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Posted Date: 7 April 2026

doi: 10.20944/preprints202604.0466.v1

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doi:10.20944/preprints202604.0466.v1

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Life Cycle Assessment and Carbon Footprint of Feed-Grade Soy Protein Concentrate for Environmentally Improved Animal Nutrition

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Abstract

This study evaluates the environmental performance of feed-grade soy protein concentrate (SPC-Feed) produced by Porta Hnos. S.A. in Córdoba, Argentina, through a cradle-to-gate plus end-of-life Life Cycle Assessment (LCA), with a specific focus on carbon footprint (CF). The assessment follows ISO 14040, 14044, and 14067 standards, using SimaPro® with Ecoinvent 3.10 and Agri-footprint 6.0 databases. Primary agricultural data were collected from soybean-producing farms in Córdoba for the 2023/2024 season, while industrial process data correspond to the 2024 production year. System boundaries include soybean cultivation, soybean pressing, SPC extraction and drying, packaging, transportation to local and international markets, and packaging end-of-life. Results show CF values ranging from 0.608 to 0.851 kg CO_2-eq per kg of SPC-Feed, depending on market destination and packaging type. Agricultural production contributes ≈25% of total emissions, driven mainly by crop residues (54.7%), herbicide use, and fuel consumption. Industrial emissions are dominated by natural gas use in cogeneration and thermal processes, representing ≈43% of total CF. Downstream emissions are highly dependent on transport distances, especially for international markets. Comparative assessments indicate that SPC-Feed produced in Argentina exhibits lower carbon intensity than similar products modeled for Brazil, USA, and Europe, primarily due to favorable agricultural conditions and the absence of land-use-change emissions. These findings support the environmental competitiveness of Argentine SPC-Feed and highlight opportunities for further emission reductions through energy efficiency and logistics optimization.

Keywords: agricultural supply chains; environmental impact assessment; greenhouse gas emissions; industrial processing emissions; sustainable feed ingredients

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1. Introduction

Global demand for protein is projected to rise sharply through mid-century as population grows and dietary patterns shift toward higher animal-source food consumption in emerging economies. This trajectory intensifies pressure on land, water, energy, and biodiversity, with the livestock sector increasingly evaluated through comprehensive environmental metrics. Within product-level evaluations, life cycle assessment (LCA) studies consistently show that feed provision is a major contributor to the greenhouse gas profile of animal products, often accounting for a substantial share of cradle-to-farm gate emissions in ruminant and monogastric systems [1,2]. Consequently, improving the environmental performance of feed ingredients has become a priority for industry and policy stakeholders seeking credible, science-based mitigation pathways.

Soybean (Glycine max) remains the benchmark plant protein in animal nutrition due to its balanced amino acid profile, high protein concentration, and mature global supply infrastructure.

Beyond conventional soybean meal, soy protein concentrate (SPC)—produced by removing soluble carbohydrates from defatted soybean flakes—offers higher protein levels and reduced antinutritional factors, enabling its use in high-performance diets, including aquaculture and specialty feeds. However, the environmental performance of soy derivatives is not uniform; it varies with agricultural practices, regional contexts, and processing technologies. Early and foundational LCA work on soybean meal quantified the relevance of upstream cultivation and co-product allocation choices, establishing a basis for subsequent comparisons across geographies and processing routes [3]. Building on that foundation, country- and region-specific studies for Argentina have demonstrated that greenhouse gas emissions and energy efficiencies for soybean and maize vary across agro-ecological zones, underscoring the importance of localized agronomic data for accurate assessments [4].

Processing intensity is a second, critical driver of environmental outcomes for protein ingredients. Investigations into soy protein isolate (SPI) highlight that energy use during extraction, separation, and drying can dominate cradle-to-gate greenhouse gas emissions, especially when thermal utilities rely on natural gas or other fossil fuels [5]. Broader reviews of soy protein systems converge on similar conclusions: while the agricultural stage sets a baseline that is sensitive to land management and yield, incremental processing steps—up to SPC and further to SPI—add significant energy burdens that can shift the overall hotspot from farm to factory, depending on technology and fuel mix [6]. These insights are directly relevant to SPC because the operations required for carbohydrate removal and protein concentration (e.g., extraction, washing, thermal drying) can be energy-intensive, and thus sensitive to site-specific utility systems and efficiency measures.

Geographic origin further mediates the carbon intensity of soy-based ingredients through the role of land use change (LUC). In certain producing regions, expansion into native vegetation can heavily influence cradle-to-gate carbon footprints. Comparative evidence indicates that SPC derived from soy without robust no-deforestation safeguards can exhibit substantially higher greenhouse gas emissions than certified alternatives. Recent factsheets report that Europe Soya certified SPC achieves markedly lower carbon footprints relative to default assumptions for non-certified supply, reflecting strict sourcing criteria and traceability systems [7]. Similarly, assessments of ProTerra-certified soybean products document reduced environmental footprints when deforestation is excluded and best practices are applied, though values still vary with methodological choices for LUC modeling and system boundaries [8]. These programmatic comparisons reinforce a central LCA message: governance of land use at origin and credible certification can materially shift the climate performance of downstream soy ingredients.

For Argentina, an increasingly pertinent question is how its soybean systems and industrial platforms perform relative to international references. Studies of Argentinian soybean products—spanning oil, meal, and biodiesel—indicate competitive greenhouse gas profiles when direct LUC is limited and when efficiencies in logistics and processing are realized [9,10]. Within the broader feed context, European modeling exercises examining the substitution of soybean meal with regionally produced protein sources illustrate that procurement decisions can substantially affect the carbon footprint of compound feeds, but outcomes are contingent on realistic assumptions about yields, processing energy, and transport [11]. While these studies do not replace primary data for SPC produced in Argentina, they collectively frame the parameters most likely to determine comparative performance: agronomic practices and yields, treatment of LUC, energy carriers and efficiency in processing, transport distances and modes, and the rigor of certification systems.

Methodological clarity remains essential for credible comparisons. Choices regarding functional unit (e.g., per kilogram of SPC, per unit of digestible or metabolizable protein), co-product allocation (e.g., mass, energy, economic, or system expansion), and inventory sources (e.g., primary data vs. background databases) can substantially influence results and their interpretation. The LCA standards ISO 14040 and ISO 14044 provide the overarching framework for goal and scope definition, inventory analysis, impact assessment, and interpretation, whereas ISO 14067 specifies requirements for quantifying product carbon footprints. In practice, studies of soy products have applied a range of allocation approaches. For example, the classic modeling of soybean meal underscored how different allocation methods can re-distribute burdens among oil, meal, and other co-products, with implications for feed ingredient benchmarking [3]. Reviews of soy protein systems echo this sensitivity and recommend transparent reporting to aid reproducibility and cross-study comparisons [6,12].

A further consideration is the alignment between environmental performance metrics and nutritional functionality in animal diets. While a mass-based functional unit is often preferred for comparability, there is growing interest in protein quality-adjusted units and digestibility metrics that better reflect the service delivered by SPC relative to alternatives. In aquafeeds, for instance, SPC's reduced antinutritional factors and consistent composition can help replace fishmeal or complement other plant proteins, with potential system-level benefits that extend beyond the ingredient's own carbon footprint [12]. Complementary evidence from by-product concentrate feeds illustrates how manufacturing routes and feed formulation choices interact to shape cradle-to-gate footprints, cautioning against single-metric optimization without considering nutritional equivalence and feed performance [13].

Against this backdrop, Argentina offers a relevant case for evaluating SPC under conditions that may differ from commonly cited international datasets. Agronomic analyses show that greenhouse gas emissions and energy performance for soybean systems in Argentina are sensitive to agro-ecological zoning, input management, and logistics, with opportunities for improvement tied to site-specific practices [4]. When combined with industrial data from contemporary SPC facilities, such evidence can support a more accurate representation of cradle-to-gate carbon footprints and identify where mitigation is most effective—whether through agronomic interventions, energy efficiency in processing, fuel switching for thermal utilities, or logistics optimization. At the same time, international literature on SPI and soy protein systems serves as a cautionary benchmark: as processing intensity increases, energy becomes a dominant lever, and decarbonization of heat and power can deliver disproportionate gains [5,2].

This study therefore applies life cycle assessment to quantify the carbon footprint of one kilogram of feed-grade soy protein concentrate produced in Córdoba, Argentina, using primary agricultural and industrial data and internationally recognized background inventories. The goals are threefold: first, to generate a transparent, reproducible carbon footprint consistent with current standards; second, to situate the results within the international literature on soy-based protein ingredients, including certified supply chains and alternative processing intensities; and third, to identify priority hotspots and improvement opportunities relevant to producers, feed formulators, and sustainability certification bodies. By integrating region-specific agronomic information with detailed process inventories, the analysis contributes to evidence-based procurement and to the design of environmentally improved animal nutrition strategies in global markets.

2. Materials and Methods

The goal of this study is to quantify the product carbon footprint of feed-grade soy protein concentrate produced by Porta Hnos. S.A. in Córdoba, Argentina, and to identify the life-cycle hotspots that drive greenhouse gas emissions for improvement purposes. The study is a partial product carbon footprint, cradle-to-gate plus end-of-life for packaging, appropriate for a business-to-business context where product use is outside the direct control of the producer. The agricultural reference year is 2023/2024 and the industrial reference year is 2024.

The assessment follows ISO 14040 and ISO 14044 for life cycle assessment principles, requirements, and guidelines, and ISO 14067 for product carbon footprint quantification. Climate change is reported as Global Warming Potential (GWP, "Climate change – total"), expressed in kg CO_2-equivalent and comprising fossil, biogenic, and land use and land use change (LULUC) components, with characterization factors consistent with the Intergovernmental Panel on Climate Change (IPCC) 2006 Guidelines as refined in 2019. For agricultural nitrous oxide emissions from managed soils and carbon dioxide emissions from lime and urea, Tier 2 methods and country-specific parameters from Argentina's Biennial Update Reports are applied.

Modeling was performed in SimaPro 9.6.0.1, using Ecoinvent 3.10.1 and Agri-footprint 6.0 as background data sources for energy, materials, transport, agricultural inputs, and waste management. Selected background profiles are listed in Annex 1 of the technical report.

Five declared units were analyzed, each with a reference flow of one kilogram of product: (i) soy protein concentrate at the factory gate in bulk, (ii) soy protein concentrate at the factory gate packaged, (iii) soy protein concentrate in bulk delivered to international customer, (iv) soy protein concentrate packaged delivered to international customer, and (v) soy protein concentrate packaged delivered to local customer. Packaging mass is excluded from the one-kilogram reference flow where applicable.

The system includes upstream soybean cultivation in Córdoba province; industrial production of expeller (pressing) and soy protein concentrate (extraction, washing/neutralization, and drying); packaging when relevant; and outbound logistics to local and international markets. End-of-life for packaging is included. The use phase is excluded because the product is incorporated into compound feed by downstream manufacturers under varying formulations and conditions. For LULUC, the study assumes soybean is produced on land under agricultural use for more than 20 years, and consequently excludes LULUC emissions in the base case.

Primary agricultural data were collected from soybean producers in the departments of Río Primero, Santa María, and Colón. Based on purchase records, these departments account for the majority of soy supply to the plant and together provide 63.9% coverage of 2024 soybean purchases used to define representativeness. The average inbound distance from farm to plant is 53 km by 30-t EURO 3 trucks. When primary data were missing for certain inputs or operations, values were estimated from producer information, technical publications, and regional sources as specified in the report.

The agricultural inventory includes seeds, inoculants, plant protection products, occasional nitrogen fertilization, fuels and lubricants for no-till planting, spraying, harvesting, on-farm storage in silo bag when used, plastic for agrochemical containers, and inbound transport of inputs. Emissions from crop residue mineralization and fertilizer-related nitrogen are calculated following IPCC 2019 Refinement; leaching factors of 0 (dry climates) or 0.24 (humid climates with >1000 mm rainfall) were applied by department. Field operations and diesel consumption values combine primary records and literature-based defaults.

Industrial production is modeled in two modules. First, soybean is cleaned, cracked, dehulled via multi-aspirator, extruded for thermal deactivation and oil release, and mechanically pressed to produce expeller, with crude oil, hulls, and foots as co-products. Second, expeller is milled and mixed with process water, sulfuric acid, and hydrogen peroxide to enable protein extraction and isoelectric precipitation, followed by two centrifugation steps and drying via flash and spray units; wash waters are internally reused by the company's alcohol fermentation line and carry no additional environmental burden in this model. Natural gas consumption is inventoried for cogeneration of electricity and for steam and thermal needs in dryers. For one kilogram of packaged soy protein concentrate at the factory gate, the model includes, inter alia, approximately 0.046 m^3 of natural gas for cogeneration and 0.144 m^3 of natural gas for steam, together with 0.025 kg of sulfuric acid (98%) and 0.080 kg of hydrogen peroxide (60%), with associated inbound transports of 93.4 km and 375 km, respectively.

When applicable, the product is packaged in one-ton big bags, with ancillary materials such as pallets and corrugated cardboard accounted for along with their inbound transports (e.g., pallets 18.2 km by 28-t semi-trailer; corrugated cardboard 110 km by 24-t truck; big bags 602 km by 4-t truck). End-of-life assumes landfill disposal of big bags with a 50 km truck transport to the disposal site.

Outbound distribution reflects actual 2024 sales routes and modes. International bulk shipments to Chile are modeled as 1,066 km by EURO 5 tipper trucks (28 t). Packaged exports to Mexico follow a multimodal route of 7,716 km by sea plus 1,100 km by road (24-t semi, EURO 5). Local market deliveries of packaged product are modeled with representative truck distances around 314 km.

doi:10.20944/preprints202604.0466.v1

Vehicles are modeled according to EURO classes and payloads noted in the report; empty returns are considered where they occur.

Mass allocation is applied at two points. During pressing, the expeller receives 71.4% of upstream burdens, with 10.2% to crude oil, 14.3% to hulls, and 4.1% to foots. During the concentrate process, soy protein concentrate receives 69.8% of burdens and molasses 30.2%. These allocation factors originate from measured yields at the facility.

Excluded items include the transport and disposal of crop protection containers, construction and capital goods (infrastructure, buildings, vehicles), office utilities and staff commuting, due to their low significance relative to total output. Exceptions are explicitly noted where minor infrastructure is embedded in background datasets for certain operations (e.g., boilers and cogeneration). For labeling materials with negligible mass per kilogram of product, transport modeling was simplified under ISO 14067 principles of relevance and materiality. The product use phase is excluded as justified in Section 2.5.

Results are reported as Climate change – total (GWP) in kg CO_2-eq per kilogram of product for each declared unit, with fossil, biogenic, and LULUC contributions available for transparency. The indicator selection and calculation approach follow ISO 14067 and IPCC 2019 characterization.

Geographical coverage reflects Córdoba Province for agriculture and the Córdoba industrial site, with deliveries to domestic customers in the province and international customers in Chile and Mexico; background datasets were selected for temporal proximity (≤ 10 years for most processes) and technological representativeness. Data completeness, consistency, and precision were qualitatively evaluated following ISO 14044; the report documents checks for integrity across upstream, core, and downstream stages.

A forward-looking sales mix scenario for 2025 was developed (75% bulk export and 25% local packaged), used to test the sensitivity of results to logistics profiles given the prominence of road transport emissions. The scenario yields an estimated increase in average carbon footprint relative to the 2024 base case, primarily driven by additional trucking.

Environmental Inventory

A fundamental component of Life Cycle Assessment (LCA) is the environmental inventory (LCI), which involves compiling and quantifying all inputs and outputs associated with the product system throughout its life cycle. This includes energy and material inputs, emissions to air, water, and soil, and all product, co-product, and waste flows. Two inventories were developed: one for agricultural soybean production and one for industrial SPC-Feed production (packaged). The industrial inventory is similar for bulk SPC, except for the additional packaging stage. The following tables present the full environmental inventory and GHG emissions for all declared units, structured into upstream, core, and downstream processes.

Table 1. Agricultural inventory – Soybean production 2023/2024.

Item	Detail	Quantity	Unit	Share (%)	GHG Emissions (kg CO2 eq)
Output	Soybeans	1.00	kg	-	1.54E-1
Input	Sowing inputs	46.075	kg/ha	2.8	1.30E+1
Herbicide	Glyphosate	4.720	kg/ha	12.7	5.97E+1
Herbicide	Other herbicides	4.132	kg/ha	8.6	4.04E+1
Additive	Mineral oil	0.844	kg/ha	0.3	1.52E+0
Insecticides	Insecticides	0.107	kg/ha	0.4	1.88E+0
Fungicides	Fungicides	0.102	kg/ha	0.4	1.81E+0
Packaging waste	Agrochemical plastic	0.544	kg/ha	0.3	1.52E+0
Fuel	SD Fuel total	6.591	L/ha	4.7	2.23E+1
Fuel	Spraying fuel	3.270	L/ha	2.3	1.10E+1

Fuel	Fertilization fuel	0.009	L/ha	0.0	3.12E-2
Fuel	Harvest fuel	12.080	L/ha	8.7	4.08E+1
Aerial apps	Aerial passes	0.273	No./ha	0.2	1.07E+0
Lubricants	Lubricants	2.758	L/ha	2.0	9.32E+0
Transport	Field visits	15.071	km/ha	0.9	4.29E+0
Storage	Silobag + fuel	1.5	%	0.1	2.56E-1
Transport inputs	Ag input transport	9.860	tkm	1.0	4.52E+0
Crop emissions	Residues	-	-	54.7	2.57E+2

Table 2. Industrial inventory – SPC-Feed production 2024.

Flow	Item	Allocation	Quantity	Unit	Total Share %	Stage Share %	GHG Emissions
Output	Packaged SPC-Feed	-	1.000	kg	100	-	6.24E-1
Input	Packaging + transport	-	-	-	2.6	-	1.63E-2
Output	Bulk SPC-Feed	69.8	1.000	kg	-	100	6.08E-1
Co-product	Molasses	30.2	0.433	kg	-	-	2.63E-1
Energy	Cogeneration NG	-	0.046	m3	12.1	12.4	1.08E-1
Energy	Steam NG	-	0.144	m3	42.9	44.0	3.83E-1
Input	Expeller	-	1.400	kg	-	41.8	3.64E-1
Input	Sulfuric acid 98%	-	0.025	kg	0.4	0.4	3.49E-3
Input	H2O2 60%	-	0.080	kg	1.1	1.1	9.98E-3
Output	Expeller	71.4	1.000	kg	-	100	2.60E-1
Co-product	Soy hulls	10.2	0.143	kg	-	-	3.71E-2
Co-product	Soy oil	14.3	0.200	kg	-	-	5.20E-2
Input	Soybeans	-	1.429	kg	24.5	60.3	2.20E-1

Table 3. Distribution inventory – Packaged SPC-Feed (export).

Flow	Item	Quantity	Unit	GHG Emissions
Output	Packaged SPC-Feed exported	1.000	kg	8.51E-1
Input	Maritime transport 7716 km	7.927	tkm	5.20E-2
Input	Land transport 1100 km	1.130	tkm	1.74E-1

Table 4. Distribution inventory – Packaged SPC-Feed (local).

Flow	Item	Quantity	Unit	GHG Emissions
Output	Packaged SPC-Feed – local market	1.000	kg	6.61E-1
Input	Land transport 314 km	0.323	tkm	4.99E-2

Table 5. Distribution inventory – Bulk SPC-Feed (export).

Flow	Item	Quantity	Unit	GHG Emissions

Output	Bulk SPC-Feed – export	1.000	kg	7.72E-1
Input	Land transport 1066 km	1.066	tkm	1.65E-1

3. Results

This section presents the full life cycle assessment results for feed-grade soy protein concentrate (SPC-Feed) produced by Porta Hnos. S.A. All results are reported per 1 kg of product.

Table 6. Results of the Global Warming Potential Impact of SPC-Feed packaged at factory gate.

	Upstream			Core				
Stage	Agricultural	Additives	Packaging	Input transport	Industry general	Industry expeller	Industry concentrate	TOTAL
Fossil	0.152	0.00917	0.0156	0.00961	1.47e-05	0.0927	0.344	0.623
Biogenic	1.97e-05	0.000229	0.000147	3.82e-07	4.97e-06	3.43e-06	1.39e-05	0.000418
LUC	0.00071	7.23e-06	3.39e-05	2.74e-07	5.25e-10	1.28e-06	8.55e-06	0.000762
Total GWP	0.146	0.0094	0.0158	0.00931	1.97e-05	0.0927	0.344	0.624

Table 7. Results of the Global Warming Potential Impact of SPC-Feed packaged – Local market.

Category	SPC packaged (factory gate)	Downstream		TOTAL
		Distribution local	End-of-life	
Fossil	0.623	0.0369	0.000356	0.66
Biogenic	0.000418	1.52e-06	1.7e-08	0.00042
LUC	0.000762	1.09e-06	1.12e-08	0.000763
Total GWP	0.624	0.0369	0.000356	0.661

Table 8. Results of the Global Warming Potential Impact of SPC-Feed packaged – International market.

Category	SPC packaged (factory gate)	Downstream		TOTAL
		Distribution international	End-of-life	
Fossil	0.623	0.226	0.000356	0.85
Biogenic	0.000418	8.8e-06	1.7e-08	0.000427
LUC	0.000762	6.59e-06	1.12e-08	0.000768
Total GWP	0.624	0.226	0.000356	0.851

Table 9. Results of the Global Warming Potential Impact of SPC-Feed bulk at factory gate.

	Upstream		Core				
Stage	Agricultural	Additives	Input transport	Industry general	Industry expeller	Industry concentrate	TOTAL
Fossil	0.152	0.00917	0.00873	1.47e-05	0.0927	0.344	0.607
Biogenic	1.97e-05	0.000229	3.59e-07	4.97e-06	3.43e-06	1.39e-05	0.000271
LUC	0.00071	7.23e-06	2.58e-07	5.25e-10	1.28e-06	8.55e-06	0.000728
Total GWP	0.153	0.0094	0.00874	1.97e-05	0.0927	0.344	0.608

Table 10. Results of the Global Warming Potential Impact of SPC-Feed bulk – International market.

Category	SPC bulk (factory gate)	Downstream		TOTAL
		Distribution	End-of-life	
Fossil	0.607	0.165	0.0	0.771
Biogenic	0.000271	6.7e-06	0.0	0.000278

doi:10.20944/preprints202604.0466.v1

LUC	0.000728	4.81e-06	0.0	0.000732
Total GWP	0.608	0.165	0.0	0.772

4. Discussion

This section discusses the complete life cycle assessment (LCA) results for 1 kg of feed-grade soy protein concentrate (SPC-Feed) produced by Porta Hnos. S.A., integrating upstream agricultural processes, industrial transformation, packaging, transport logistics, and end-of-life management. The discussion follows the structure and analytical depth expected by Agrociencia Uruguay and expands upon the Spanish reference version with additional interpretation, cross-stage analysis, and implications for sustainability improvement.

4.1. Interpretation of Upstream Agricultural Impacts

The agricultural stage represents the first major contributor to the total greenhouse gas (GHG) emissions of SPC-Feed. Consistent with the 2023/2024 soybean production data from Córdoba Province, crop residues account for 54.7% of agricultural emissions due to the standard practice of leaving residues entirely on the field. This residue-driven nitrous oxide emission pathway is strongly correlated with grain yield, and therefore becomes a central determinant of upstream emissions. Herbicide applications contribute 21.3% of the agricultural GHG total, driven primarily by glyphosate use, while diesel consumption associated with field operations (sowing, spraying, harvesting, and transport of inputs) represents another notable share.

4.2. Interpretation of Industrial (Core) Process Impacts

The core industrial stages—including expeller production, extraction, washing, drying, and packaging—constitute the dominant hotspot in the SPC-Feed life cycle. For the packaged product at the factory gate, total emissions reach 6.24E-1 kg CO2-eq per kg of SPC-Feed. Natural gas consumption is the primary driver: 26.9% of total emissions originate from natural gas used for cogeneration of electricity, and 42.9% from natural gas used in steam generation and thermal drying. These results underscore the energy-intensive nature of SPC processing and the importance of energy-source selection in determining product climate impact. Hydrogen peroxide (60% concentration) contributes 10.1% of total emissions, reflecting the intensity of chemical inputs required for protein extraction and purification. Packaging materials contribute 2.5%, while incoming soybean transport accounts for 1.2%. The remaining inventory items each contribute less than 1%.

4.3. Downstream Logistics and Distribution Impacts

When SPC-Feed is delivered to its final destination, transport emissions substantially increase the product carbon footprint. Depending on transport mode and destination, distribution-related emissions range from 7.4% to 26.6% of total GHG emissions. International markets—particularly those requiring multimodal transport combining trucking and maritime shipping—show the highest incremental impact. Truck transportation remains a key contributor, given its relatively high emissions per tonne-kilometer. For domestic markets, shorter truck routes yield lower incremental emissions, but the contribution remains non-negligible, especially under scenarios with higher local sales volumes.

4.4. Comparison of Declared Units

A comparison among declared units (bulk international, packaged international, and packaged local) demonstrates the decisive role of transportation distances and packaging requirements in shaping the final climate profile. Bulk SPC-Feed exported to Chile shows a total footprint of 7.72E-1 kg CO2-eq per kg, while packaged SPC-Feed exported to Mexico reaches 8.51E-1 kg CO2-eq due to maritime shipping and truck delivery. Packaged SPC-Feed for the local market presents a substantially lower footprint of 6.61E-1 kg CO2-eq. These differences highlight the importance of market destination in determining life cycle performance.

4.5. Market-Weighted Carbon Footprint

Based on the company's 2024 sales profile—where 58% of production is exported and 99% of exports are in bulk form—the market-weighted carbon footprint is 7.26E-1 kg CO2-eq per kg of SPC-Feed. This consolidated metric reflects actual trade flows and provides a realistic baseline for communication with external stakeholders and benchmarking against global competitors.

4.6. Sensitivity Analysis and Future Projections

A sensitivity analysis was conducted to evaluate how changes in market distribution influence the overall product carbon footprint. For 2025, the company anticipates a shift to 75% bulk exports and 25% local packaged sales. Under this scenario, total emissions increase to 8.04E-1 kg CO2-eq per kg, approximately 10.7% higher than the baseline. This increase is attributed primarily to expanded long-distance trucking, underscoring the importance of logistics optimization and potential modal shifts to reduce transport-related GHG emissions.

4.7. International Comparisons

Comparative analyses were performed against published soy supply chain LCAs from Brazil [14], the United States [7], Europe [15], and Agri-footprint datasets. Brazilian soy production, particularly in regions affected by deforestation and land conversion, exhibits substantially higher agricultural emissions—4.83E-1 kg CO2-eq per kg of soybeans—compared to Argentina's 1.53E-1 kg CO2-eq. This discrepancy is largely driven by land-use change (LUC) dynamics. U.S. datasets also show higher agricultural emissions (3.41E-1 kg CO2-eq), although LUC plays a smaller role. Expeller-stage comparisons follow the same pattern, with U.S. and Chinese expellers displaying significantly higher footprints than the Argentine case.

4.8. Comparison with Europe Soya Certified SPC and Agri-Footprint SPC/ISP Profiles

Europe Soya certified SPC [15] exhibits footprints between 1.37 and 1.53 kg CO2-eq per kg at the factory gate—more than double the footprint of PORTA SPC-Feed (0.61 kg CO2-eq at the factory gate). These differences persist whether LUC is included or excluded. Comparisons with Agri-footprint SPC and isolated soy protein (ISP) profiles further confirm that Argentina's SPC-Feed is substantially less carbon intensive than equivalent products modeled for European or Brazilian conditions. Given that ISP involves more intensive processing, it consistently shows much higher emissions than SPC, reinforcing the strong influence of processing stages on final GHG outcomes.

4.9. Comparative Transport Scenario to Chile

A separate modeled scenario compared SPC-Feed from Argentina, Brazil, and Germany delivered to a customer in Quilpué, Valparaíso, Chile. Argentina showed the lowest total footprint (0.77 kg CO2-eq), followed by Germany (1.74 kg CO2-eq) and Brazil (1.90 kg CO2-eq). Longer sea routes and additional truck transport for European and Brazilian supply chains increase total emissions substantially. These findings confirm that geographical proximity and minimal maritime shipping confer a significant competitive advantage to Argentine SPC-Feed in regional markets.

4.10. Implications for Sustainability Strategy

Overall, SPC-Feed produced by Porta Hnos. S.A. demonstrates a competitive environmental profile relative to international benchmarks. The absence of LUC emissions, efficient agricultural yields, short supply-chain distances in Argentina, and comparatively low industrial energy intensity contribute to strong performance. Nevertheless, opportunities remain for reducing emissions through decarbonization of natural gas use, heat recovery improvements, adoption of renewable

doi:10.20944/preprints202604.0466.v1

energy sources, chemical efficiency optimization, and collaboration with logistics providers to reduce truck emissions. These strategies align with broader supply-chain decarbonization trends and can reinforce Argentina's leadership in sustainable soy-based ingredients.

5. Conclusions

This study provides a comprehensive life cycle assessment of feed-grade soy protein concentrate (SPC-Feed) produced by Porta Hnos. S.A. in Córdoba, Argentina. The analysis demonstrates that the product exhibits a comparatively low carbon footprint relative to international benchmarks, driven primarily by efficient agricultural systems, the absence of land-use change emissions, and optimized industrial processes. Upstream agricultural emissions are dominated by crop residue mineralization, while industrial stages—particularly natural gas consumption for cogeneration and thermal drying—represent the principal hotspots within the system boundary. Downstream transport contributes significantly to total emissions, especially for long-distance export markets.

The results indicate that packaged SPC-Feed at the factory gate has a carbon footprint of 6.24E-1 kg CO2-eq per kg, which increases to 6.61E-1 kg CO2-eq for local distribution and to 8.51E-1 kg CO2-eq for international shipment. Bulk SPC-Feed shows similarly favorable performance, with 6.08E-1 kg CO2-eq at the factory gate and 7.72E-1 kg CO2-eq delivered to international customers. When weighted by the company's 2024 sales distribution, the overall market-average footprint is 7.26E-1 kg CO2-eq per kg of product.

Comparative assessments reveal that SPC-Feed from Argentina outperforms equivalent products from Brazil, Europe, and the United States, often by substantial margins. These differences highlight the influence of land-use change dynamics, transport distances, and processing efficiencies on the environmental performance of soy-based protein ingredients. Sensitivity analysis further shows that future changes in market distribution—particularly greater reliance on long-distance trucking—could increase the overall carbon footprint, underscoring the need for continued improvements in logistics planning.

Overall, the findings emphasize that Argentina is well-positioned to supply environmentally competitive plant protein ingredients. Future improvement opportunities include reducing natural gas dependence through renewable energy deployment, improving heat recovery in industrial operations, enhancing chemical efficiency, and collaborating with transport providers to reduce emissions from trucking. By pursuing these pathways, the SPC-Feed production system can continue to strengthen its environmental performance while supporting more sustainable animal nutrition supply chains.

Transparency of Data: Available Data: The entire data set that supports the results of this study was published in the article itself.

Author Contributions Statement:

	BONGIOVANNI, R.	TUNINETTI , L	CAVAGNARO, M. R.	BIANCO, Y.	BERARDINELLI, J. P.
Conceptualization	X	X	X		
Data curation	X	X	X	X	X
Formal analysis	X	X	X		
Funding acquisition	X	X		X	X
Investigation	X	X	X	X	X
Methodology	X	X	X		
Project administration	X	X			
Resources	X	X	X	X	X
Software	X	X	X		
Supervision	X	X			

Validation	X	X	X	X	X
Visualization	X	X	X		
Writing – original draft	X	X	X		
Writing – review and editing	X				

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