Article

Not peer-reviewed version

Life Cycle Assessment of Soy Protein Concentrate: A Case Study in Argentina

Rodolfo Bongiovanni * , Leticia Tuninetti , María Raquel Cavagnaro , Yamila Bianco , Juan Pablo Berardinelli

Posted Date: 9 April 2026

doi: 10.20944/preprints202604.0587.v1

Keywords: footprints; impacts; food; environmental product declaration; sustainability; cradle-to-gate

Preprints.org is a free multidisciplinary platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This open access article is published under a Creative Commons CC BY 4.0 license, which permit the free download, distribution, and reuse, provided that the author and preprint are cited in any reuse.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 9 April 2026 doi:10.20944/preprints202604.0587.v1

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

Article

Life Cycle Assessment of Soy Protein Concentrate: A Case Study in Argentina

Rodolfo Bongiovanni [1,*], Leticia Tuninetti [2], María Raquel Cavagnaro [2], Yamila Bianco [3] and Juan Pablo Berardinelli [3]

[1] Instituto Nacional de Tecnología Agropecuaria, Manfredi, Córdoba, Argentina
[2] Instituto Nacional de Tecnología Industrial, Córdoba, Argentina
[3] Porta Hnos. S.A., Córdoba, Argentina
* Correspondence: bongiovanni.rodolfo@inta.gob.ar

Abstract

The purpose of this paper is to assess the environmental impacts associated with the production and commercialization of concentrated soy protein manufactured by PORTA Hnos. S.A. in Córdoba, Argentina. The study was conducted to support the verification of an Environmental Product Declaration (EPD) under the International EPD® System, following ISO 14025, ISO 14040 and ISO 14067 standards. A cradle-to-gate with options approach was applied, encompassing upstream agricultural production, industrial processing of soybean meal, core manufacturing of soy protein, and downstream packaging disposal. Life Cycle Assessment (LCA) was performed using primary data from the 2022/2023 soybean crop season and industrial operations in 2023. Seven impact categories were evaluated, including global warming potential, ozone depletion, acidification, eutrophication (freshwater, marine, terrestrial), photochemical ozone formation, abiotic resource depletion, and water scarcity. The declared unit is one kilogram of packaged, concentrated soy protein. Results indicate that the industrial phase, particularly natural gas consumption, is the main contributor to most impact categories. Agricultural production significantly affects eutrophication and water scarcity. The findings provide actionable insights for improving environmental performance and guiding responsible sourcing and process optimization.

Keywords: footprints; impacts; food; environmental product declaration; sustainability; cradle-to-gate

1. Introduction

The food industry faces increasing pressure to reduce its environmental footprint while maintaining product quality and operational efficiency. Life Cycle Assessment (LCA) has emerged as a robust scientific methodology for quantifying environmental impacts across the entire life cycle of food products—from raw material extraction to processing, packaging, and distribution [1]. In recent years, LCA has become a cornerstone of sustainability strategies in agro-industrial systems, enabling companies to identify environmental hotspots and implement targeted improvements [2,3].

Soy protein, a widely used plant-based ingredient, plays a central role in the transition toward sustainable food systems. Its high protein content, functional versatility, and compatibility with meat analogues and fortified foods have positioned it as a key component in the global protein market. However, the environmental implications of soy production—particularly related to land use change, eutrophication, and fossil energy consumption—require careful evaluation [4]. Comparative studies have shown that soy protein generally exhibits lower greenhouse gas emissions and water use than animal-based proteins, but its environmental performance varies significantly depending on agricultural practices, processing technologies, and supply chain logistics [5,6].

This study presents a comprehensive LCA of concentrated soy protein produced by PORTA Hnos. S.A., an agro-industrial company based in Córdoba, Argentina. The analysis covers the entire

© 2026 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 9 April 2026 doi:10.20944/preprints202604.0587.v1

production chain, including soybean cultivation, soybean meal processing, protein concentration, packaging, and distribution.

The primary objective is to quantify the environmental impacts associated with soy protein production and identify critical stages for improvement. The results are intended to support process optimization and inform sustainability strategies within the company and the broader agro-industrial sector. While the study also supports the verification of an Environmental Product Declaration (EPD), its main contribution lies in advancing scientific understanding of the environmental performance of soy-based food ingredients.

2. Materials and Methods

2.1. Goal and Scope Definition

This study employed a detailed Life Cycle Assessment (LCA) to quantify the environmental impacts associated with the production of concentrated soy protein by PORTA Hnos. S.A., an agro-industrial company located in Córdoba, Argentina. The assessment was conducted in accordance with ISO 14040 and ISO 14044 standards and aligned with the methodological framework of the International EPD® System (General Programme Instructions, version 4). The declared unit (DU) for the analysis was one kilogram of packaged soy protein concentrate (SPC), grade food, excluding the packaging weight.

The system boundaries were defined as “cradle-to-gate with options,” encompassing the entire production chain from soybean cultivation to packaging disposal (Figure 1). The study included upstream processes (agricultural production of soybeans, processing into soybean meal, and additive manufacturing), core processes (industrial transformation of soybean meal into soy protein concentrate), and downstream processes (packaging, distribution, and end-of-life treatment of packaging materials). The scope excluded consumer use and conservation phases, as the product is marketed under a business-to-business (B2B) model.

2.2. Life Cycle Inventory (LCI)

A fundamental component of Life Cycle Assessment (LCA) for calculating environmental impacts is the Life Cycle Inventory (LCI). This phase involves the systematic collection and quantification of all inputs and outputs associated with the product system throughout its life cycle, as defined by the study’s goal and scope.

The inventory includes all inputs entering the system—such as energy and material resources—and all outputs released into the environment, including products, co-products, waste, and gaseous and liquid emissions.

Once the input and output inventories were compiled for each operation and life cycle stage, unit emissions associated with each input (e.g., raw materials, energy, packaging) were obtained from international databases. These emissions were then multiplied by the quantities used in the system to calculate the environmental impact of each inventory element.

Primary data for agricultural inputs were obtained from the Bolsa de Cereales de Córdoba [7] and Márgenes Agropecuarios, covering the 2022/2023 soybean crop season [8]. These inputs included fertilizers, herbicides, insecticides, seeds, fuel, and packaging materials.

© 2026 by the author(s). Distributed under a Creative Commons CC BY license.

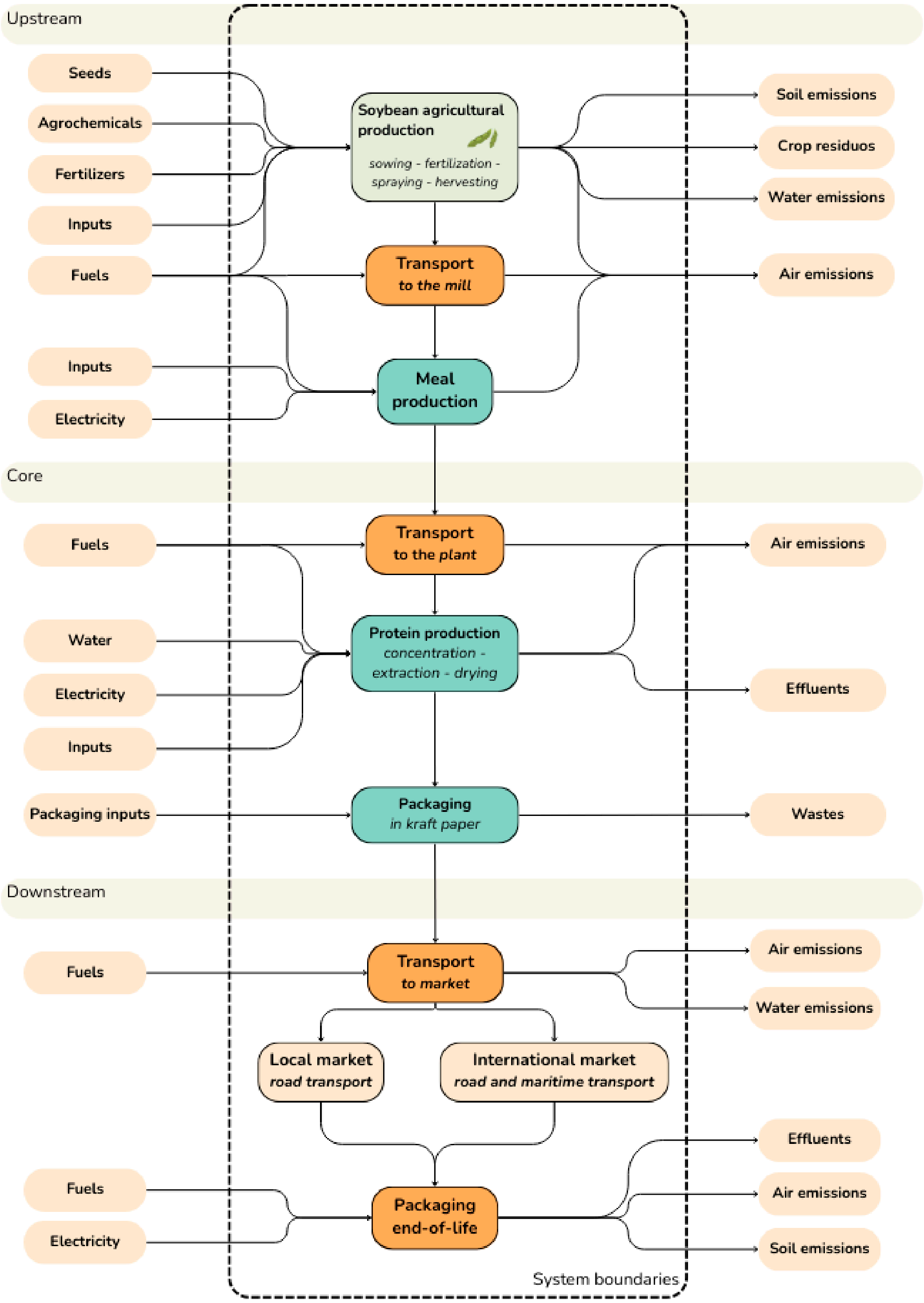

Figure 1. System Boundaries.

Table 1 provides the weighted inventory for the agricultural stage of soybean production, based on departmental contributions within the province of Córdoba, Argentina. It includes the production and use of agricultural inputs such as agrochemicals, fertilizers, fuels, and seeds, as well as the manufacturing of their packaging materials. Emissions from fuel combustion during agricultural operations—such as sowing, fertilization, spraying, and harvesting—are accounted for, along with emissions resulting from the application of nitrogen fertilizers and the decomposition of crop residues (both aerial and underground). Fuel consumption data for field operations were sourced from the Revista Márgenes Agropecuarios [8]. The inventory reflects a regionally weighted average, considering the relative production volumes of each department (Table 1).

© 2026 by the author(s). Distributed under a Creative Commons CC BY license.

Table 1. Weighted Life-Cycle Inventory for the agricultural stage of soybean production.

Item	**kg/ha**
Seeds RR soybeans	80.000
Fertilizers	
Monoammonium phosphate	9.221
Diammonium phosphate	0.749
Solmix	0.019
Triple superphosphate	2.954
Simple superphosphate	23.121
Microessentials Sz	1.797
Nutrimax	0.005
Agricultural gypsum	0.013
Herbicides	
Glyphosate 54%	7.817
Texaro	0.043
Metsulfurol Metil	0.010
2,4 D 100%	0.967
Roundup control max	1.100
Insecticides	
Karate zeon 25%	0.032
Coragen	0.030
Engeo	0.260
Fungicides	
Inoculant + fungicide	1.599
Opera	0.530
Packaging	
Paper	0.001
Plastic	0.651
Silo bag (180 t)	0.000
Gasoil consumption	
No till planting	5.568
Sprayer (x4)	2.244
Aerial (x2)	0.380
Harvest	10.940
Lubricant oils	1.313
Handling	0.001

Industrial data were provided directly by PORTA Hnos. S.A. for the year 2023, including energy consumption (electricity and natural gas), water use, chemical inputs (e.g., sulfuric acid, hydrogen peroxide, sodium hydroxide), and emissions from wastewater treatment.

Prior to the concentration stage, soybean meal is obtained through a conventional crushing process that includes cleaning, dehulling, and mechanical milling of soybeans, followed by solvent

© 2026 by the author(s). Distributed under a Creative Commons CC BY license.

extraction using hexane to remove oil. The resulting meal is then toasted to deactivate antinutritional factors, dried, and cooled before storage. This process yields three main co-products: soybean meal (approximately 72.8% of output), crude soybean oil (19.6%), and soybean hulls (7.6%), with mass-based allocation applied to distribute upstream impacts among them. Energy inputs primarily consist of electricity and natural gas, complemented by minor quantities of hexane and water, and the system generates solid waste and effluents managed according to local regulations (Table 2).

Table 2. Life-Cycle Inventory for the industrial stage of soybean meal production.

Item	Quantity	Unit	Mass allocation (%)
Products			
Crude soybean oil, in transformation process{AR}	190.00	kg	19.6%
Soybean meal, in transformation process {AR}	**706.00**	**kg**	**72.8%**
Soybean hulls, in transformation process	74.00	kg	7.63%
Resources			
Hexane	0.800	kg	
Base oil	0.020	kg	
Soybean, grain	1000.00	kg	
Electricity, low-voltage grid	55.556	kWh	
Natural gas	1200.00	MJ	
Effluents	0.250	m^3	
Waste	30.00	kg	
Transport of soybeans to the mill	200.00	tkm	

The SPC production process involved milling, extraction, neutralization, drying, and packaging, with detailed operational parameters recorded monthly.

The industrial transformation of soybean meal into concentrated soy protein involves six main stages:

1) Protein Structure Disruption: The process begins with mechanical milling using a hammer mill equipped with a 0.5 mesh screen. The resulting material is then sieved to distribute it according to the spray nozzles used in subsequent stages.
2) Extraction and pH Adjustment: The sieved flour enters two tanks—one for mixing and one for extraction—where water (at a 1:11 ratio), sulfuric acid, and hydrogen peroxide are added. This stage aims to adjust protein parameters for centrifugation and includes the first pH adjustment. All water used is recovered from another business unit within the company.
3) Centrifugation: Two centrifugation steps are performed to increase the solids concentration from 10% to 26%, achieving a protein content of 67%.
4) Neutralization and Functionalization: The protein solution is transferred to a neutralization tank for residence time, where an alkaline solution of ammoniacal water and sodium hydroxide is added to reach a pH of 6.70. This restores protein functionality and prepares it for drying. Hydrogen peroxide is added again for sanitization.
5) Bleaching: The product enters a bleaching tank for a minimum residence time of two hours, without the addition of further substances.
6) Drying and Packaging: The final stage involves drying with flash steam followed by atomization in a stream of hot air generated by burners. The dried protein is then separated in a cyclone and packed into 20 kg bags.

© 2026 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 9 April 2026 doi:10.20944/preprints202604.0587.v1

Packaging consists of triple-layer kraft paper bags with stitched bottoms and open tops, which are sewn after filling. Pallets and stretch film are used for both domestic and international markets. Environmental profiles for packaging materials were sourced from international databases and tailored using technical specifications provided by the company.

To quantify inputs and outputs for this stage, a detailed life cycle inventory was compiled based on primary data from PORTA Hnos. S.A. The inventory includes material inputs such as sulfuric acid, sodium hydroxide, hydrogen peroxide, ammoniacal water, and soybean meal; energy carriers including electricity and natural gas; water consumption; and packaging materials. Outputs comprise the main product (SPC), co-product (molasses), packaging waste, and liquid effluents. Transport flows for inbound materials and outbound products were also considered. Tables 3 and 4 summarize these data normalized to the declared unit of 1 kg of SPC.

Table 4. Life-Cycle Inventory for SPC production (Outputs).

Output Item	**Quantity**	**Unit**	**Mass allocation (%)**
Outputs: Packaging end-of-life			
Packaged soy protein with end-of-life disposal	**1.000**	**kg**	
Packaging disposal	0.058	kg	
Waste transport	0.003	tkm	
Packaged soy protein delivered to the customer	**1.000**	**kg**	
External land transport	0.298	tkm	
Maritime transport	0.989	tkm	
Local land transport	0.380	tkm	
Packaged soy protein at the factory gate	**1.000**	**kg**	
Outputs: Products and by-products			
Unpackaged soy protein	**1.000**	**kg**	**67.1%**
Molasses	0.490	kg	32.9%
Waste, emissions & effluents			
Generated liquid effluents	0.001	m^3	
Ribbons	0.000	kg	
Transport to co-processing	0.000	tkm	

Table 3. Life-Cycle Inventory for SPC production (Inputs).

Input Item	**Quantity**	**Unit**
Inputs: Materials		
Sulfuric acid (98%)	0.025	kg
Input transport (outbound – return with product)	0.009	tkm
Ammoniacal water (2%)	0.005	kg
Input transport (outbound – return with product)	0.004	tkm
Sodium hydroxide (50%)	0.018	kg
Input transport (outbound – return with product)	0.007	tkm
Hydrogen peroxide (60%)	0.016	kg
Input transport (outbound – return with product)	0.009	tkm
Soybean meal	1.427	kg

© 2026 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 9 April 2026 doi:10.20944/preprints202604.0587.v1

Input transport (outbound – return with product)	0.614	tkm
Inputs: Energy, fuels and water		
Electricity from Argentine grid	0.013	kWh
Electricity cogeneration with natural gas	0.277	m^3
Electric forklift	0.000	kWh
Electric forklift	0.000	m^3
Inter-warehouse movements	0.011	tkm
Natural gas	0.700	m^3
Municipal tap water	0.008	m^3
Recovered water from the Alcohol Plant (no impact)	-	m^3
Inputs: Packaging		
Automatic stretch film per pallet	0.000	kg
Wooden pallet (ARLOG)	0.002	units
3-ply paper bag with polyethylene lining (20 kg/bag)	0.050	units
White self-adhesive labels 100 × 50 mm, 1,000 units per roll	0.001	kg
White sticker 150 / 152 mm × 1,000 units per roll	0.000	kg
White thread spool 20/6, 600 m	0.000	kg
Green crepe paper	0.000	kg
Wax ribbons 110 × 300	0.000	kg
Corrugated board sheet 1200 mm × 1000 mm × 1.00 unit	0.001	kg
Packaging transport	0.041	tkm

On-site emissions include those from wastewater treatment lagoons, which handle process and cleaning water. The treatment system comprises two stages: a vermifilter that reduces chemical oxygen demand (COD) by approximately 60%, followed by an anaerobic reactor. The system complies with local environmental regulations, and treated effluent is assumed to have no residual environmental impact upon discharge.

Secondary data for background processes were sourced from the Ecoinvent v3.9.1 and Agri-footprint v6.0 databases. These were integrated into the SimaPro® 9.5.0.1 software to model environmental impacts. The databases provided life cycle inventory profiles for materials, energy carriers, transport modes, and waste treatment processes, ensuring consistency with international standards.

Impact assessment was performed using the ReCiPe 2008 method [9] for most categories and the AWARE method [10] for water scarcity. The following impact categories were evaluated: Global Warming Potential (GWP), Ozone Layer Depletion (ODP), Acidification Potential (AP), Eutrophication Potential (EP) for freshwater, marine, and terrestrial ecosystems, Photochemical Ozone Creation Potential (POCP), Abiotic Depletion Potential (ADP) for minerals and fossil resources, and Water Deprivation Potential (WDP). Emissions from fertilizer application and crop residue decomposition were calculated using Tier 2 IPCC guidelines [11], with region-specific emission factors derived from Argentina's Biennial Update Reports [12]).

2.3. Life Cycle Allocation

The allocation of environmental burdens is a mandatory step in LCA studies whenever co-products are generated alongside the main product. Its purpose is to distribute upstream environmental impacts among the different outputs of a process. Allocation can be based on various criteria, such as mass, energy content, economic value, or other relevant physical properties,

© 2026 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 9 April 2026 doi:10.20944/preprints202604.0587.v1

depending on the nature of the process. In this study, two allocation situations were identified, and in both cases, a mass-based allocation approach was applied:

Soybean milling: The process yields soybean meal (72.8%), crude soybean oil (19.6%), and soybean hulls (7.63%). Environmental burdens from upstream agricultural production were distributed among these outputs based on their respective mass fractions.

Protein concentration process: The industrial transformation of soybean meal results in concentrated soy protein (67.1%) and molasses (32.9%). Environmental burdens from upstream processing and inputs were allocated proportionally to the mass of each output.

This allocation method ensures consistency with international LCA standards [13] and reflects the physical reality of the production system, allowing for accurate impact attribution to the soy protein product under study.

Transport modelling included inbound logistics for raw materials and outbound distribution to domestic and international markets. Average distances and vehicle types were used, including truck and maritime transport. Packaging disposal was modelled as landfill, with a default transport distance of 50 km.

3. Results and Discussion

The results presented in Tables 2 and 3 correspond to the LCA of concentrated soy protein produced by PORTA Hnos. S.A. They are disaggregated into upstream, core, and downstream processes, and further subdivided into relevant sub-stages within each phase.

Global Warming Potential (GWP) was 2.31 kg CO_2 eq. per Declared Unit (i.e., one kilogram of packaged soy protein concentrate), which is slightly lower than the 2.4 kg CO_2 eq. / kg reported by the literature [14] or the 20.22 kg CO_2 eq. / kg estimated for soy protein isolate (SPI) [15]. The highest emissions were observed in the industrial stage, primarily due to natural gas consumption, which accounted for 72.39% of total emissions. Within this, 19.29% was attributed to cogeneration and 53.09% to boiler operations. Soybean production contributed 9.31%, mainly from crop residue decomposition, glyphosate use, and fuel consumption during harvesting. Soybean meal production contributed 6.33%, and product distribution 4.80%, with 52.77% of distribution emissions linked to domestic sales.

Ozone Layer Depletion Potential (ODP) was 7.67E-8 kg CFC11 eq. Over half of the impact (57.92%) originated from the industrial stage, again due to natural gas use (57.44% of the total). Soybean production contributed 13.71%, mainly from seeds and agrochemicals. Additive production accounted for 12.03%, with sodium hydroxide being the most significant contributor (11.36%).

Acidification Potential (AP) was 4.04E-3 mol H^+ eq. This impact was more evenly distributed. The industrial stage was the largest contributor (31.07%), primarily due to natural gas use (30.82%). Soybean production followed with 29.31%, driven by fuel use, seeds, and nitrogen fertilizers (14.73%). Distribution contributed 12.09%, and additive production 8.22%, with sulfuric acid responsible for 4.68%. Nitrogen oxides and sulfur dioxide were the dominant emission types.

Eutrophication Potential (EP) Freshwater was 2.06E-3 kg P eq. Soybean production was the dominant contributor (97.29%), mainly due to phosphate emissions from fertilizer application. This is significantly lower than the 0.01 kg P equivalents per kg SPI [15].

Eutrophication Potential (EP) Marine totalled 1.64E-3 kg N eq, with a more distributed impact. Soybean production contributed 46.63%, driven by seed and fuel emissions. The industrial stage accounted for 25.12%, mostly from natural gas use, and distribution added 9.44%.

Eutrophication Potential (EP) Terrestrial was 2.81E-2 mol N eq. Soybean production was again the largest contributor (66.94%), primarily due to nitrate (NO_3^-) emissions from nitrogen fertilizers and, to a lesser extent, ammonia (NH_3). The industrial stage contributed 15.92%, and distribution 5.91%.

Photochemical Ozone Creation Potential (POCP) was 0.00571 kg NMVOC eq, representing emissions of non-methane volatile organic compounds. The industrial stage contributed 54.90%,

© 2026 by the author(s). Distributed under a Creative Commons CC BY license.

mainly from natural gas combustion. Soybean production followed with 15.73%, driven by fuel and glyphosate use, and distribution added 9.70%.

Abiotic Depletion Potential – Minerals and Metals (ADP) was 1.94E-6 kg Sb eq. Additive production was the main contributor (54.33%), with sulfuric acid being the most significant input. Soybean production contributed 33.76%, with fertilizers accounting for 29.16% of the total.

Abiotic Depletion Potential – Fossil Fuels was 32.1 MJ (net calorific value). The industrial stage was the dominant contributor (77.14%), primarily due to natural gas consumption. The literature estimates 3.6 kg oil equivalents (150.7 MJ) per kg SPI [15].

Water Deprivation Potential (WDP) was 0.209 m^3 world eq deprived. Additive production contributed 30.07%, with hydrogen peroxide responsible for 18.85%. Soybean production followed with 25.88%, mainly due to agrochemicals such as glyphosate and simple superphosphate. Soybean meal production contributed 17.28%, with electricity being the main factor. The industrial stage added 15.61%, mostly from natural gas (12.97%) and, to a lesser extent, grid electricity (2.53%). This result compares to the 40 m^3 of water per kg of SPI [15].

The results indicate that the overall environmental performance of the Argentine SPC system falls within moderate impact ranges when compared to international benchmarks. However, several critical points were identified that warrant attention and improvement.

The agricultural stage, particularly soybean cultivation, was significantly affected by an exceptionally dry crop season during the 2022/2023 campaign. This led to reduced yields and elevated environmental impacts, especially in eutrophication categories due to increased nutrient emissions per unit of output. These findings underscore the importance of implementing adaptive agronomic practices and enhancing supplier engagement to improve environmental performance at the farm level. Strategies such as precision fertilization, improved residue management, and selection of resilient seed varieties could contribute to mitigating these impacts.

In the industrial stage, natural gas consumption emerged as the dominant contributor to fossil fuel depletion and greenhouse gas emissions. The process hotspots were concentrated in thermal operations, including cogeneration and boiler use. Scenario modelling demonstrated that a 20% reduction in natural gas consumption could lead to a significant decrease in GWP and other impact categories. This highlights the potential of energy efficiency measures and process optimization as effective levers for environmental improvement.

Water deprivation impacts were distributed across additive production, agriculture, and industrial processing, with hydrogen peroxide and agrochemical inputs being key contributors. This suggests that water footprint reduction strategies should address both upstream supply chains and internal water management practices.

Table 5. Environmental Impacts of Soy Protein Concentrate: Results for Declared Unit of 1 kg.

PARAMETER		**Upstream**				**Core**		**Downstream**		**TOTAL**
		Grain	**Flour**	**Additives**	**Packaging**	**Transp.**	**Industry**	**Distr.**	**End of life**	
Global warming potential (GWP) (kg CO_2 eq.)	Fossil	2.11E-1	1.41E-1	3.35E-2	3.96E-2	7.38E-2	1.68E+0	1.11E-1	7.24E-4	2.29E+0
	Biogenic	9.97E-5	4.74E-3	8.88E-4	4.96E-4	3.96E-6	1.29E-2	5.93E-6	4.68E-8	1.91E-2
	Land use and land transformation	4.31E-3	5.88E-4	4.71E-5	2.41E-4	2.53E-6	1.54E-4	3.81E-6	2.72E-8	5.35E-3
	Global warming potential	**2.15E-1**	**1.46E-1**	**3.44E-2**	**4.03E-2**	**7.38E-2**	**1.69E+0**	**1.11E-1**	**7.24E-4**	**2.31E+0**
Ozone layer depletion (ODP) (kg CFC 11 eq.)		1.05E-8	5.24E-9	9.22E-9	4.75E-9	1.01E-9	4.44E-8	1.52E-9	1.00E-11	7.67E-8
Acidification potential (AP) (mol H^+ eq.)		1.19E-3	3.30E-4	3.33E-4	2.32E-4	2.16E-4	1.26E-3	4.89E-4	3.06E-6	4.04E-3
Eutrophication potential (EP)	Aquatic freshwater (kg P eq.)	2.01E-3	4.00E-6	1.43E-5	1.86E-5	1.45E-6	1.54E-5	2.10E-6	1.58E-8	2.06E-3

© 2026 by the author(s). Distributed under a Creative Commons CC BY license.

	Aquatic marine (kg N eq.)	7.63E-4	1.25E-4	3.71E-5	6.53E-5	7.93E-5	4.11E-4	1.54E-4	1.24E-6	1.64E-3
	Aquatic terrestrial (mol N eq.)	1.88E-2	1.29E-3	3.74E-4	6.37E-4	8.41E-4	4.47E-3	1.66E-3	1.34E-5	2.81E-2
Photochemical oxidant creation potential (POCP) (kg NMVOC eq.)		8.98E-4	4.53E-4	1.31E-4	2.31E-4	3.02E-4	3.13E-3	5.54E-4	4.40E-6	5.71E-3
Abiotic depletion potential (ADP)*	Metals & minerals (kg Sb eq.)	6.54E-7	1.57E-7	1.05E-6	2.98E-8	4.38E-9	3.36E-8	6.28E-9	3.97E-11	1.94E-6
	Fossil resources (MJ)	1.69E+0	2.11E+0	4.54E-1	7.47E-1	9.84E-1	2.52E+1	1.47E+0	9.52E-3	3.27E+1
Water deprivation potential (WDP) (m^3 world eq. deprived)		5.40E-2	3.61E-2	6.28E-2	1.98E-2	1.39E-3	3.26E-2	2.04E-3	1.34E-5	2.09E-1

Table 6. Energy Resources Used in the Production of Soy Protein Concentrate: Results for Declared Unit of 1 kg.

PARAMETER		**Upstream**				**Core**		**Downstream**		**TOTAL**
		Grain	**Flour**	**Additives**	**Packaging**	**Transp.**	**Industry**	**Distr.**	**End of life**	
Primary energy resources – Renewable (MJ)	Use as energy carrier	6.32E-2	1.13E-1	3.03E-2	2.28E-2	1.28E-3	5.61E-2	1.93E-3	1.94E-5	2.89E-1
	Used as raw materials	1.36E+0	4.87E-3	5.55E-3	1.56E+0	1.63E-4	5.91E-3	2.45E-4	5.78E-6	2.93E+0
	TOTAL	1.42E+0	1.18E-1	3.58E-2	1.58E+0	1.44E-3	6.20E-2	2.18E-3	2.52E-5	3.22E+0
Primary energy resources – Non Renewable (MJ)	Use as energy carrier	5.75E-1	1.31E+0	0.00E+0	0.00E+0	0.00E+0	1.94E+1	0.00E+0	0.00E+0	2.13E+1
	Used as raw materials	1.58E+0	2.57E+1	4.54E-1	7.47E-1	9.84E-1	2.52E+1	1.47E+0	9.37E-3	5.62E+1
	TOTAL	2.15E+0	2.70E+1	4.54E-1	7.47E-1	9.84E-1	4.46E+1	1.47E+0	9.37E-3	7.75E+1

Table 7. Relative or Percentage Contribution of Each Life Cycle Stage to the Total Impact.

PARAMETER		**Upstream**				**Core**		**Downstream**	
		Grain	**Flour**	**Additives**	**Packaging**	**Transp.**	**Industry**	**Distr.**	**End of life**
Global warming potential (GWP) (kg CO_2 eq.)	Fossil	9.22%	6.16%	1.46%	1.73%	3.22%	73.32%	4.85%	0,03%
	Biogenic	0.52%	24.80%	4.64%	2.59%	0.02%	67.38%	0.03%	0,00%
	Land use and land transformation	80.62%	11.00%	0.88%	4.50%	0.05%	2.88%	0.07%	0,00%
	Global warming potential	**9.31%**	**6.33%**	**1.49%**	**1.74%**	**3.19%**	**73.11%**	**4.80%**	**0,03%**
Ozone layer depletion (ODP) (kg CFC 11 eq.)		13.71%	6.84%	12.03%	6.20%	1.31%	57.92%	1.99%	0.01%
Acidification potential (AP) (mol H^+ eq.)		29.31%	8.17%	8.22%	5.73%	5.33%	31.07%	12.09%	0.08%
Eutrophication potential (EP)	Aquatic freshwater (kg P eq.)	97.29%	0.19%	0.69%	0.90%	0.07%	0.75%	0.10%	0,00%
	Aquatic marine (kg N eq.)	46.63%	7.62%	2.27%	3.99%	4.85%	25.12%	9.44%	0,08%
	Aquatic terrestrial (mol N eq.)	66.94%	4.59%	1.33%	2.27%	3.00%	15.92%	5.91%	0,05%
Photochemical oxidant creation potential (POCP) (kg NMVOC eq.)		15,73%	7.94%	2.30%	4.05%	5.29%	54.90%	9.70%	0.08%

© 2026 by the author(s). Distributed under a Creative Commons CC BY license.

Abiotic depletion potential (ADP)*	Metals & minerals (kg Sb eq.)	33.76%	8.08%	54.33%	1.54%	0.23%	1.73%	0.32%	0,00%
	Fossil resources (MJ)	5.16%	6.47%	1.39%	2.29%	3.01%	77.14%	4.51%	0,03%
Water deprivation potential (WDP) (m^3 world eq. deprived)		25.88%	17.28%	30.07%	9.50%	0.67%	15.61%	0.98%	0.01%

4. Conclusion

This study presents a Life Cycle Assessment (LCA) of concentrated soy protein (SPC) produced in Argentina, benchmarking its environmental profile against global references. The SPC system achieved a Global Warming Potential of 2.31 kg CO_2 eq/kg, substantially lower than soy protein isolate (≈20 kg CO_2 eq/kg) and competitive with other plant-based proteins. Water use and eutrophication impacts were moderate compared to international benchmarks, underscoring SPC's comparative advantage as a sustainable ingredient for global markets.

Despite this favorable performance, two improvement hotspots were identified:

- Industrial stage, dominated by natural gas consumption for thermal operations.
- Agricultural stage, sensitive to climatic variability and nutrient emissions.

Future strategies should focus on energy efficiency, precision agriculture, and low-emission logistics, complemented by renewable energy integration and circular water management. These measures will strengthen SPC's sustainability credentials and support Argentina's positioning in climate-smart protein supply chains.

Looking forward, research should explore scenario modeling under climate change, carbon-neutral technologies, and policy frameworks that incentivize low-impact protein production. Such efforts will accelerate the transition toward resilient agro-industrial systems and reinforce Argentina's role in meeting global sustainability targets.

References

1. Chung, M. M. S., et al. LCA on Environmental Sustainability of Food Processing. Annual review of food science and technology, 13, 217–237. 2022. https://doi.org/10.1146/annurev-food-062420-014630.
2. Ahmad, Shamraiz, Wong, Kuan Yew & Riaz, Ahmad. Life cycle assessment for food production and manufacturing: recent trends, global applications and future prospects. Procedia Manufacturing. 34. 49-57. 2019. 10.1016/j.promfg.2019.06.113.
3. Arena, Pablo, et al. Hotspots of the Food and Beverage Sector in Argentina. Project: POW 2019-2021: Resource Efficiency. 2021. https://sites.google.com/view/cliopeorg/investigaci%C3%B3n/proyectos?authuser=0.
4. LCA of Soybean Meal. Dalgaard, R., et al. 3, 2008, International Journal of Life Cycle Assessment, Vol. 13, pp. 240–254.
5. Hilbert, Jorge Antonio, Camardelli, Ariana & Ponieman, Karen. Greenhouse gas emissions from Argentinian soybean products. Biofuels, Bioproducts and Biorefining (Biofpr) 2025. https://doi.org/10.1002/bbb.2816.
6. Piastrellini, R., Civit, B. M. & Arena, A. P. (2015). Influence of Agricultural Practices on Biotic Production Potential and Climate Regulation Potential. A Case Study for Life Cycle Assessment of Soybean (Glycine max) in Argentina. Sustainability, 7(4), 4386-4410. 2015. https://doi.org/10.3390/su7044386.
7. Bolsa de Cereales de Córdoba. http://www.bccba.com.ar/ 2025.
8. Márgenes Agropecuarios. 2025. https://www.margenes.com/.
9. Goedkoop, Mark, et al. ReCiPE 2008: A life cycle impact assessment method. 2008.
10. Boulay, Anne-Marie, et al. The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). The International Journal of Life Cycle Assessment volume 23, pages368–378 (2018). 2018. https://doi.org/10.1007/s11367-017-1333-8.

© 2026 by the author(s). Distributed under a Creative Commons CC BY license.

11. IPCC. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change (IPCC) 2019. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html.
12. MAyDS. Quinto Informe Bienal de Actualización de Argentina a la Convención Marco de las Naciones Unidas sobre el Cambio Climático. 2023. https://ciam.ambiente.gob.ar/images/uploaded/recursos/372/BUR5.pdf .
13. EPD. Guiding Rules of the International EPD System - General Programme Instructions. International EPD System (IES). 2025. https://www.environdec.com/resources/general-programme-instructions.
14. Braun, Michelle; Muñoz, Ivan; Schmidt, Jannick H.; Thrane, Mikkel. 2016. Sustainability of Soy Protein from Life Cycle Assessment. The FASEB Journal 30 supplement.894.5 ISSN 0892-6638. https://doi.org/10.1096/fasebj.30.1_
15. Berardy, A., Costello, C., & Seager, T. Life cycle assessment of soy protein isolate. 2015. Proceedings of the international symposium on sustainable systems and technologies, Dearborn, MI, USA (Vol. 3).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

© 2026 by the author(s). Distributed under a Creative Commons CC BY license.