovered through reprocessing or use as raw material in other lines.	13.8%
Byproduct – Skin: sold for generation of energy.	3.8%
Byproduct – Peanuts for industry: sold for the peanut oil industry.	2.0%
Production of roasted peanuts (3)	
Roasted peanuts without additives	86.6%
Byproduct – Peanuts for industry: sold for the peanut oil industry.	13.4%
Production of fried peanuts (4)	
Fried peanuts without additives	99.0%
Byproduct – Peanuts for industry: sold for the peanut oil industry.	1.0%
Production of peanut granules (5)	
Peanut granules	80.1%
Byproduct - Peanut flour: traded as a product	4.4%
Byproduct – Peanuts for industry: sold for the peanut oil industry.	15.6%

Life Cycle Assessment modeling and impact calculations were performed using SimaPro software version 9.6, and environmental profiles for processes not covered by primary data collection were sourced from the Ecoinvent database version 3.10 (Wernet *et al.*, 2016). These tools provided background data and methodological support essential for completing the life cycle inventory and impact assessment in accordance with ISO standards.

RESULTS AND DISCUSSION

The results of the LCA of peanut products (shelled peanuts (Table 4), blanched peanuts (Table 5), roasted peanuts (Table 6), fried peanuts (Table 7), peanut butter (Table 8), peanut paste (Table 9), and peanut granules (Table 10), from peanut production in the field, through industrial processes to produce each product, packaging and storage, to their commercialization in international markets, are detailed in Tables 4 to 10. Results are grouped into upstream, core and downstream processes, and their corresponding substages. For impact categories involving precursor emissions and characterization models (e.g. acidification and eutrophication), a brief description of the calculation pathway is provided prior to result interpretation.

Table 4. Indicators of impact category and of use of resources for the declared unit 1 kilogram of packaged SHELLED peanuts delivered to the customer.

PARAMETER		UNIT	Upstream		Core		Downstream		Total
			Agricultural production	Packaging production	Transport from field	Industry	Distribution	End-of-life	
Global warming potential (GWP)	Fossil	kg CO_2 eq	6.99E-2	8.00E-3	2.47E-2	3.00E-2	1.49E-1	3.51E-5	2.82E-1
	Biogenic		9.99E-2	9.43E-5	9.95E-7	2.27E-4	5.40E-6	1.67E-9	1.00E-1
	Land use and land use change		2.49E-1	1.06E-5	7.15E-7	4.08E-4	4.28E-6	1.11E-9	2.49E-1
	TOTAL		4.19E-1	8.11E-3	2.47E-2	3.06E-2	1.49E-1	3.51E-5	6.31E-1
Ozone depletion potential (ODP)		kg CFC 11 eq	2.39E-7	2.16E-10	3.28E-10	5.29E-10	2.10E-9	4.79E-13	2.42E-7
Acidification potential (AP)		mol H^+ eq	6.54E-4	2.85E-5	6.12E-5	4.77E-5	2.38E-3	1.41E-7	3.17E-3
Eutrophication potential (EP)	Aquatic freshwater	kg P eq	5.58E-5	2.01E-6	4.97E-7	5.11E-7	1.93E-6	7.85E-10	6.08E-5
	Aquatic marine	kg N eq	2.09E-4	7.46E-6	2.14E-5	1.17E-5	5.64E-4	5.74E-8	8.13E-4
	Aquatic terrestrial	mol N eq	2.21E-3	6.59E-5	2.34E-4	1.23E-4	6.27E-3	6.28E-7	8.91E-3
Photochemical ozone creation potential (POCP)		kg NMVOC eq	6.91E-4	3.90E-5	9.14E-5	7.88E-5	1.78E-3	2.12E-7	2.68E-3
Abiotic depletion potential (ADP)	Metals and minerals	kg Sb eq	2.11E-8	1.25E-9	1.45E-9	1.30E-9	4.99E-9	1.92E-12	3.01E-8
	Fossil resources	MJ, net calorific value	1.02E+0	1.88E-1	3.27E-1	5.26E-1	1.90E+0	4.62E-4	3.96E+0
Water deprivation potential (WDP)		m^3 world eq deprived	1.03E-2	4.26E-3	3.01E-4	2.62E-2	1.23E-3	4.24E-7	4.24E-2
Primary energy resources - Renewable	Use as energy carrier	MJ, net calorific value	2.23E-2	1.66E-2	5.24E-4	7.14E-2	3.35E-3	1.01E-6	1.14E-1
	Used as raw materials		0.00E+0	1.02E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0	1.02E-2
	TOTAL		2.23E-2	2.68E-2	5.24E-4	7.14E-2	3.35E-3	1.01E-6	1.24E-1
Primary energy resources - Non-renewable	Use as energy carrier		1.02E+0	1.88E-1	3.27E-1	5.26E-1	1.90E+0	4.62E-4	3.96E+0
	Used as raw materials		0.00E+0	8.51E-2	0.00E+	0.00E+0	0.00E+0	0.00E+0	8.51E-2
	TOTAL		1.02E+0	2.73E-1	3.27E-1	5.26E-1	1.90E+0	4.62E-4	4.05E+0

Table 5. Indicators of impact category and of use of resources for the declared unit 1 kilogram of packaged BLANCHED peanuts delivered to the customer.

PARAMETER		UNIT	Upstream			Core		Downstream		Total
			Agricultural production	Packaging	Pre-industry	Transport	Industry	Distribution	End-of-life	
Global warming potential (GWP)	Fossil	kg CO_2 eq	7.13E-2	8.00E-3	2.98E-2	2.52E-2	3.68E-2	1.49E-1	3.51E-5	3.20E-1
	Biogenic		1.02E-1	9.43E-5	2.25E-4	1.02E-6	1.01E-4	5.40E-6	1.67E-9	1.02E-1
	Land use and land use change		2.54E-1	1.06E-5	4.05E-4	7.31E-7	1.75E-4	4.28E-6	1.11E-9	2.54E-1
	TOTAL		4.27E-1	8.11E-3	3.04E-2	2.52E-2	3.71E-2	1.49E-1	3.51E-5	6.77E-1
Ozone depletion potential (ODP)		kg CFC 11 eq	2.43E-7	2.16E-10	5.25E-10	3.36E-10	7.00E-10	2.10E-9	4.79E-13	2.47E-7
Acidification potential (AP)		mol H^+ eq	6.67E-4	2.85E-5	4.73E-5	6.26E-5	3.50E-5	2.38E-3	1.41E-7	3.22E-3
Eutrophication potential (EP)	Aquatic freshwater	kg P eq	5.69E-5	2.01E-6	5.11E-7	5.09E-7	3.99E-7	1.93E-6	7.85E-10	6.23E-5
	Aquatic marine	kg N eq	2.13E-4	7.46E-6	1.16E-5	2.18E-5	9.34E-6	5.64E-4	5.74E-8	8.27E-4
	Aquatic terrestrial	mol N eq	2.25E-3	6.59E-5	1.22E-4	2.40E-4	9.85E-5	6.27E-3	6.28E-7	9.05E-3
Photochemical ozone creation potential (POCP)		kg NMVOC eq	7.05E-4	3.90E-5	7.87E-5	9.35E-5	7.64E-5	1.78E-3	2.12E-7	2.77E-3
Abiotic depletion potential (ADP)	Metals and minerals	kg Sb eq	2.15E-8	1.25E-9	1.30E-9	1.48E-9	4.88E-10	4.99E-9	1.92E-12	3.11E-8
	Fossil resources	MJ, net calorific value	1.04E+0	1.88E-1	5.22E-1	3.34E-1	6.08E-1	1.90E+0	4.62E-4	4.59E+0
Water deprivation potential (WDP)		m^3 world eq deprived	1.05E-2	4.26E-3	2.60E-2	3.08E-4	1.16E-2	1.23E-3	4.24E-7	5.40E-2
Primary energy resources - Renewable	Use as energy carrier	MJ, net calorific value	2.27E-2	1.66E-2	7.08E-2	5.36E-4	3.18E-2	3.35E-3	1.01E-6	1.46E-1
	Used as raw materials		0.00E+0	1.02E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	1.02E-2
	TOTAL		2.27E-2	2.68E-2	7.08E-2	5.36E-4	3.18E-2	3.35E-3	1.01E-6	1.56E-1
Primary energy resources - Non-renewable	Use as energy carrier		1.04E+0	1.88E-1	5.22E-1	3.34E-1	6.08E-1	1.90E+0	4.62E-4	4.59E+0
	Used as raw materials		0.00E+0	8.51E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	8.51E-2
	TOTAL		1.04E+0	2.73E-1	5.22E-1	3.34E-1	6.08E-1	1.90E+0	4.62E-4	4.68E+0

Table 6. Indicators of impact category and of use of resources for the declared unit 1 kilogram of packaged ROASTED peanuts delivered to the customer.

PARAMETER		UNIT	Upstream				Core		Downstream		Total
			Agriculture	Additives	Packaging	Pre-industry	Transport	Industry	Distribution	End-of-life	
Global warming potential (GWP)	Fossil	kg CO_2 eq	7.36E-2	5.21E-4	4.61E-2	5.17E-2	3.05E-2	9.13E-2	1.61E-1	8.62E-5	4.55E-1
	Biogenic		1.05E-1	9.83E-7	1.76E-3	2.89E-4	1.23E-6	2.46E-4	5.88E-6	4.11E-9	1.08E-1
	Land use and land use change		2.62E-1	4.38E-7	1.47E-4	5.18E-4	8.83E-7	4.28E-4	4.65E-6	2.72E-9	2.63E-1
	TOTAL		4.41E-1	5.23E-4	4.81E-2	5.25E-2	3.05E-2	9.19E-2	1.61E-1	8.62E-5	8.26E-1
Ozone depletion potential (ODP)		kg CFC 11 eq	2.51E-7	5.13E-11	1.20E-9	9.41E-10	4.06E-10	1.75E-9	2.27E-9	1.18E-12	2.58E-7
Acidification potential (AP)		mol H^+ eq	6.89E-4	4.81E-6	2.14E-4	6.86E-5	7.65E-5	8.40E-5	2.49E-3	3.47E-7	3.63E-3
Eutrophication potential (EP)	Aquatic freshwater	kg P eq	5.88E-5	2.31E-7	1.45E-5	7.55E-7	6.14E-7	1.00E-6	2.14E-6	1.93E-9	7.80E-5
	Aquatic marine	kg N eq	2.20E-4	1.47E-6	7.37E-5	1.73E-5	2.69E-5	2.30E-5	5.93E-4	1.41E-7	9.55E-4
	Aquatic terrestrial	mol N eq	2.33E-3	2.07E-5	5.98E-4	1.82E-4	2.95E-4	2.42E-4	6.60E-3	1.54E-6	1.03E-2
Photochemical ozone creation potential (POCP)		kg NMVOC eq	7.28E-4	3.00E-6	2.48E-4	1.25E-4	1.14E-4	1.96E-4	1.88E-3	5.19E-7	3.29E-3
Abiotic depletion potential (ADP)	Metals and minerals	kg Sb eq	2.22E-8	1.42E-9	2.15E-8	1.62E-9	1.79E-9	1.14E-9	5.58E-9	4.71E-12	5.53E-8
	Fossil resources	MJ, net calorific value	1.08E+0	4.95E-3	8.64E-1	8.85E-1	4.04E-1	1.51E+0	2.06E+0	1.13E-3	6.81E+0
Water deprivation potential (WDP)		m^3 world eq deprived	1.09E-2	1.43E-4	1.90E-2	3.35E-2	3.72E-4	2.84E-2	1.36E-3	1.04E-6	9.36E-2
Primary energy resources - Renewable	Use as energy carrier	MJ, net calorific value	2.35E-2	1.79E-4	8.95E-1	9.12E-2	6.48E-4	7.79E-2	3.63E-3	2.49E-6	1.09E+0
	Used as raw materials		0.00E+0	0.00E+0	6.32E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	6.32E-1
	TOTAL		2.35E-2	1.79E-4	1.53E+0	9.12E-2	6.48E-4	7.79E-2	3.63E-3	2.49E-6	1.72E+0
Primary energy resources - Non-renewable	Use as energy carrier		1.08E+0	4.95E-3	8.65E-1	8.85E-1	4.04E-1	1.51E+0	2.06E+0	1.13E-3	6.81E+0
	Used as raw materials		0.00E+0	0.00E+0	2.58E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	2.58E-1
	TOTAL		1.08E+0	4.95E-3	1.12E+0	8.85E-1	4.04E-1	1.51E+0	2.06E+0	1.13E-3	7.07E+0

Table 7. Indicators of impact category and of use of resources for the declared unit 1 kilogram of packaged FRIED peanuts delivered to the customer.

PARAMETER		UNIT	Upstream				Core		Downstream		
			Agriculture	Additives	Packaging	Pre-industry	Transport	Industry	Distribution	End-of-life	Total
Global warming potential (GWP)	Fossil	kg CO_2 eq	6.95E-2	3.98E-2	3.00E-2	6.33E-2	3.11E-2	1.58E-1	1.60E-1	4.12E-4	5.52E-1
	Biogenic		9.92E-2	7.67E-5	4.88E-4	3.13E-4	1.26E-6	2.71E-4	5.82E-6	1.97E-8	1.00E-1
	Land use and land use change		2.47E-1	3.20E-5	6.49E-5	5.58E-4	9.03E-7	4.69E-4	4.60E-6	1.30E-8	2.48E-1
	TOTAL		4.16E-1	3.99E-2	3.06E-2	6.42E-2	3.11E-2	1.59E-1	1.60E-1	4.13E-4	9.01E-1
Ozone depletion potential (ODP)		kg CFC 11 eq	2.37E-7	3.99E-9	6.72E-10	1.17E-9	4.15E-10	3.07E-9	2.25E-9	5.62E-12	2.49E-7
Acidification potential (AP)		mol H^+ eq	6.50E-4	3.67E-4	1.40E-4	7.86E-5	7.86E-5	1.29E-4	2.47E-3	1.66E-6	3.91E-3
Eutrophication potential (EP)	Aquatic freshwater	kg P eq	5.54E-5	1.80E-5	7.67E-6	8.70E-7	6.28E-7	1.66E-6	2.12E-6	9.22E-9	8.64E-5
	Aquatic marine	kg N eq	2.07E-4	1.12E-4	4.05E-5	2.00E-5	2.77E-5	3.71E-5	5.86E-4	6.74E-7	1.03E-3
	Aquatic terrestrial	mol N eq	2.19E-3	1.58E-3	3.87E-4	2.11E-4	3.04E-4	3.90E-4	6.52E-3	7.37E-6	1.16E-2
Photochemical ozone creation potential (POCP)		kg NMVOC eq	6.86E-4	2.25E-4	1.70E-4	1.48E-4	1.17E-4	3.27E-4	1.86E-3	2.48E-6	3.53E-3
Abiotic depletion potential (ADP)	Metals and minerals	kg Sb eq	2.10E-8	1.11E-7	1.14E-8	1.72E-9	1.83E-9	1.72E-9	5.51E-9	2.25E-11	1.54E-7
	Fossil resources	MJ, net calorific value	1.02E+0	3.75E-1	5.93E-1	1.08E+0	4.13E-1	2.59E+0	2.04E+0	5.43E-3	8.10E+0
Water deprivation potential (WDP)		m^3 world eq deprived	1.03E-2	1.12E-2	1.43E-2	3.62E-2	3.80E-4	3.13E-2	1.34E-3	4.98E-6	1.05E-1
Primary energy resources - Renewable	Use as energy carrier	MJ, net calorific value	2.21E-2	1.39E-2	7.80E-1	9.86E-2	6.62E-4	8.69E-2	3.59E-3	1.19E-5	1.01E+0
	Used as raw materials		0.00E+0	0.00E+0	4.99E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	4.99E-1
	TOTAL		2.21E-2	1.39E-2	1.28E+0	9.86E-2	6.62E-4	8.69E-2	3.59E-3	1.19E-5	1.51E+0
Primary energy resources - Non-renewable	Use as energy carrier		1.02E+0	3.75E-1	5.93E-1	1.08E+0	4.13E-1	2.59E+0	2.04E+0	5.43E-3	8.10E+0
	Used as raw materials		0.00E+0	0.00E+0	1.96E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	1.96E-1
	TOTAL		1.02E+0	3.75E-1	7.89E-1	1.08E+0	4.13E-1	2.59E+0	2.04E+0	5.43E-3	8.30E+0

Table 8. Indicators of impact category and of use of resources for the declared unit 1 kilogram of packaged peanut BUTTER delivered to the customer.

			Upstream				Core		Downstream		
PARAMETER		UNIT	Agriculture	Additives	Packaging	Pre-industry	Transport	Industry	Distribution	End-of-life	Total
Global warming potential (GWP)	Fossil	kg CO_2 eq	6.65E-2	5.95E-2	1.56E-1	1.29E-1	4.37E-2	1.52E-2	1.69E-1	1.20E-3	6.41E-1
	Biogenic		9.50E-2	1.07E-3	1.10E-3	4.84E-4	1.77E-6	1.69E-4	6.17E-6	5.73E-8	9.79E-2
	Land use and land use change		2.37E-1	-2.61E-2	3.60E-4	8.53E-4	1.27E-6	2.97E-4	4.88E-6	3.79E-8	2.12E-1
	TOTAL		3.98E-1	3.45E-2	1.58E-1	1.31E-1	4.37E-2	1.57E-2	1.69E-1	1.20E-3	9.51E-1
Ozone depletion potential (ODP)		kg CFC 11 eq	2.27E-7	3.67E-9	3.81E-9	2.47E-9	5.84E-10	2.63E-10	2.38E-9	1.64E-11	2.40E-7
Acidification potential (AP)		mol H^+ eq	6.22E-4	1.11E-3	6.36E-4	1.42E-4	1.13E-4	2.75E-5	2.62E-3	4.83E-6	5.27E-3
Eutrophication potential (EP)	Aquatic freshwater	kg P eq	5.31E-5	1.88E-5	3.66E-5	1.79E-6	8.84E-7	2.28E-7	2.25E-6	2.68E-8	1.14E-4
	Aquatic marine	kg N eq	1.98E-4	6.45E-4	1.49E-4	3.77E-5	4.03E-5	6.14E-6	6.22E-4	1.96E-6	1.70E-3
	Aquatic terrestrial	mol N eq	2.10E-3	4.89E-3	1.52E-3	4.01E-4	4.42E-4	6.46E-5	6.92E-3	2.15E-5	1.64E-2
Photochemical ozone creation potential (POCP)		kg NMVOC eq	6.57E-4	4.13E-4	8.54E-4	2.92E-4	1.69E-4	4.31E-5	1.97E-3	7.24E-6	4.41E-3
Abiotic depletion potential (ADP)	Metals and minerals	kg Sb eq	2.01E-8	1.64E-7	2.33E-8	3.78E-9	2.58E-9	3.98E-10	5.85E-9	6.57E-11	2.20E-7
	Fossil resources	MJ, net calorific value	9.72E-1	4.73E-1	3.65E+0	2.17E+0	5.81E-1	2.84E-1	2.16E+0	1.58E-2	1.03E+1
Water deprivation potential (WDP)		m^3 world eq deprived	9.83E-3	1.99E-2	5.63E-2	5.59E-2	5.35E-4	1.95E-2	1.42E-3	1.45E-5	1.63E-1
Primary energy resources - Renewable	Use as energy carrier	MJ, net calorific value	2.12E-2	3.09E+0	1.54E+0	1.53E-1	9.32E-4	5.28E-2	3.81E-3	3.47E-5	4.86E+0
	Used as raw materials		0.00E+0	0.00E+0	9.53E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	9.53E-1
	TOTAL		2.12E-2	3.09E+0	2.49E+0	1.53E-1	9.32E-4	5.28E-2	3.81E-3	3.47E-5	5.81E+0
Primary energy resources - Non-renewable	Use as energy carrier		9.72E-1	5.22E-1	3.65E+0	2.17E+0	5.81E-1	2.84E-1	2.16E+0	1.58E-2	1.04E+1
	Used as raw materials		0.00E+0	0.00E+0	1.70E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	1.70E+0
	TOTAL		9.72E-1	5.22E-1	5.36E+0	2.17E+0	5.81E-1	2.84E-1	2.16E+0	1.58E-2	1.21E+1

Table 9. Indicators of impact category and of use of resources for the declared unit 1 kilogram of packaged peanut PASTE delivered to the customer.

PARAMETER		UNIT	Upstream			Core		Downstream		
			Agricultural production	Packaging	Pre-industry	Transport	Industry	Distribution	End-of-life	Total
Global warming potential (GWP)	Fossil	kg CO_2 eq	7.38E-2	1.54E-1	1.44E-1	5.44E-2	4.40E-2	1.66E-1	1.32E-3	6.37E-1
	Biogenic		1.05E-1	2.97E-4	5.45E-4	2.21E-6	4.89E-4	6.03E-6	6.29E-8	1.07E-1
	Land use and land use change		2.63E-1	1.14E-4	9.61E-4	1.58E-6	8.58E-4	4.77E-6	4.16E-8	2.65E-1
	TOTAL		4.42E-1	1.54E-1	1.46E-1	5.44E-2	4.53E-2	1.66E-1	1.32E-3	1.01E+0
Ozone depletion potential (ODP)		kg CFC 11 eq	2.52E-7	1.14E-9	2.76E-9	7.27E-10	7.59E-10	2.33E-9	1.80E-11	2.59E-7
Acidification potential (AP)		mol H^+ eq	6.90E-4	6.47E-4	1.59E-4	1.42E-4	7.94E-5	2.60E-3	5.30E-6	4.32E-3
Eutrophication potential (EP)	Aquatic freshwater	kg P eq	5.89E-5	5.65E-5	2.00E-6	1.10E-6	6.58E-7	2.18E-6	2.95E-8	1.21E-4
	Aquatic marine	kg N eq	2.20E-4	1.54E-4	4.21E-5	5.06E-5	1.77E-5	6.18E-4	2.15E-6	1.10E-3
	Aquatic terrestrial	mol N eq	2.33E-3	1.58E-3	4.48E-4	5.54E-4	1.86E-4	6.87E-3	2.36E-5	1.20E-2
Photochemical ozone creation potential (POCP)		kg NMVOC eq	7.29E-4	5.65E-4	3.26E-4	2.11E-4	1.24E-4	1.96E-3	7.95E-6	3.92E-3
Abiotic depletion potential (ADP)	Metals and minerals	kg Sb eq	2.23E-8	6.79E-7	4.21E-9	3.21E-9	1.15E-9	5.65E-9	7.21E-11	7.16E-7
	Fossil resources	MJ, net calorific value	1.08E+0	1.83E+0	2.42E+0	7.24E-1	8.20E-1	2.11E+0	1.74E-2	9.00E+0
Water deprivation potential (WDP)		m^3 world eq deprived	1.09E-2	3.38E-2	6.30E-2	6.67E-4	5.64E-2	1.38E-3	1.59E-5	1.66E-1
Primary energy resources - Renewable	Use as energy carrier	MJ, net calorific value	2.35E-2	1.27E+0	1.72E-1	1.16E-3	1.52E-1	3.73E-3	3.81E-5	1.62E+0
	Used as raw materials		0.00E+0	7.37E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	7.37E-1
	TOTAL		2.35E-2	2.01E+0	1.72E-1	1.16E-3	1.52E-1	3.73E-3	3.81E-5	2.36E+0
Primary energy resources - Non-renewable	Use as energy carrier		1.08E+0	1.83E+0	2.42E+0	7.24E-1	8.20E-1	2.11E+0	1.74E-2	9.00E+0
	Used as raw materials		0.00E+0	1.51E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	1.51E-1
	TOTAL		1.08E+0	1.98E+0	2.42E+0	7.24E-1	8.20E-1	2.11E+0	1.74E-2	9.15E+0

Table 10. Indicators of impact category and of use of resources for the declared unit 1 kilogram of packaged peanut GRANULES delivered to the customer.

PARAMETER		UNIT	Upstream: Agricultural production	Upstream: Packaging	Upstream: Pre-industry	Core: Transport	Core: Industry	Downstream: Distribution	Downstream: End-of-life	Total
Global warming potential (GWP)	Fossil	kg CO_2 eq	7.36E-2	4.69E-2	1.43E-1	3.02E-2	6.33E-2	1.61E-1	5.27E-4	5.19E-1
	Biogenic		1.05E-1	1.09E-3	5.35E-4	1.22E-6	7.01E-4	5.87E-6	2.51E-8	1.08E-1
	Land use and land use change		2.62E-1	1.07E-4	9.45E-4	8.75E-7	1.23E-3	4.64E-6	1.66E-8	2.65E-1
	TOTAL		4.41E-1	4.81E-2	1.45E-1	3.02E-2	6.52E-2	1.61E-1	5.27E-4	8.91E-1
Ozone depletion potential (ODP)		kg CFC 11 eq	2.51E-7	1.21E-9	2.74E-9	4.02E-10	1.09E-9	2.26E-9	7.18E-12	2.59E-7
Acidification potential (AP)		mol H^+ eq	6.89E-4	2.03E-4	1.57E-4	7.57E-5	1.14E-4	2.49E-3	2.12E-6	3.73E-3
Eutrophication potential (EP)	Aquatic freshwater	kg P eq	5.88E-5	1.24E-5	1.98E-6	6.09E-7	9.44E-7	2.14E-6	1.18E-8	7.69E-5
	Aquatic marine	kg N eq	2.20E-4	6.23E-5	4.17E-5	2.66E-5	2.54E-5	5.91E-4	8.60E-7	9.68E-4
	Aquatic terrestrial	mol N eq	2.33E-3	5.50E-4	4.44E-4	2.92E-4	2.67E-4	6.58E-3	9.41E-6	1.05E-2
Photochemical ozone creation potential (POCP)		kg NMVOC eq	7.28E-4	2.58E-4	3.24E-4	1.13E-4	1.78E-4	1.87E-3	3.17E-6	3.48E-3
Abiotic depletion potential (ADP)	Metals and minerals	kg Sb eq	2.22E-8	1.71E-8	4.18E-9	1.78E-9	1.65E-9	5.56E-9	2.88E-11	5.26E-8
	Fossil resources	MJ, net calorific value	1.08E+0	9.82E-1	2.40E+0	4.00E-1	1.18E+0	2.06E+0	6.93E-3	8.10E+0
Water deprivation potential (WDP)		m^3 world eq deprived	1.09E-2	1.90E-2	6.20E-2	3.68E-4	8.08E-2	1.35E-3	6.36E-6	1.74E-1
Primary energy resources - Renewable	Use as energy carrier	MJ, net calorific value	2.35E-2	8.34E-1	1.69E-1	6.42E-4	2.18E-1	3.62E-3	1.52E-5	1.25E+0
	Used as raw materials		0.00E+0	5.60E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	5.60E-1
	TOTAL		2.35E-2	1.39E+0	1.69E-1	6.42E-4	2.18E-1	3.62E-3	1.52E-5	1.81E+0
Primary energy resources - Non-renewable	Use as energy carrier		1.08E+0	9.82E-1	2.40E+0	4.00E-1	1.18E+0	2.06E+0	6.93E-3	8.10E+0
	Used as raw materials		0.00E+0	3.74E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	3.74E-1
	TOTAL		1.08E+0	1.36E+0	2.40E+0	4.00E-1	1.18E+0	2.06E+0	6.93E-3	8.47E+0

Environmental impact parameters for each declared unit

Global Warming Potential

Global Warming Potential (GWP) results for each declared unit were obtained through a cradle-to-grave LCA following ISO 14040/14044 and ISO 14067 standards. For each product, greenhouse gas emissions were first quantified at the lifecycle inventory level by compiling activity data for agricultural production, industrial processing, packaging, transportation and end-of-life. Emissions of CO_2, CH_4 and N_2O were calculated using primary data and IPCC Tier 2 equations with Argentina-specific emission factors. Inventory flows were then converted into GWP using the IPCC 100-year characterization factors (IPCC, 2021).

The resulting impacts were aggregated by lifecycle stage and expressed per declared unit (1 kg of product, excluding packaging weight), after allocation of shared processes based on mass, as described in the Methods section. Final GWP values reported here therefore represent the sum of fossil, biogenic and landuserelated CO_2 equivalents across all stages of the product life cycle.

Based on the aggregation of stage-level GWP results, this parameter was considerably higher in the products with greater degree of industrial processing, with values ranging from 0.631 kg CO_2 eq kg^{-1} for shelled peanuts (Table 4) to 1.009 kg CO_2 eq kg^{-1} for peanut paste (Table 9). In all cases, most of the GHG emissions were concentrated in the agricultural production stage, accounting for 40% to 66% of the total (Table 11). In the field, 80% of the emissions were from carbon loss through soil management and from harvest residues. On two of the farms, conventional planting was used, which has a greater impact on soil carbon content than no-till.

Table 11. Distribution of the GWP impact by product and by stage.

Stage / Products	Shelled	Blanched	Roasted	Fried	Butter	Paste	Granules
Agricultural production	66.4%	63.1%	53.4%	46.2%	41.9%	43.8%	49.5%
Production of additives	0.0%	0.0%	0.1%	4.4%	3.6%	0.0%	0.0%
Packaging production	1.3%	1.2%	5.8%	3.4%	16.6%	15.3%	5.4%
Farm-industry transportation	3.9%	3.7%	3.7%	3.5%	4.6%	5.4%	3.4%
Pre-processing	0.0%	4.5%	6.4%	7.1%	13.7%	14.5%	16.3%
Processing	4.9%	5.5%	11.1%	17.7%	1.7%	4.5%	7.3%
Distribution	23.6%	22.0%	19.5%	17.7%	17.8%	16.4%	18.1%
End of life	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%

The second most significant stage in terms of GWP was distribution of finished products, with a 16%-24% contribution to the total (Table 11). Environmental burden at this stage was distributed between marine and land transport, with the former being up to 2% higher than the latter. Emissions from products with higher added value tend to concentrate at the industrial stage, with the use of electricity and burning of fossil fuels being the main factors increasing total emissions, besides the addition of other inputs, like salt, sugar and other additives.

For clarity, the international comparisons in Table 1 are limited to the carbon footprint indicator (Global Warming Potential, GWP) and do not encompass the full range of environmental impact categories assessed in the complete LCA.

Based on this analysis, a direct comparison was performed using published carbon footprint values of comparable peanut products, with clearly defined system boundaries. The comparison contrasts Argentine peanut butter produced locally and exported to international markets (including overseas maritime transport), as quantified in this study, with peanut butter produced and consumed within the United States, as reported in the cradle-to-grave assessment by McCarty *et al.* (2014).

Although some reference studies used for international comparison were conducted more than a decade ago, the results presented in this study are not based on historical secondary data, but on primary activity data collected during the 2023/2024 agricultural season and the 2024 industrial and logistics operations. Changes in production processes, management practices, energy use and logistics patterns were therefore explicitly captured through updated farm records, industrial energy and fuel consumption data, and current transportation distances and modes. Older studies are used exclusively for contextual comparison and benchmarking purposes; differences observed should thus be interpreted not only as geographical contrasts, but also as the result of technological progress, improved efficiency and structural changes in the Argentine peanut value chain over time.

Despite the inclusion of long-distance marine transportation in the Argentine case, results show that the cradle-to-grave carbon footprint of Argentine peanut butter is substantially lower than the U.S. national benchmark. Similarly, blanched peanuts produced in Argentina exhibit a 21% lower carbon footprint than those reported for Brazil under comparable cradle-to-gate system boundaries. Distribution includes truck transport (620 km) to port and international maritime transport (11,928 km to Europe). Marine transport represents between 60% and 75% of the distribution stage GWP, but less than 14% of total cradle-to-grave emissions. These results reinforce that production system characteristics may outweigh transport distance in determining total life cycle impacts.

The comparative results between Argentina and the United States highlight that differences in life cycle environmental performance are primarily driven by structural agronomic and supply chain factors rather than by isolated management practices.

In the Argentine system, lower impacts at the farm stage are associated with a combination of characteristics that reduce both direct and indirect emissions. Peanut production is predominantly rainfed, avoiding the energy requirements and emissions associated with irrigation. In addition, fertilization rates are minimal, as the crop relies largely on biological nitrogen fixation, which substantially reduces upstream emissions linked to synthetic inputs. Crop rotations and favorable agroecological conditions contribute to lower disease pressure, limiting the need for agrochemical applications. Together, these factors result in a relatively low-input production system with moderate fuel requirements and reduced overall emission intensity.

Beyond field-level management, post-harvest handling represents an additional source of differentiation. In Argentina, peanut drying is primarily performed at the industrial stage using centralized, large-scale facilities, which are more energy-efficient than decentralized on-farm drying systems. This contrasts with systems where drying is conducted at the farm level, typically with lower energy efficiency per unit of product.

Recent data from the American Peanut Council's Sustainable U.S. Peanuts initiative indicate a clear downward trend in farm-level greenhouse gas intensity in the United States, reflecting continuous improvements in agronomic efficiency. However, structural differences between production systems remain relevant. These include a relatively greater reliance on irrigation and external inputs in the U.S., as well as differences in post-harvest configurations and supply chain organization.

As a result, even under ongoing efficiency gains, these underlying structural characteristics continue to influence the overall life cycle performance. The findings suggest that system-level attributes -such as input intensity, water management, and process configuration- play a more decisive role than transport distance in determining total cradle-to-grave environmental impacts.

Ozone Depletion Potential

For all the products, this impact category was concentrated (94-99%) in peanut production on the farm due to the use of fungicides and herbicides. The contribution of herbicides and fungicides to ozone depletion potential does not arise from their field application, but from upstream emissions associated with the production of active ingredients and energy use during agrochemical manufacturing.

Acidification Potential

Acidification potential (AP) was calculated by first quantifying emissions of acidifying substances along the entire life cycle of each declared unit, including nitrogen oxides (NO_x), sulfur dioxide (SO_2) and ammonia (NH_3). These emissions arise primarily from fuel combustion during agricultural operations, industrial processing and transportation, as well as from upstream production of inputs such as fertilizers, agrochemicals, packaging materials and additives.

Inventory flows were converted into acidification potential using midpoint characterization factors from the ILCD/European framework, as implemented in SimaPro, which express the acidifying effect of each substance as moles of hydrogen ions (mol H^+ eq). Characterized emissions were then aggregated by life-cycle stage and normalized to the declared unit (1 kg of product), after allocation of shared processes based on mass, following the applicable Product Category Rules.

For the products that contain no additives, such as shelled, blanched and roasted peanuts, emissions of nitrogen oxides and sulfur dioxide related to fuel combustion during final product distribution accounted for more than 69% of this impact category. Agricultural production ranked second, with 21% of the total, whereas for fried peanut, peanut paste and peanut butter, emissions were associated with production of additives and more complex packaging.

Derivation Of Eutrophication Potential Values.

Eutrophication Potential (EP) was calculated by quantifying emissions of nutrientenriching substances along the full life cycle of each declared unit. These include nitrogen compounds (NO_x, NH_3, nitrates) and phosphorus compounds associated with agricultural practices, fuel combustion, industrial processing, packaging production and transportation activities.

Inventory flows were converted into eutrophication potential using midpoint characterization factors from the ReCiPe/ILCD framework, distinguishing freshwater, marine and terrestrial eutrophication pathways. Results are expressed as kg P eq for freshwater eutrophication, kg N eq for marine eutrophication and mol N eq for terrestrial eutrophication. Characterized emissions were aggregated by lifecycle stage and normalized to the declared unit (1 kg of product), following massbased allocation rules.

The resulting EP values reflect the cumulative potential of each product system to contribute to nutrient enrichment in different environmental compartments, enabling consistent identification of hotspots and crossproduct comparison.

Eutrophication Potential - Freshwater

For shelled and blanched peanuts, this parameter was concentrated (more than 90%) in field production due to the use of herbicides. For roasted peanuts and peanut granules, field contribution decreased to 75% due to emissions associated with packaging production, especially pallets, corrugated cardboard supplies, big-bags and bags.

Eutrophication Potential - Marine Aquatic

In most of the products, more than 50% of marine eutrophication impact corresponded to product distribution, with the contribution of marine transportation being much higher than that of land transportation. Agricultural production ranked second, with at least 20% of emissions, which are attributable to the use of fossil fuels in agricultural practices. Peanut butter production was an exception to this trend, with the production of additives, specifically sugar and stabilizers, being hotspots, amounting to 37.9%.

Eutrophication Potential - Terrestrial

The principal hotspot in terrestrial eutrophication was the distribution of the final product. In all cases, the emissions associated with burning of heavy fuel oil in maritime transportation made the greatest contribution to this category.

Photochemical Ozone Creation Potential

Photochemical Ozone Creation Potential (POCP) was calculated by quantifying emissions of ozone-precursor substances along the life cycle of each declared unit, primarily nitrogen oxides (NO_X) and nonmethane volatile organic compounds (NMVOCs). These emissions originate mainly from fuel combustion in agricultural machinery, industrial processes, and transportation activities, as well as from upstream production of inputs.

Inventory emissions were converted into POCP using midpoint characterization factors from the ReCiPe/ILCD framework, expressing results as kilograms of NMVOC equivalents (kg NMVOC eq). Characterized emissions were aggregated by lifecycle stage and normalized to the declared unit (1 kg of product), following mass-based allocation of shared processes. Resulting POCP values therefore represent the cumulative potential of each product system to contribute to tropospheric ozone formation.

In all the studied products, the emissions contributing to this parameter were mainly concentrated in the distribution of the finished product, being 45 to 66% higher in products with low industrial processing. The greatest proportion corresponded to maritime transportation, with emissions of nitrogen oxides, followed by peanut production on the farm (about 21%), caused largely by fuels used in agricultural practices and, to a lesser extent, to herbicides use.

Abiotic Resources (metals And Minerals) Depletion Potential

The results show significant variations among products; yet all the impacts were concentrated in the upstream stage. For shelled and blanched peanuts, field production accounted for approximately 70% of the total impact, which is associated with the use of agrochemicals. Field production was also dominant in roasted peanuts and peanut granules, with 41% of the impact, followed by packaging production, which contributed nearly 36%. Packaging was the dominant factor in peanut paste, accounting for 95% of the impact, with a great influence of the metal drum. Finally, the impact for fried peanut and peanut butter was concentrated in the production of additives, which represented about 73%, followed by peanut production and packaging production.

Derivation Of Resource Depletion Potential Values.

Resource depletion potential quantifies the consumption of nonrenewable natural resources throughout the life cycle of each declared unit, including fossil energy carriers, minerals and metals. This impact category is derived by compiling lifecycle inventory data on the extraction and use of energy carriers, raw materials and resourceintensive inputs associated with agricultural production, industrial processing, packaging and transportation. Inventory flows were converted into resource depletion potential using midpoint characterization factors from the CML framework, expressing results as energy content for fossil resources (MJ) and antimony equivalents for minerals and metals (kg Sb eq). Characterized results were aggregated by lifecycle stage and normalized to the declared unit (1 kg of product), after massbased allocation of shared processes, thus representing the cumulative pressure placed on finite natural resources by each product system.

Abiotic Resources (fossil Fuels) Depletion Potential

Depletion of fossil abiotic resources was directly associated with the use of fossil fuels. The stages that most contributed to this indicator were the distribution of finished products, followed by agricultural production, the latter being related to fuel consumption in agricultural practices. Depletion of fossil fuels increases in products with a higher degree of industrial processing. In addition, hotspots were recorded in packaging of peanut butter and paste, due to the use of plastic buckets and metal drums, respectively.

Water Deprivation Potential

Water Deprivation Potential (WDP) was calculated by quantifying freshwater consumption along the life cycle of each declared unit, including direct and indirect water use associated with agricultural production, industrial processing, energy generation, packaging and transportation. Water consumption refers to freshwater withdrawn and not returned to the same watershed in a usable form.

Inventory water flows were converted into water deprivation potential using the AWARE (Available Water Remaining) midpoint characterization method, which accounts for local water scarcity conditions and expresses results as cubic meters of worldequivalent deprived water (m^3 world eq). Characterized values were aggregated by lifecycle stage and normalized to the declared unit (1 kg of product), after mass-based allocation of shared processes, representing the relative pressure exerted on freshwater availability by each product system.

Water deprivation potential was concentrated in the industrial processes (46% to 82%). This result can be attributed to the electricity consumption in the Argentine energy matrix, with a high percentage coming from hydroelectric sources that store water. According to the method used to calculate electricity consumption, the water resource is considered consumed when it evaporates from the reservoirs.

Sensitivity analysis

This analysis consists of modifying a variable of interest and analyzing the effects of this change on the result of each environmental impact category. Sensitivity analyses were performed by modifying yield (scenarios 1 and 2) and management type (scenario 3). A 25% increase in yield reduced total GWP by 8% to 12%, but a 25% reduction increased GWP by 13% to 20%; yield losses caused larger penalties than the benefits of yield increase (Table 12 and Table 13). Table 14 shows the change of agricultural practices, with no-tillage and cover crops. Changes in yield strongly affect the results because most agricultural inputs and emissions are related to land area (ha); therefore, higher yields dilute impacts per kilogram of product, whereas lower yields concentrate them.

Table 12. Scenario 1: Effects of mean 25% INCREASE in peanut harvest yield per ha, in absolute and relative values.

Parameter / Products	Shelled	Blanched	Roasted	Fried	Butter	Paste	Granules
Global warming	-12%	-11%	-10%	-8%	-8%	-8%	-9%
Ozone depletion	-20%	-20%	-19%	-19%	-19%	-19%	-19%
Acidification	-4%	-4%	-4%	-3%	-2%	-3%	-4%
Fresh water eutrophication	-18%	-18%	-15%	-13%	-9%	-10%	-15%
Marine water eutrophication	-5%	-5%	-5%	-4%	-2%	-4%	-5%
Terrestrial eutrophication	-5%	-5%	-5%	-4%	-3%	-4%	-4%
Photochemical ozone creation potential	-5%	-5%	-4%	-4%	-3%	-4%	-4%
Metals and minerals	-14%	-14%	-8%	-3%	-2%	-1%	-8%
Fossil fuels	-5%	-5%	-3%	-3%	-2%	-2%	-3%
Water deprivation	-5%	-4%	-2%	-2%	-1%	-1%	-1%

Table 13. Scenario 2: Effects of mean 25% DECREASE in peanut harvest yield per ha, in absolute and relative values

Parameter / Products	Shelled	Blanched	Roasted	Fried	Butter	Paste	Granules
Global warming	20%	19%	16%	14%	13%	13%	15%
Ozone depletion	33%	33%	32%	32%	32%	32%	32%
Acidification	7%	7%	6%	6%	4%	5%	6%
Fresh water eutrophication	31%	30%	25%	21%	16%	16%	25%
Marine water eutrophication	84%	85%	76%	66%	38%	66%	75%
Terrestrial eutrophication	105%	106%	96%	80%	54%	82%	94%
Photochemical ozone creation potential	9%	8%	7%	6%	5%	6%	7%
Metals and minerals	23%	23%	13%	5%	3%	1%	14%
Fossil fuels	9%	8%	5%	4%	3%	4%	4%
Water deprivation	8%	7%	4%	3%	2%	2%	2%

Table 14. Scenario 3: The relative change to global warming (kg CO_2 eq kg^{-1}) due to use of no-tillage and cover crops.

Product	Relative changes with respect to the baseline			
	Fossil	Biogenic	Land use and land use change	Total
Shelled peanuts	0%	-25%	-47%	-23%
Blanched peanuts	0%	-25%	-47%	-22%
Roasted peanuts	0%	-25%	-47%	-18%
Fried peanuts	0%	-25%	-47%	-16%
Peanut butter	0%	-25%	-53%	-14%
Peanut paste	0%	-25%	-47%	-15%
Peanut granules	0%	-25%	-47%	-17%

Comparative analysis

This comparative analysis is illustrative rather than exhaustive and is restricted to the carbon footprint indicator (Global Warming Potential), reflecting the limited availability of published LCA's that are methodologically comparable at the product level. The objective is not to derive global averages or rank countries, but to contextualize the results obtained for Argentine peanut products within the existing peer-reviewed literature on comparable peanut products.

Two product-level benchmarks were identified as suitable for comparison based on system boundary definition, declared unit consistency and transparency of methodological documentation: (i) blanched peanuts produced in São Paulo State, Brazil, evaluated under a cradle-to-gate system boundary by Ramos *et al.* (2023), and (ii) peanut butter produced and consumed in the United States, evaluated under a cradle-to-grave system boundary with production data collected from Georgia by McCarty *et al.* (2014).

Other major peanut-producing countries (e.g., China and India) were not included because, at the time of writing, no peer-reviewed LCA studies with clearly defined system boundaries, declared units and inventory transparency were available for comparable peanut products. This exclusion is therefore related to data availability and methodological compatibility rather than to geographic relevance. Although Brazil was excluded from generic background-database benchmarks, it is explicitly included here through the product-specific LCA of blanched peanuts (Ramos *et al.*, 2023), who reported a cradle-to-gate carbon footprint of 0.67 kg CO_2 eq kg^{-1} of product. Under comparable system boundaries, the results obtained in the present study show values approximately 21% lower. In a similar context, for peanut butter, McCarty *et al.* (2014) reported mean cradle-to-grave emissions of 2.88 kg CO_2 eq kg^{-1}, including downstream stages such as retail, consumer use, and end-of-life. According to that study, emissions associated with retail, consumer use and end-of-life stages amount to approximately 1.35 kg CO_2 eq kg^{-1}, resulting in an industry-gate value of 1.53 kg CO_2 eq kg^{-1}.

In the present study, greenhouse gas emissions for peanut butter up to the industry gate, corresponding to the agricultural and industrial processing stages defined as the core production system, amount to 0.781 kg CO_2 eq kg^{-1}.

When comparing the entire life cycle, Argentine peanut butter exhibits a total carbon footprint of 0.951 kg CO_2 eq kg^{-1}, despite the inclusion of long-distance terrestrial and maritime transport to export markets.

It is important to emphasize that the differences observed in this comparative analysis should not be interpreted as a definitive ranking of environmental performance across countries, but rather as contextual insights derived from studies with differing methodological approaches, temporal scopes, and system configurations. In particular, the U.S. reference study represents a geographically distributed, national-scale system combining data from multiple production regions and processing facilities, whereas the Argentine system analyzed here reflects a more regionally concentrated and vertically integrated supply chain. These differences in data structure and system representation limit the robustness of direct quantitative comparisons.

Within this context, the lower values observed in the Argentine system are associated with specific sources of efficiency along the production chain. At the farm level, gains arise primarily from reduced energy and input requirements, including the absence or limited use of irrigation, low fertilization rates linked to biological nitrogen fixation, and comparatively lower agrochemical intensity. In addition, crop management practices adapted to local agroecological conditions contribute to relatively stable yields with moderate use of machinery and fuel.

At the industrial stage, efficiency gains are associated with process integration and scale, particularly in post-harvest operations such as drying and primary processing, which are concentrated in specialized facilities rather than dispersed across multiple locations. This configuration may contribute to lower energy use per unit of processed product.

Overall, these factors help explain the differences observed in this study; however, given the heterogeneity of methodological frameworks and data sources across the literature, such comparisons should be interpreted as indicative of underlying system characteristics rather than conclusive evidence of superior environmental performance.

CONCLUSIONS

The LCA revealed the main hotspots in the environmental performance of the products analyzed. Agricultural production stood out as the most determinant stage in most of the environmental impact indicators, particularly in global warming (40 to 66% of the emissions, mostly associated with soil management) and freshwater eutrophication (up to 90%). Agricultural production also contributed significantly to depletion of abiotic resources (metals and minerals) due to the use of agrochemicals, as well as important impacts on acidification, marine eutrophication and photochemical ozone creation potential, which are related to use of both agrochemicals and fuels.

Production of inputs had important impacts associated with packaging and additives, which contribute to depletion of abiotic resources (metals and minerals, and fossils) as well as to marine and freshwater eutrophication.

Industrial production generated important impacts on depletion of abiotic resources (fossil fuels) and water deprivation (up to 82%), as well as a contribution to global warming (5 to 25%).

Finally, distribution was the most critical stage in terms of acidification, marine and terrestrial eutrophication, and photochemical ozone creation potential mainly due to marine transportation with heavy fuels. This stage also accounts for 16 to 24% of GHG emissions of the entire life cycle.

In this context, the improvement opportunities are oriented to: 1) optimize the use of inputs through precision agriculture and/or regenerative agriculture; 2) increase the use of renewable resources and gradually replace fossil fuels; 3) reduce the amount of packaging and give priority to reusable or recyclable packaging; and 4) improve the accuracy of the estimation of changes in soil organic carbon stock, which influences CO_2 removal or emission.

The comparison of our results with those of other works at the global level demonstrates that peanut production studied in this work in Argentina is intrinsically sustainable. Indeed, peanut butter has up to 67% lower carbon footprint than that in the USA; in addition, blanched peanut production has a 21% lower impact than that in Brazil, although these differences reflect contrasting system representations and should not be interpreted as direct equivalence.

The results of this work are relevant to several stakeholders. First, the peanut industry in the central region of Argentina, since the work provides a scientific and verifiable method to demonstrate production sustainability and to enter demanding markets. The identification of hotspots offers a clear pathway towards continuous improvement. Second, public policy makers, since the results of the LCA and the sensitivity analysis provide reliable data to promote more sustainable agricultural practices (like digital agriculture) and improved energy efficiency in the industry. Third, the scientific community, because this study contributes primary data and specific emission factors. Finally, consumers and diverse actors of the value chain benefit from greater transparency about the environmental impact of the products, which allows them to make more informed purchasing decisions in line with their own sustainability strategies.

Despite the robustness of the study, it is important to mention some limitations. Because of the lack of emission factors specific for peanuts in some areas, such as indirect nitrogen emissions, it was necessary to use assumptions. The lack of inventory data of the life cycle for certain inputs, such as hydrogenated oil or sugar, required the use of international database profiles. However, while they are the most representative, they may not capture the characteristics of local production. These limitations, though typical of any work of this kind, reveal areas for future research.

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