Discover Sustainability

Research

A global study on the Life Cycle Assessment (LCA) of the modern cow leather industry

F. Brugnoli[1] · K. Sena[2] · L. Zugno[2] · A. Oggioni[1]

Received: 3 August 2024 / Accepted: 2 January 2025
Published online: 10 February 2025

Abstract
The leather industry lacks aggregated studies regarding the Life Cycle Assessment (LCA) of leather production. Existing studies to date are outdated, incomplete, use old methodologies, or do not represent the whole leather segment. There is a need for more complete, reliable, and updated studies in modern state-of-the-art leather production sites (tanneries), which are more representative of global leather production than the current limited and isolated studies. This work aims to provide an average LCA for the leather industry, without focusing on specific tanneries or locations. The goal is to produce high quality, up-to-date, and aggregated LCA data that accurately represents leather in comparison with synthetic and alternative materials. SimaPro 9.1.0.8 [1],a robust and reliable LCA software used to ensure the credibility of life cycle assessment results, and the Ecoinvent 3.6 [2] database, that features more than 2,200 new and 2,500 updated datasets, were used to conduct 56 LCA studies of bovine leathers produced by 6 leather groups in 16 facilities distributed among eleven countries (Argentina, Australia, Brazil, China, Italy, Sweden, Thailand, United Kingdom, the United States, Uruguay, and Vietnam) and for different types of leather (automotive, shoe, upholstery, and leather goods) that represent most types of leathers produced globally. The ISO 14044 [3] LCA methodology was used for LCA and life cycle inventory (LCI) studies providing the scope, interpretation, reporting, and critical review of the LCA. The LCA results indicate that, of the six impact categories studied (Global Warming, Eutrophication, Abiotic Depletion, Water Use, Water Consumption, and Freshwater Ecotoxicity), the farming stage (upstream) significantly contributes to the impact of five of them. A need for more basic data on raw material allocation, processing, and chemicals was identified. Nonetheless, the study revealed that the values for several parameters were much lower than previously indicated, particularly regarding allocation to raw materials. These new results can be used as a benchmark for complementary studies in this area and to recommend opportunities for process improvements that will make the leather industry more sustainable in the future. The paper contains important information for understanding the LCA hot spots and provides insights into the industry regarding the improvements needed in specific process areas. It also allows for a better understanding of data gaps that, when addressed, will allow for more reliable aggregated bovine leather LCAs.

Keywords LCE · LCI · Tannery · Cow Leather · Tanning · Functional Units · SimaPro · Ecoinvent

1 Introduction

Commercial leather production is mostly based on hides and skins produced as by-products of the meat industry. The largest fraction of leather production is made from cow hides. Approximately 270 million bovine hides are produced every year [4] and it is estimated that 70% of these hides are converted into leather (industry data). We define hide

✉ L. Zugno, drzleather@gmail.com | [1]Spin 360, 20123 Milan, Italy [2]Leather Naturally, 2132 Hoofddorp, The Netherlands.

(or rawhide) as the skin of cattle and leather as the hide (skin) after undergoing the tanning process. Bovine leather is mainly produced in Brazil, China, the United States, India, Italy, Vietnam, and South Korea, but almost all countries have some bovine leather production. As a by-product of the meat industry, hides are allocated a proportion of the environmental impact of the rearing of animals. This allocation is typically based on the economic value of the hide and covers environmental parameters, including water consumption, eutrophication, CO_2 emissions, etc. There is a lack of availability of primary data to allow proper allocation to cow hides, and the most important data are derived from the European Commission Publication [5] and De Rosa-Giglio et al. [6]. Using the standard Product Environment Footprint Category Rule (PEFCR) defined allocation factors and the Ecoinvent 3.6 [2] database, bovine leather products have a significantly higher CO_2 eq. load than fossil-based products. However, the use of the updated primary data might describe the actual attributional allocation more precisely.

Several LCA studies have been conducted on the leather industry, and each of them presents limitations, such as limited geographical representativeness or the use of old methodologies and not including global data from rawhide to finished leather. Several published works have focused on specific processes, for example: comparing the chrome tanning process with other tanning methods [7]; comparing vegetable, wet-white, and chromium tanning [8]; comparing waterproofing versus conventional vegetable tanning [9]; using a new degreasing formulation for tanning [10]; developing a new tanning process [11]; comparing vegetable and chrome tanning [12]; with the oxidative unhairing process [13]; with a new wet-white tanning process using a tannic acid and laponite nano clay [14]; using nano-hydroxyapatite for fireproofing application [15]; evaluating re-tanning, fatliquoring, and dyeing [16]; comparing chrome tanning, chrome-free metal tanning, and metal-free tanning [17] and evaluating the impact of different leather thickness [18]. Few LCAs were made in defined countries or regions. LCA for a tannery in Latin America [19], Bangladesh [20, 21], New Zealand [22], for the Catalan eco-label leather [23], a tannery in Indonesia [24] and a tannery in Turkey [25]. A literature review on LCAs was made by Navarro et al. [26]; carbon footprint for tanneries on five countries [27] and using lab experiments to collect data for chrome tanned upper leather [28].

Cow hides is the generic term used for all hides of cows, heifers, steers, and bulls. The size, thickness, and weight of a hide vary based on the animal's sex and age. The most common cow hides have between 30 and 40 kg of raw weight and a surface area of 4 to 5 square meters. The hides' thickness is usually 6 to 10 mm, and after tanning, the hides are split into two parts; the top is called the grain and the bottom, flesh. The thickness of the finished leather can be 0.6 mm for garments and 2.0 mm for shoes.

Bovine hides can be used fresh, salted, or brine cured. Salted and brine-cured hides are processed for at least 24 h with salt or a saturated brine solution.

A tannery is the manufacturing facility that converts raw hide to leather. Tanneries may carry out processing from raw to tanned or finished leather or process from wet blue to crust or wet-blue to finish.

Leather processing is described with the following terminology. Beamhouse is the process of cleaning the hide and removing hair and subcutaneous material (flesh). Tanning is the process of stabilizing the hide collagen into a non-putrescible, stable product called leather. Tanning can be performed with chrome III salts originating from the wet-blue leather in the intermediate stage. Leather is called wet-white when made with organic tanning materials and vegetable leather when tanned with vegetable extracts. After the tanning process, chemicals are added to the wet leather to modify its properties, a process called re-tanning, and oils and waxes are added for softening and effects. Dyes can be added to the leather to change its color. The dry leather after re-tanning is called crust. Crust leather is finished with coatings (transparent or colored) to uniformize the surface and offer more protection. The finishing steps may include light or heavy embossing, sanding, or polishing to modify the surface. A complete overview of modern leather manufacturing is available in the Leather Naturally [4] publication.

The locations of and the processes undertaken by the tanneries in this study are listed in Table 1.

Table 1 List of the leather manufacturing processes and locations where the LCAs took place:

Process	Tannery locations
Beamhouse and Tanning	Argentina, Australia, Brazil, Italy, Sweden, United Kingdom, the United States and Uruguay
Post-tanning	Argentina, Brazil, China, Italy, Sweden, United Kingdom, Uruguay, and Vietnam
Finishing	Argentina, Brazil, China, Italy, Sweden, Thailand, United Kingdom, Uruguay, and Vietnam

The objective of this LCA is to broaden the understanding of the potential quantifiable externalities of the modern cow leather industry. The work represents 16 facilities in eleven different countries with diverse climatic conditions: Argentina, Australia, Brazil, China, Italy, Sweden, Thailand, United Kingdom, United States of America, Uruguay, and Vietnam. The climatic conditions impacted energy and water consumption mostly in upstream and core processes. The study encompasses all four steps of leather manufacturing: Beamhouse, Tanning, Post-tanning and Finishing for a variety of types and weights of raw materials (bovine hides). Ultimately, the data from 56 assessments for upholstery, footwear and automotive leather were used to create a modern and global LCA for bovine leather.

For data evaluation, SimaPro 9.1.0.8 [1] LCA software was used with the Ecoinvent 3.6 [2] database and the EPD® System 3.1 [29] as an independent data verifier. This LCA is a benchmark for the future LCA studies for the leather industry and provides insights to the improvements needed to minimize environmental impacts in specific process areas.

The new study is the most up-to-date representation of the LCA status of the current leather industry. It reveals several parameters that are significantly lower compared to previous figures, especially in terms of raw material allocation. This data is crucial for identifying the LCA hot spots and offers valuable insights into the industry on areas where specific process improvements are necessary. The characterized results were comprehensively detailed for six impact categories. The conclusions are as follows: a) The production of raw hides significantly influenced five out of the six categories considered and b) chemicals were major contributors to all impact categories, except for Eutrophication.

2 Materials and methods

This work evaluated 16 facilities in eleven different countries, encompassing all four steps of leather manufacturing for a variety of types and weights of raw materials (bovine hides) for upholstery, footwear and automotive leather; a total of 56 assessments The 56 studies were run separately, with the use of both primary and secondary data. The cattle farming inventories used were the most well-adjusted PEF compliant datasets for each specific raw material, and the allocation was done according to the PEFCR-Leather [6]. The specific recipes for the wet batch stages (i.e., Beamhouse, Tanning and Post-tanning) were used to calculate the chemical inputs. Samples were collected at the drum exhaust to properly account for the pollutants sent to the effluent treatment plant. The treated effluent was also analyzed to assess water purity. The local energy matrix included both electric and thermal energy balances, with the specific power of each process machine considered.

2.1 Life Cycle Assessment

2.1.1 The LCA study details are listed in Table 2, with information on the product classification, references, software, and study countries.

Table 2 LCA study details

Parameter	Details
Product System	Global Leather Average of 56 Studies
Product classification	Division 29—Leather and leather products; footwear Group 291—Tanned or dressed leather, composition leather Class 2912—Other leather, of bovine or equine animals, furless
Reference standard	ISO 14040 [30] and 14,044 [3]
Source of sector-specific information	PEFCR-Leather [6]. Program operator: The EPD® System 3.1 [29]
LCA software used	SimaPro 9.1.0.8 [1]
Database used	Ecoinvent 3.6 [2]
Study countries	Argentina, Australia, Brazil, China, Italy, Sweden, Thailand, United Kingdom, the United States, Uruguay, and Vietnam

Table 3 Product characteristics that define the leather type and properties

Characteristics	Details
Animal type, origin	Bovine (Argentina, Australia, Brazil, UK, US, and Uruguay)
Type of leather	Grain splits (grain-split part)
Raw material: average unitary weight (kg/piece)	41.24
Raw material: average mass fraction of the live animal	8.46%
Raw material: average economic allocation of the live animal	1.82%
Main tanning agents	Chrome and chrome-free
Stage of the product sold	Finished leather
Uses of the leathers	Upholstery, footwear, automotive and leather goods
Average thickness	1.34 mm
Average area per kg of leather (dry matter)	1.0632 m^2
Reference years of this study	2021–2022

2.1.2 Product characteristics

The product characteristics were defined as simple averages from LCA studies carried out on 56 leather products and are listed on Table 3. The leathers were produced for automotive, footwear, upholstery, and leather goods in 40 different and specific supply chain configurations.

All materials and energy flows were considered in this study, excluding the packaging materials of chemicals entering the processes and non-processing chemicals in the tanneries, e.g., chemicals for maintenance and cleaning. The material outflows of the packaging materials were accounted for in the waste streams. The electric energy was 100% from the specific production mix of the suppliers of the tanneries involved. All transportation was accounted for.

2.1.3 System boundaries

The system boundaries were the "cradle to tannery exit gate" including all environmentally relevant processes, such as wastewater treatment. All livestock-stage processes were also included in the system boundaries. Leather is an intermediate product; therefore, the manufacturing of goods using leather and the related impacts were not included in the system boundaries. Additionally, the transfer of finished leather to the subsequent steps of processing, distribution, and end-of-life (EOL) treatment of the final product was beyond the scope of this study (Table 4).

Table 4 Details of the upstream and core processes

Upstream	Core
Farming (bovine species are raised for meat production) Slaughter (killing the animals for meat) and removing the hides for tanning	Beamhouse (removal of hair) Tanning (conversion of the hide to leather) Post-tanning (coloring and defining the leather types) Finishing (aesthetic and protection coatings and processes)

Table 5 SWOT analysis

Strengths	Weaknesses
Data structure defined for detailed primary data collection at the tanneries Actual processes High-quality information Innovative sectorial approach Data referring to an actual trend, supported by strong producers on the market	Medium confidence of the dataset for upstream processes (bovine farming) Medium confidence in data quality on chemicals
Opportunities	**Threats**
Opens the debate on leather LCA Establishes a benchmark for future LCA studies	The comparison of the present study results with those of others LCA studies are not based on real processes but on average production

2.1.4 Cut off criteria, assumptions, and impact evaluations

To meet the ISO standard 14,040 [30] and 14,044 [3] requirements, we combined the assumptions and limitations with a Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis (Table 5) to ensure a more comprehensive scope.

The following assumptions and cut-offs were used in this study:

Default data available on Ecoinvent 3.6 [2] for rawhides (Product Environmental Footprint (PEF) rules compliant) for farming processes, as no specific data were available on the actual upstream supply chain; Default values for transportation from the farm to the slaughterhouse; Data describing processes carried out in tanneries described the actual situation.

When the chemical producers did not disclose the exact compositions of the chemicals used in production, the reference compositions found in PEFCR-Leather [6] were used as approximations. The water quality data from the tanneries' measurements were used as inputs and outputs for a water treatment model. The model was based on previous work carried out by Spin360 [31], where the mass balance of the pollutants was calculated to model the quality of water being sent to the biosphere.

The impacts generated to produce the packaging of the chemicals entering the product system were not considered, while their disposal/recycling after use was included.

The chemicals used for the maintenance and cleaning of the buildings and machinery were not considered since previous studies with the same approach and under critical review were validated.

The significant limitations of this study were the lack of primary data on upstream farming impacts and the need to rely on approximations for certain chemical compositions, which could affect accuracy of the results. Pandemic-related restrictions also constrained data collection, limiting on-site visits and engagements with tannery personnel. Knowledge gaps remain around rawhide production, chemical impacts, and water management practices, which future studies could address for a more comprehensive assessment.

The Ecoinvent datasets could not fully capture the uniqueness of the leather manufacturing process concerning the specific treatment of waste generated in the process.

The lack of accurate knowledge about the compositions of chemicals limited the options for reporting their environmental impact. Therefore, proxies based on chemical categories were used to model their behavior and effects. The impact categories selected for this study are listed in Table 6.

Table 6 Impact categories, methods, and units of measure (UOM) considered in this study

Impact category	Method	Version	UOM
IPCC GWP 100a	IPCC 2013 GWP 100	1.03	kg CO_2 eq
Eutrophication	CML-IA BASELINE	3.06	kg PO_4 – eq
Abiotic depletion, fossil fuels	CML-IA BASELINE	3.06	MJ
Water use	AWARE	1.02	m^3
Freshwater ecotoxicity	USEtox (recommended + interim)	1.4	CTUe
Water consumption	ReCiPe 2016 Midpoint H V1.00	1.4	m^3

The difference between Water use and Water consumption is that Water use accounts for all the water withdrawn from the ecosphere, while Water consumption refers to the difference between the water withdrawn and the water sent back, directly impacting water availability.

2.2 Life cycle inventory analysis (LCI)

2.2.1 Data collection procedure

Data collection was carried out through the analysis of documents, direct interviews, and on-site measurements for all tanneries involved.

The analysis was carried out on the average of 56 different products, each derived from one of the 6 tanneries, thus considering a global perspective and different supply chains, as compared to other sectoral studies which have mainly been produced using data referring to the whole production of a reference tannery in a reference period. A "bottom up" approach was used in which all the different process steps that contribute to the production of the average leather product were analyzed in detail. This approach significantly increased the reliability of the data and information produced by this study and, therefore, the potential effects of improvement and corrective measures. According to the structure of the system boundaries, data had to be collected and allocated for some life cycle stages outside the tannery (farming) and for different processes inside the tannery.

2.2.2 Upstream processes

Farming—Economic Allocation and Mass Fraction

Due to the nature of the farms providing live animals to the slaughterhouses supplying hides to the tanneries that took part in this study, the Ecoinvent 3.6 [2] PEF-compliant dataset "Beef co-product, hides and skins, from beef cattle, at slaughterhouse, PEF compliant/IE Economic/Mass" was considered more appropriate for this study than the default dataset proposed by the PEF, which refers to dairy farms. Analyzing the composition of the Ecoinvent 3.6 dataset in detail revealed it was built using the default allocation factors in Table 15 of the PEFCR-Leather [6] and shown in Table 7.

The default values of the PEFCR-Leather [6] on which the allocation of animal farming leather is based are 7.00% for the mass fraction and 3.50% for the economic allocation. Considering the variability in raw materials, the applied allocation factors (mass and economic) were calculated as the average of 230 previously performed studies. The revised values were 8.46% for the mass fraction and 1.82% for the economic allocation.

Since the tanneries taking part in this study were able to collect primary data referring to a full calendar year of production, a specific dataset was created, modifying the allocation factors according to the available primary data, which in turn were used to calculate all impact indicators by inputting their primary values to SimaPro 9.10.8 [1].

Table 7 From Table 15 of the PEFCR-Leather [6] built with the default allocations

Process	Type of Allocation	Products	Mass Fraction	Allocation Rate (AR)	Allocation Factor
Farming	Biophysical	Milk		88.0%	
		Live animal to slaughter		12.0%	
Slaughtering	Economic	Fresh meat and edible offal	49.0%	92.9%	1.90
		Hides and skins	7.0%	3.5%	0.51
		Food-grade fat	7.0%	1.8%	0.25
		Food-grade bones	8.0%	1.0%	0.12
		Cat. 3 slaughterhouse by-products	7.0%	0.8%	0.11
		Cat. 1/2 material and waste	22.0%	0.0%	0.00

2.2.3 Core processes

The core processes are represented by the tannery production processes, which include industrial externalities and impacts from sourced materials (e.g., chemicals and packaging). Emissions from general areas in the tanneries such as the cafeteria and entrance gate were outside the scope of this study (General) and the emissions from animal farming are expressed independently (Upstream).

2.2.3.1 Chemical supply For the chemical supply used in the tanneries, "market" datasets from Ecoinvent were used that, as per the following Ecoinvent definition: "already include average transports of that product within the geography, as well as inputs of the product itself to cover losses in trade and transport".

2.2.3.2 Tannery The approach followed in this LCA study was to perform calculations on the specific leather articles of the tanneries. Therefore, a bottom-up process analysis was applied, using a detailed measure of all input and output flows besides the energy consumption of each phase.

The factories and the machinery involved in production were characterized, qualitatively and quantitatively describing their interaction with the environment (energy supply, water uptake and discharge, etc.).

For each waste category, as defined by the European Waste Codes (EWC) classification of waste produced from Tanning processes, the % of waste sent to disposal and recycling was specified, as obtained from the documentation of the tanneries. The locations of the waste treatment platforms and their distances from the production sites were also specified.

All the different processes carried out in production were fully characterized by analyzing the documentation (production recipes) of the companies, describing the machinery and processes.

The leather production process was based on four "essential" stages: Beamhouse, Tanning, Post-tanning, and Finishing.

Each process was carried out (even if in different phases) in the same type of process reactor:

A beamhouse drum, in which hides are washed, soaked, de-haired, and prepared for tanning.

A tanning drum, in which hides are transformed into leather via the tanning process.

A Post-tanning drum, in which leathers are re-tanned, dyed, and fatliquored to acquire additional technical properties.

A finishing line, in which leathers are surface-coated and acquire more performance properties.

Data referring to all environmental inputs and outputs were collected following the procedures described below.

2.2.3.3 Process inputs All process input (water, electricity, thermal energy, and chemicals) data were collected by analyzing the process recipes provided by the technical managers of the companies.

2.2.3.4 Process outputs Wastewater quality data were collected by reporting the results of the specific laboratory analyses of the effluent of each process phase. Data describing and quantifying waste (including their destination) were collected from the environmental documentation of the companies for the year 2021 and via direct measurements for each machine.

2.2.3.5 Water treatment The data on water treatment was derived using an LCA model plant elaborated by Spin 360 [31] and process-specific primary data on wastewater quantity and water quality.

2.2.3.6 General consumption Apart from production processes, factories consume water and energy for general services (cleaning, lighting, heating, compressed air, etc.). This consumption was accounted for taking data from direct measurements and reports produced by the companies and comparing them with the relevant BREF technical literature for validity. BREF are the Best Available Technique Reference Documents [32], which are used as a reference for environmental standards in different sectors and industries. Each of them is a result of years of multifunctional team work to converge onto best available techniques and methods for several different industrial sectors [33].

2.2.4 Data calculation

The data calculation was performed considering all elements and data collected as described in the previous section. The results were calculated by averaging the corresponding results of 56 products. All key environmental indicators for the average product were first calculated based on a data collection of primary data on the unitary weight of finished leather.

The key environmental and impact indicators were converted for expression on the weight of the finished leather. For commercial reasons, the details of the calculation procedures are confidential. However, the calculated data was verified by an independent external reviewer.

2.3 Allocation

Leather production is a typical case of multi functionality. Specific allocation factors were applied to assess the environmental impacts to be assigned to the leather in the core processes:

The calculation of the impacts of animal farming was carried out using a PEF-compliant dataset, modified according to the economic allocations and mass fractions specific to each supply chain configuration, based on primary data provided by the tanneries.

The equivalent raw material weight necessary to produce 1 kg of product was calculated based on the dry matter content of leather at different stages and of the co-products generated during production.

The materials and energy inputs and outputs of each core process step were allocated to finished leather based on the dry matter content of the finished leather, considering co-production.

All environmental interactions of the core processes took into consideration not only the production but also each interaction with the environment related to the general services of the companies, expressed as a percentage of the inputs and outputs of the production processes, either quantifying the values with the primary data from the tanneries or with default values obtained from the relevant literature.

2.4 Validation of data

The primary data underwent internal and external validation processes. The internal validation was performed by the personnel of the tanneries and the external validation by Spin360 using a set of manual and automated procedures in the Spin 360 [31] proprietary calculation software before the input of the activity data into SimaPro 9.1.0.8 [1] software.

Some data related to upstream processes and core processes were unavailable (inventory data on farming and water treatment). For the upstream processes, since no primary data were available, secondary data in the Ecoinvent 3.6 [2] were modified according to the information on mass fractions and economic allocation provided by the tanneries. For the core processes, the best possible estimations were adopted.

Other primary data was used to indirectly obtain other information of interest (*e.g.*, aggregated yearly declarations on waste was used to identify specific waste production per functional unit and electric bills to estimate the electricity use for general consumptions).

As per the provisions of Paragraph 4.2.3.6 of the ISO 14040 [30] this LCA study involved various activities that aimed to measure the data reliability to assess the data quality. These activities included using data quality indicators, setting data quality requirements, and verifying data quality.

In accordance with the provisions of Paragraph 4.2.3.6 of the ISO 14040 [30], what follows provides evidence on the main parameters to be taken in consideration for data Quality: Time Related Coverage, Geographical Coverage, Technological Coverage, Completeness, Representativeness, Consistency, Reproducibility, Sources of Data and Uncertainty of the Information.

2.4.1 Time related coverage

All primary data collected in tanneries refer to 2021–2022. Since the data refers to a specific process, reference for data have been collected and used as a reference the whole year. All datasets used for modeling are sourced from Ecoinvent 3.6 [2] (except for raw hide, for which the process from the Agri Footprint database was taken into consideration) with different time representativeness among the processes.

2.4.2 Geographical coverage

All primary data collected refer to the exact location where the processes occur. Datasets used for modelling have been taken as well referring to the specific location where the environmental aspect is generated. In particular:

- Thermal and electrical energy: the company established the energy mixes in the data collection file, which were then modelled by selecting the Vietnamese processes for the Post-tanning phase and Vietnam and China for the Finishing phase. Where processes were not available, the Rest of the World (RoW) or Global (GLO) processes were considered.
- Chemicals: since the real production site where a chemical is produced is not often known, to adopt a conservative approach and in compliance with the indications of the PEFCR-Leather [6], the "market" category of the datasets has been chosen, where possible providing the specific region. Market datasets include average transport of that product within the geography, as well as inputs of the product itself to cover losses in trade and transport.

2.4.3 Technology coverage

Regarding upstream processes, primary and verified data have been used to measure and calculate the input of raw hides needed to produce one kg of leather product under study.. Considering the nature of the farms supplying live animals to the slaughterhouse and subsequently to the production plant located in the US, the Ecoinvent 3.6 PEF-compliant database, which is specific for the raw hides deriving for the beef cattle production, was deemed more suitable for the purposes of this study compared to the default dataset suggested by PEF, which specifically pertains to dairy farms.

All technologies involved in the core processes have been described in detail, characterized and modelled according to data collected during on site interviews, document consultations and measurements campaigns, therefore the study can be considered to properly represent the technologies involved.

2.4.4 Completeness

As described above, all technologies involved in the core processes have been described in detail, characterized and modelled according to primary data collected during specific sessions and measurements campaigns (carried out by personnel of the tanneries involved). All materials and energy inputs and outputs (with the only exception of packaging of chemicals entering the factories and chemicals used for cleaning and maintenance of buildings and machinery) have been taken into consideration. Slaughtering processes follow the cut off rule of 0,1%.

2.4.5 Precision

Core process data refers to actual production of the product in scope carried out in the reference period. Data has been therefore taken and an average has been calculated (when needed) from official information either coming from the companies' informative systems or included in official documents with legal value. The precision of data is therefore to be considered high.

2.4.6 Representativeness

Despite the attention put in place to obtain precise and representative primary data, during the implementation of the study several limitations related to the availability of representative datasets in Ecoinvent have been identified. The most relevant case refers to chemicals, where lack of precise information from chemical producers and a lack of proper representation of their composition in the available datasets have been identified as the two most important findings of the study.

2.4.7 Consistency

The same methodology has been uniformly applied to the various components of the analysis during the execution of the study.

Table 8 Overall DQR results

Product	Time Representativeness	Proximity and verifiability of the data	Technological Representativeness	Geographical Representativeness	Global Data Quality Rating
Final Study Average	1.00	1.00	2.59	3.55	2.03

2.4.8 Reproducibility

The reproducibility of the results of this study by an independent LCA practitioner, based only on the data included in the present report, is low as most of the primary data from industrial processes and recipes have been kept confidential by the participating companies.

2.4.9 Sources of data

As previously described, official and verified documents of the tanneries involved, together with measurements campaigns carried out directly by their personnel, were the most important and relevant data sources for primary data representing the processes studied. A smaller portion of data was obtained through estimations or default values.

2.4.10 Uncertainty of the information

The most relevant assumptions of the study have been already detailed and are briefly summarized as follows:

•Default data have been used for farming processes, since no specific data have been collected on the actual upstream processes.

•Exact composition of chemicals used in production approximated to the references found in table IX of the PEFCR [5], when not explicitly declared by the producer.

•Dry matter content of chemicals used in production approximated to an industry average, when not explicitly declared by the producer.

•Inputs and outputs on water treatment have been modelled using real data on water quality taken from measurements done by the tanneries and inputting them in a model plant created thanks to previous sectoral work carried out by Spin360.

2.5 Data quality rating (DQR)

In alignment with ISO 14040 [30] and ISO 14044 [3] standards, a Data Quality Rating (DQR) assessment was conducted to evaluate the reliability and accuracy of the data used in this study, focusing on each component of the final product's composition. The DQR analysis included several dimensions to ensure a comprehensive assessment of data quality:

Time Representativeness: Evaluates how current the data is in relation to the reporting period, ensuring it reflects recent conditions.

Proximity and Verifiability: Assesses the extent to which the data sources are directly related to the processes analyzed, as well as the ease of verifying the data through credible sources.

Technological Representativeness: Reflects the accuracy of the data in representing the specific technology and processes used in the production stages.

Geographical Representativeness: Determines how well the data aligns with the specific locations where the activities occur, ensuring the data accurately reflects local conditions and practices.

Each of these quality dimensions was rated to produce a Global Data Quality Rating for the study, summarized in Table 8.

The Global Data Quality study achieved a rating of 2.03, categorizing it as "good" according to the International Reference Life Cycle Data System (ILCD) [34] Data Quality Requirements (DQR) guidelines. This rating reflects a high level of confidence in the data, with robust representation across key quality dimensions such as time representativeness, proximity and verifiability, technological representativeness. As a "good" quality study, this DQR score aligns well with ISO 14040 [30] and ISO 14044 [3] standards.

3 Results

Table 9 contains the average results of the life cycle impact assessment and the Uncertainty Analysis for all six impact categories considered for a 1 kg leather.

Table 9 Overall average results per impact category for 1 kg leather (1.0632 m^2) with the respective uncertainties

Impact category	Value	Uncertainty	UOM
IPCC GWP 100a	$2.20\times10^{+1}$	±1.54	kg CO_2 eq
Eutrophication	1.52×10^{-1}	±0.011	kg PO_4 – eq
Abiotic depletion, fossil fuels	$1.40\times10^{+2}$	±9.8	MJ
Water use	$1.13\times10^{+1}$	±0.791	m^3
Freshwater ecotoxicity	$2.56\times10^{+2}$	±17.92	CTUe
Water consumption	3.44×10^{-1}	±0.024	m^3

The uncertainty analysis is conducted using the final Data Quality Rating (DQR) of the study, which is 2. According to ILCD guidelines, a DQR of 2 corresponds to an expected standard deviation in results between 7 and 10%. This range indicates that, while the study's data quality is rated as "good," there remains a moderate level of variability that could influence the life cycle impact results.

The data in Table 10 shows that chemical use and solid waste are two of the most important contributors among all six impact categories. The production of raw hides is the major contributor to the impact of five out of the six categories considered: Global Warming Potential (Fig. 1); Eutrophication (Fig. 2); Water Use (Fig. 3); Water Consumption (Fig. 4) and Abiotic Depletion, Fossil Fuels (Fig. 5). For Freshwater Ecotoxicity the impacts were more evenly distributed between the Upstream, Beamhouse, Tanning and Post-tanning stages, its source being the solid waste generated in the different processes (Fig. 6). Chemicals were relevant impact sources in all categories except Eutrophication. It is important to highlight that Eutrophication's primary source is the raw material (hides) due to agricultural inputs such as fertilizers. Synthetic inputs have low Eutrophication contributions, due to these

Table 10 Hot spot analysis and contribution of the different process factors to the six impact categories

Environmental aspect	IPCC GWP 100a	Eutrophication	Abiotic depletion, fossil fuels	Water use	Freshwater ecotoxicity	Water consumption
Raw materials	67.8%	91.4%	33.0%	64.9%	13.7%	59.0%
Water Consumption	0.0%	0.0%	0.0%	13.6%	0.0%	21.1%
Thermal energy	0.9%	0,2%	2.1%	0.1%	0.5%	0.1%
Electrical energy	3.8%	0.9%	6.4%	1.9%	1.9%	5.9%
Chemicals	18.3%	4.6%	44.9%	21.4%	33.8%	19.8%
Transport	6.0%	1.0%	13.3%	0.6%	3.8%	0.7%
Emissions to air	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Emissions to Water	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
Solid waste	3.1%	1.7%	0.2%	0.1%	46.2%	0.1%
Wastewater	0.0%	0.1%	0.0%	– 2.5%	0.1%	– 6.8%
Total impact	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

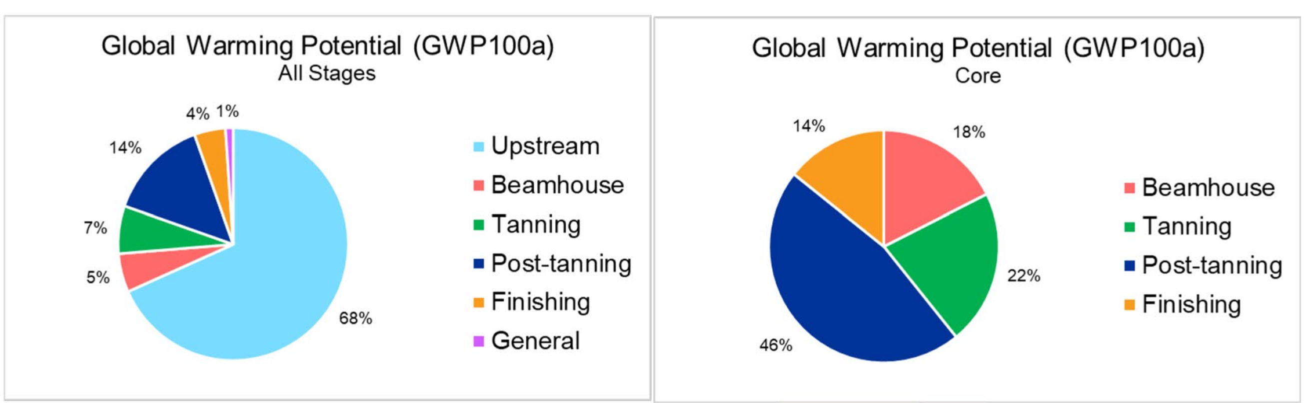

Fig. 1 Relative global warming potential of different processes (UOM kg CO_2 eq)

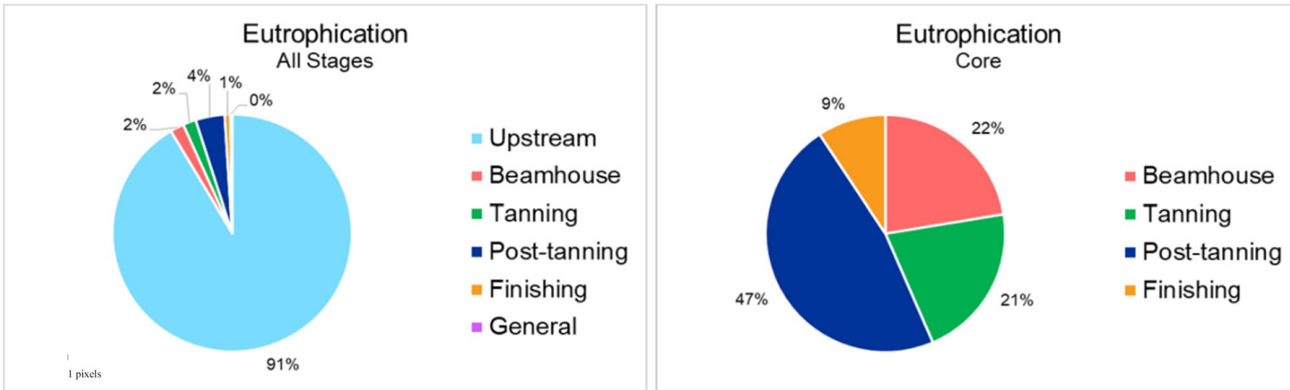

Fig. 2 Relative eutrophication caused by different processes (UOM kg PO_4-eq)

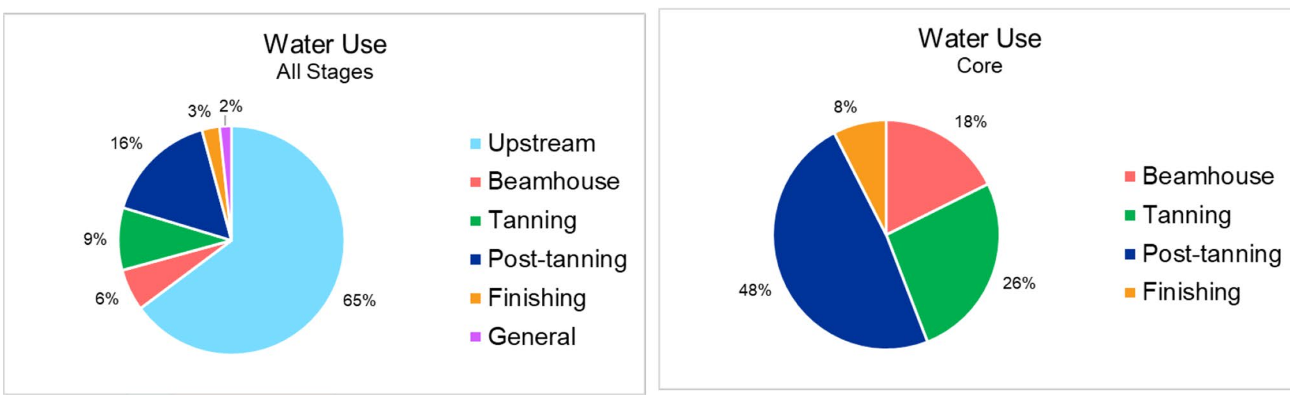

Fig. 3 Relative water use (UOM m^3)

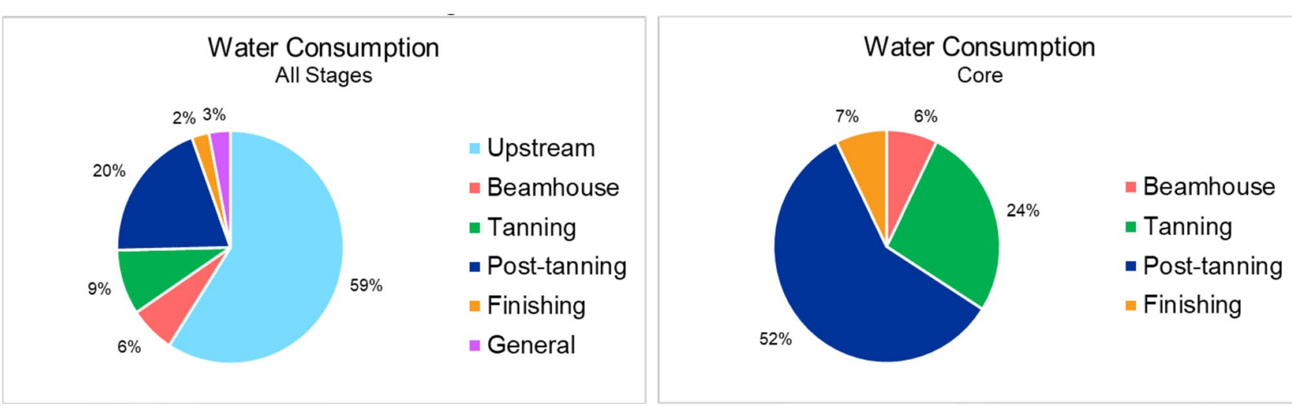

Fig. 4 Relative water consumption of different processes (UOM m^3)

chemicals being mainly fossil based. The following figures provide the relative contribution of each process factor and for each life cycle stage/process for the six impact categories considering two views: all stages (left) and core processes only (right).

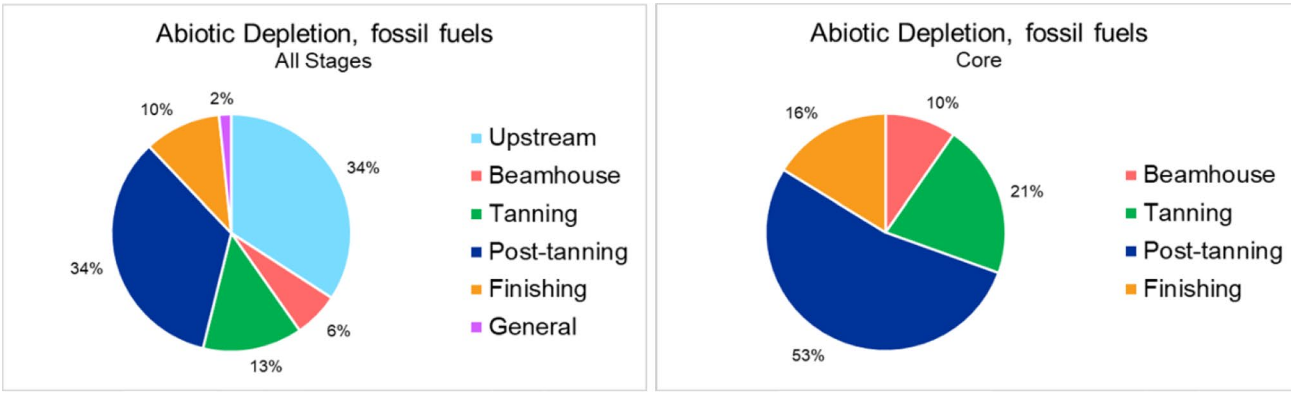

Fig. 5 Relative abiotic depletion, fossil fuels of different processes (UOM MJ)

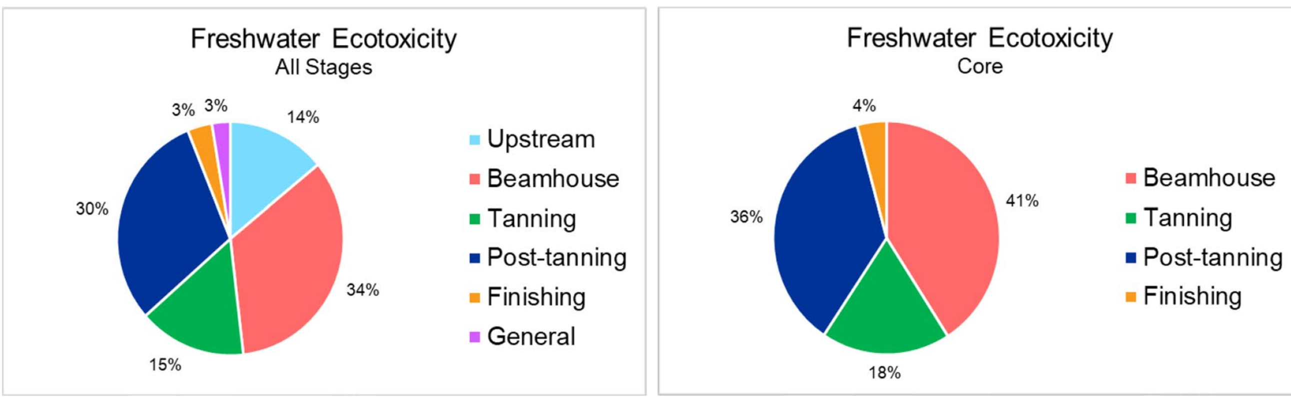

Fig. 6 Relative freshwater ecotoxicity caused by different processes (UOM CTUe)

3.1 Sensitivity analysis

Sensitivity analysis is a method of testing how the LCA results change when one or more input parameters or assumptions is varied. It can help assess the reliability, validity, and uncertainty of LCA results, and reveal the most influential factors that affect the environmental performance of the product or service.

For the average leather product under study, four different scenarios were elaborated to verify the effects of changing key variables of main hotspots (raw hides, chemicals and electric energy).

For raw hides, changes in the Economic Allocation Factor were investigated in scenarios A1 and A2 (Table 11). The scenario of "100% renewables" was calculated based on global mix of renewable energies [36], 2023 data, and

Table 11 Characterization of different scenarios

Ref	Description	Baseline	To be scenario
A1	Increasing economic allocation for raw hides (1 percentage point)	1.82%	2.82%
A2	Decreasing economic allocation for raw hides (1 percentage point)	1.82%	0.82%
B	100% switch to renewables	Actual energy mixes specific for each of the plant involved in the products under study	100.00% renewable energy, in a mix reflecting the production of renewable energy from different sources at global level
C	Reduction of chemical use	Actual chemical use in processes	30% reduction for dosage of all chemicals

is displayed in Scenario B. Finally, the effects of a reduction of 30% in the dosage of chemicals used in the process were calculated in Scenario C.

The main assumptions used for alternative scenarios are listed in Table 11.

3.1.1 Scenario A1—increasing economic allocation

The sensitivity analysis for each scenario is shown in Table 12., In the interests of brevity, the specific breakdown per stage is shown for Global Warming Potential only for all scenarios. The breakdown for scenario A1 can be viewed in

Table 12 Sensitivity Analysis – Scenario A1 (Increasing Economic Allocation) for 1 kg leather (1.0632 m^2) average

Environmental impact	UOM	Baseline	Scenario A1	VAR %
Global warming potential (IPCC GWP 100a)	kg CO_2 eq	2.20E+01	3.02E+01	37.27%
Eutrophication	kg PO_4 – eq	1.52E–01	2.28E–01	50.20%
Abiotic depletion, fossil fuels	MJ	1.40E+02	1.65E+02	18.13%
Water use	m^3	1.13E+01	1.54E+01	35.64%
Freshwater ecotoxicity	CTUe	2.56E+02	2.75E+02	7.53%
Water consumption	m^3	3.44E–01	4.55E–01	32.43%

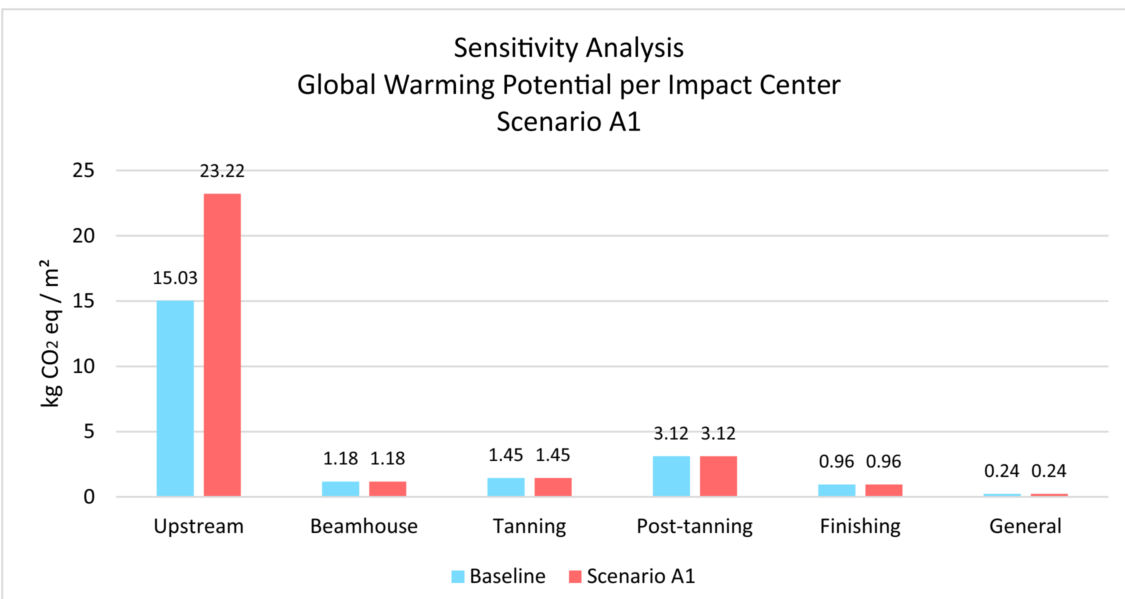

Fig. 7 Effects on Global Warming Potential of Increasing economic allocation comparison by Impact Center (Scenario A1)

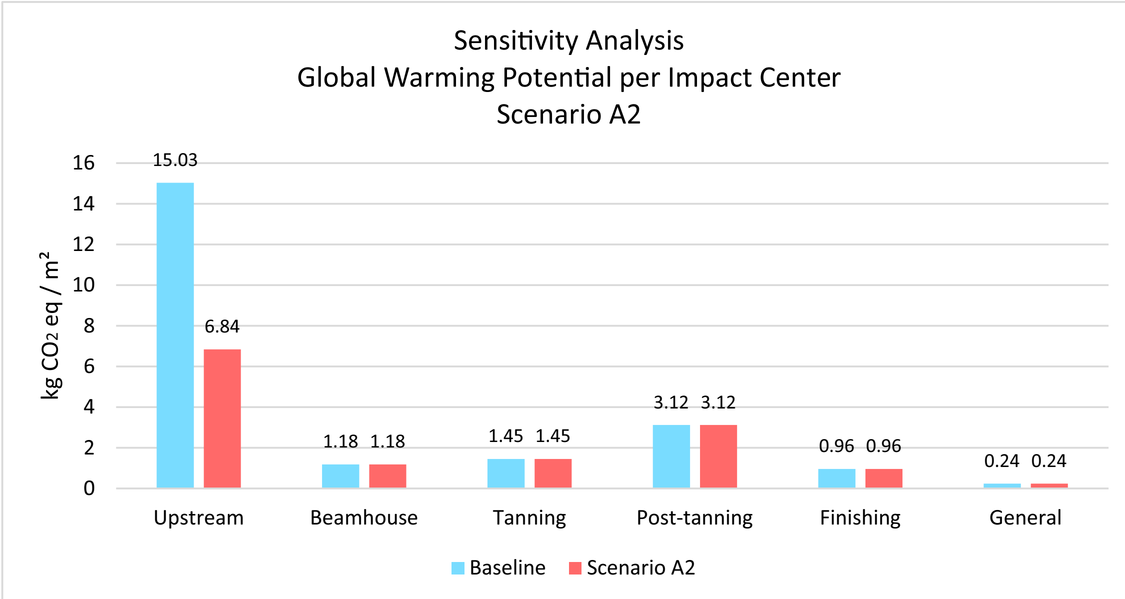

Fig. 8 Effects on Global Warming Potential of decreasing Economic Allocation by Impact Center (Scenario A2)

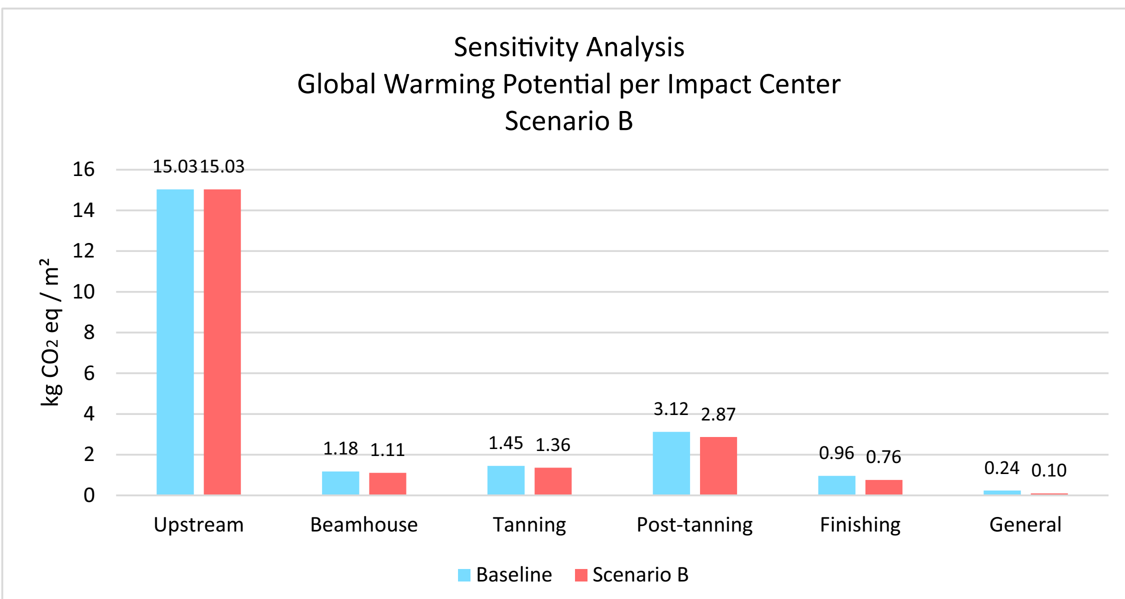

Fig. 9 Effects on Global Warming Potential of 100% renewable energy by Impact Center (Scenario B)

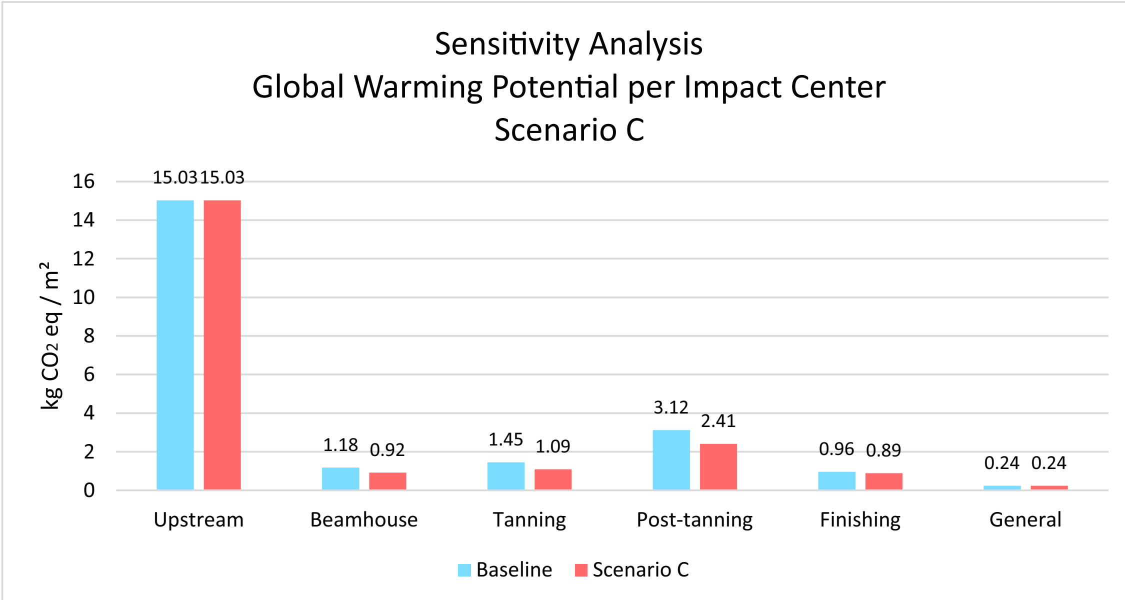

Fig. 10 Effects on Global Warming Potential of reducing the use of chemicals by Impact Center (Scenario C)

Table 13 Sensitivity Analysis – Scenario A2 (Decreasing Economic Allocation) for 1 kg leather (1.0632 m^2) average

Environmental impact	UOM	Baseline	Scenario A2	VAR %
Global Warming Potential (IPCC GWP 100a)	kg CO_2 eq	2.20E+01	1.38E+01	−37.27%
Eutrophication	kg PO_4 − eq	1.52E−01	7.56E−02	−50.20%
Abiotic Depletion, Fossil Fuels	MJ	1.40E+02	1.14E+02	−18.13%
Water Use	m^3	1.13E+01	7.29E+00	−35.64%
Freshwater Ecotoxicity	CTUe	2.56E+02	2.37E+02	−7.53%
Water Consumption	m^3	3.44E−01	2.32E−01	−32.43%

Table 14 Sensitivity analysis—Scenario B (100% Renewables) for 1 kg leather (1.0632 m^2) average

Environmental impact	UOM	Baseline	Scenario B	VAR %
Global warming potential (IPCC GWP 100a)	kg CO_2 eq	2.20E+01	2.12E+01	−3.43%
Eutrophication	kg PO_4 − eq	1.52E−01	1.51E−01	−0.75%
Abiotic depletion, fossil fuels	MJ	1.40E+02	1.32E+02	−5.70%
Water use	m^3	1.13E+01	1.14E+01	0.22%
Freshwater ecotoxicity	CTUe	2.56E+02	2.56E+02	−0.02%
Water consumption	m^3	3.44E−01	3.31E−01	−3.61%

Table 15 Sensitivity analysis – Scenario C (Chemical Dosage Reduction) for 1 kg leather (1.0632 m^2) average

Environmental impact	UOM	Baseline	Scenario C	VAR %
Global warming potential (IPCC GWP 100a)	kg CO_2 eq	2.20E+01	2.06E+01	−6.37%
Eutrophication	kg PO_4−eq	1.52E−01	1.49E−01	−1.90%
Abiotic depletion, fossil fuels	MJ	1.40E+02	1.21E+02	−13.55%
Water use	m^3	1.13E+01	1.06E+01	−6.44%
Freshwater ecotoxicity	CTUe	2.56E+02	1.96E+02	−23.36%
Water consumption	m^3	3.44E−01	3.23E−01	−5.97%

Table 12, Fig. 7; for the scenario A2 in Table 13, Fig.8; for scenario B in Table 14, Fig.9 and for scenario C in Table 15, Fig.10.

3.2 Conclusions of the sensitivity analysis

To understand the dynamics underlying the variations in terms of environmental impact following the setting of alternative scenarios compared to the initial ones, it is appropriate to summarize the results on three different dimensions:

3.2.1 Changes in terms of impact of the six environmental footprint (EF) categories under study

With reference to scenarios A1 (increasing economic allocation by 1 percentage point) and A2 (decreasing economic allocation by 1 percentage point) it can be observed that the most influenced categories are Eutrophication (±53.20%) and Climate Change (±37.27%).

As per the Scenario B (100% switch to renewable energies) the most influenced categories are Abiotic Depletion fossil fuels (−5.70%) and Climate Change (−3.43%), while it can be observed that the Water Use moves upwards (+0.22%) mainly due to the increased use of hydroelectric energy.

Finally, as regards the scenario C (reducing chemicals), the most influenced category are Freshwater Ecotoxicity (−23.36%) and Abiotic Depletion Fossil Fuels (−13.55%) (.

3.2.2 Detail of changes for the category "climate change", at impact center level

In the case of scenarios A1 and A2 (Increasing/Decreasing Economic Allocation), the changes focus solely on the Raw Material emission factors, while all other factors remain unchanged. In the same way, the impact of a different energy mix (Scenario B) only reflects on the impact deriving from the use of Electric Energy. Finally, as per scenario C (Reducing Chemicals), in addition to the reduction in the impact of chemicals (equal to their reduction in dosage), waste is also affected due to a lower production of sludges.

3.2.3 Detail of the changes for the category "climate change" at the environmental aspect level

Also in this case, the scenarios that provide for different economic allocation (A and B) only affect the activities upstream of the tanning ones. As per scenarios B and C, the variation of impact is higher in the departments where the resources under analysis are used most (for chemicals: Tanning and Post-Tanning department; for energy: Post-Tanning and Finishing Dept.).

4 Discussion

This LCA study was carried out to assess the environmental impacts related to production of 56 leather products manufactured by 6 leather groups in multiple supply chain configurations.

For tannery operations, this study was based on high-quality primary data obtained directly from the official documentation of the tanneries involved and complemented by specific measurements of energy (for the specific machinery involved) and wastewater quality (taking samples from the water streams produced from the specific processes involved in the production of the article itself).

The present report adheres to the 14,040 [30] and 14,044 [3] standards and has been critically reviewed [35].

All primary data collected from tanneries refer to the years 2021–2022 and the exact locations where the processes occurred. The datasets used for modeling were obtained as well, referring to the specific location where the environmental aspect was generated.

Primary and verified data were used to measure and calculate the input of rawhides needed to produce 1 kg of finished leather. All technologies involved in the core processes were described in detail, characterized, and modeled according to data collected during on-site interviews, document consultations, and measurement campaigns; therefore, this study properly represents the technologies involved using high-quality primary data.

This study endeavored to obtain exact and typical primary data, but several difficulties were encountered due to the unavailability of characteristic Ecoinvent [2] datasets, most significantly regarding rawhides and chemicals.

The global pandemic caused travel restrictions that limited the possibility of directly interacting with leather technicians and factory personnel and visiting different plants.

Thanks to their relationships with raw material suppliers, tanneries were able to collect primary data referring to the overall supply of hides to the different supply chain configurations, such as mass fractions and economic allocations, obtaining results that were significantly different and more updated than the default ones proposed by the PEFCR-Leather [6].

All the different processes carried out for production were fully characterized by analyzing the official documentation (production recipes) of the companies describing machinery and processes. All transport was accounted for.

Some data related to upstream processes as well as core processes were unavailable (inventory data on farming and water treatment). For the upstream processes, since no primary data were available, and secondary data in the Ecoinvent [2] dataset "Beef co-product, hides and skins, from beef cattle, at slaughterhouse, PEF compliant/IE economic/mass (Agrofootprint)" were used and modified according to the information on mass fractions and economic allocation provided by suppliers.

The characterized results were presented in detail for six impact categories, and the conclusion is as follows:

1. The production of raw hides substantially contributed to the impact of five out of the six categories considered.
2. Chemicals were major contributors to the impact categories, except for Eutrophication.

Another important point is the difference in the relevance of the Beamhouse stage when comparing water use and water consumption. By focusing on water use, the consequences of the fact that multiple beamhouses have water recovery systems in place, effectively reducing the consumption of water, can be seen.

Additionally, the study highlighted the significance of the Post-tanning stage in all the different impact categories studied. This highlights the need to address the nature and use of chemicals in the post-tanning stage in order to reduce the environmental impact of leather.

Software and methodologies are always being updated. Repeating this work in a few years will generate significantly more accurate results, as this research will help to indicate the most impactful process areas and provide an opportunity to reduce this impact. This study also highlights the need for more data gathering and modeling for the different management practices at the farm level and in leather chemistry.

5 Conclusions

The present study with the aggregated data of 56 LCA studies of 16 facilities in 11 countries provided a broad representation of the LCA status of the current bovine leather industry and can hopefully guide future studies. It shows several parameters that are much lower than previous data, particularly the economic allocation of the impact of livestock rearing to the raw material.

The data contains important information for understanding the LCA hot spots and provides insights into the industry regarding the improvements needed in specific process areas.

The numeric findings highlighted the significant relevance of animal farming (Upstream) and chemicals in the environmental impact of the different impact categories. Concomitantly, it made clear the importance of the solid waste management processes to minimize freshwater ecotoxicity.

The Upstream processes were especially pertinent in Eutrophication (91%), Global Warming Potential (68%), Water Use (65%) and Water Consumption (59%). This highlights the importance of the promotion of better farming practices and more accuracy in the datasets available for animal farming.

Representing as much as 44.9% of the source of impacts for Abiotic Depletion, Fossil Fuels and 33.8% for Freshwater Ecotoxicity, the pursuit of lower impact chemicals and decrease in their use through process recipe improvements must continue.

Considering the evidence presented and the collection and analysis of data from multiple products within different tanneries and countries, the findings have the potential to provide a benchmark for continuous improvement in sustainable practices, encouraging ongoing research and incentivizing advancements from farms to tanneries.

The LCA study of the global cow leather industry reveals several important implications for stakeholders. For tanneries, this study highlights areas for improvements, particularly in rawhide production, water use, batch processes in drums, and chemical applications. The findings provide a benchmark for sustainable practices, encouraging ongoing improvements across the industry. Policymakers can use this data to guide regulations on sustainable sourcing and production methods, supporting the adoption of greener technologies. Additionally, consumers can benefit from increased transparency, enabling informed choices that may drive demand for sustainably produced leather.

Author contributions Conceptualization, L.Z.; methodology, F.B.; software, F.B., A.O.; validation, F.B., A.O. and K.S.; formal analysis, F.B. and K.S.; investigation, F.B. and K.S.; resources, K.S.; data curation, F.B. and A.O.; writing—original draft preparation, L.Z.; writing—review and editing, L.Z., A.O. and K.S.; visualization, L.Z.; supervision, K.S.; project administration, L.Z.; funding acquisition, K.S.

Funding This research was privately funded by the following tanneries: ISA TanTec, JBS Couros, PrimeAsia, Rino Mastrotto Group, SADESA, and Scottish Leather Group. This publication was sponsored by Leather Naturally.

Data availability The data is not publicly available because each leather-producing facility has proprietary technology to produce leather and environmental controls. The publication of proprietary data would disclose technological aspects related to chemicals, chemical and physical processes, and machinery. The details of the calculation procedures are confidential, as contractually stipulated. Data are however available from the authors upon reasonable request and with permission of the Funding companies.

Declarations

Competing interests The authors declare no competing interests.

References

1. SimaPro 9.1.0.8. PRé Sustainability, Stationsplein 121, 3818, Amersfoort, The Netherlands; 2020.
2. Ecoinvent 3.6. Ecoinvent, Technoparkstrasse 1, 8005, Zurich, Switzerland; 2019.
3. ISO 14044. Environmental Management - Life cycle assessment - Definition, requirements and guidelines (ISO 14044:2006); 2006.
4. Leather Naturally (2022). Modern Cow Leather Processing. 2022. https://www.leathernaturally.org/ (accessed on December 22, 2024).
5. European Commission Publication. Baseline Approaches for the Cross-Cutting Issues of the Cattle Related Product Environmental Footprint Pilots in the Context of the Pilot Phase 2013–2016, DG ENV A1. Brussels: Belgium; 2016.
6. PEFCR-Leather. Product Environmental Footprint Category Rules, De Rosa-Giglio P, Fontanella A et al. European Commission: Brussels, Belgium; 2018.
7. Mahdi S, Messaoud-Boureghda MZ, Aksas H. Comparative study of environmental impact of three-leather process production by life cycle analysis. Ind J Chem Technol. 2021;28:305–18. https://doi.org/10.56042/ijct.v28i3.43989.
8. Bacardit A, Combalia F, et al. Comparison of the sustainability of the vegetable, wet-white and chromium tanning processes through the life cycle analysis. J Am Leather Chem Assoc. 2020;115:105–11. https://doi.org/10.34314/jalca.v115i03.1628.

9. Barquero G, Sorolla S, et al. Analysis of the Environmental impacts of waterproofing versus conventional vegetable tanning process—a life cycle analysis study. J Clean Prod. 2021;325:129344. https://doi.org/10.1016/j.jclepro.2021.129344.
10. Rosa R, Pini M, et al. Environmental sustainability assessment of a new degreasing formulation for the tanning cycle within leather manufacturing. Green Chem. 2017;19:4571–82. https://doi.org/10.1039/C7GC01900A.
11. Puccini M, Seggiani M, et al. Sustainability in process innovation: development of a green tanning process supported by LCA methodology. J Am Leather Chem Assoc. 2014;109:110–6.
12. Laurenti R, Redwood M, et al. Measuring the environmental footprint of leather processing technologies. J Ind Ecol. 2017;21(5):1180–7. https://doi.org/10.1111/jiec.12504.
13. Castiello D, Puccini M, et al. Life Cycle Assessment (LCA) of the oxidative unhairing process by hydrogen peroxide. J Am Leather Chem Assoc. 2008;103(1):1–6.
14. Shi J, Puig R, et al. A comprehensive evaluation of physical and environmental performance for wet-white leather manufacture. J Clean Prod. 2016;139:1512–9. https://doi.org/10.1016/j.jclepro.2016.08.120.
15. Ingrao C, Vesce E, et al. Chemical behind leather: Life Cycle Assessment of nano-hydroxyapatite preparation lab-scale for fireproofing application. J Clean Prod. 2021;279: 123837. https://doi.org/10.1016/j.jclepro.2020.123837.
16. Tasca A, Puccini M. Leather tanning: life cycle assessment of retanning. Fatliquoring and Dyeing J Clean Prod. 2019;226:720–9. https://doi.org/10.1016/j.jclepro.2019.03.335.
17. Yu Y, Lin Y, et al. Life Cycle Assessment for chrome tanning, chrome-free metal tanning and metal-free tanning systems. ACS Sustain Chem Eng. 2021;9(19):6720–31. https://doi.org/10.1021/acssuschemeng.1c00753.
18. Chen KW, Lin LC, Lee WS. Analyzing the carbon footprint of the finished bovine leather: a case study of aniline leather. Energy Procedia. 2014;61:1063–6. https://doi.org/10.1016/j.egypro.2014.11.1023.
19. Rivela B, Moreira M, et al. Life Cycle Assessment as a tool for the environmental improvement of the tannery industry in developing countries. Environ Sci Technol. 2004;38(6):1901–9. https://doi.org/10.1021/es034316t.
20. Chowdhury Z, Ahmed T, Hashem A. Materials and energy flow in the life cycle of leather: a case study of Bangladesh. Mater et Tech. 2017;105:502. https://doi.org/10.1051/mattech/2018013.
21. Chowdhury Z, Ahmed T, et al. Environmental life cycle assessment of leather processing industry: a case study in Bangladesh. J Soc Leather Technol Chem. 2018;102:18–26.
22. Kiliç E, McLaren S, et al. Product environmental footprint of new zealand leather production. Int J Life Cycle Assess. 2023;28:349–66. https://doi.org/10.1007/s11367-023-02143-3.
23. Llorenç M, Xavir D, et al. Pere, F. Use of Life Cycle Assessment in the procedure for the establishment of environmental criteria in the Catalan ECO-label of leather. Int J Life Cycle Assess. 2002;7:39–46. https://doi.org/10.1007/bf02978908.
24. Ulya M, Arifuddin A, Hidayat K. Life Cycle Assessment of Cow Tanned Leather Products. IOP Conference Series: Earth Environ Sci. 2021;757:1. https://doi.org/10.1088/1755-1315/757/1/012066.
25. Kılıç E, Puig R, et al. (2018) Corporate carbon footprint for country climate change mitigation: a case study of a tannery in Turkey. Sci Total Environ. 2018;1:1. https://doi.org/10.1016/j.scitotenv.2018.04.111.
26. Navarro D, Wu J, Lin W, et al. Life cycle assessment and leather production. J Leather Sci Eng. 2020;2:26. https://doi.org/10.1186/s42825-023-00121-x.
27. Chen M, Duan Y, Dong L, et al. Country-level life cycle assessment of carbon footprint in processing of bovine upper leather. J Am Leather Chem Assoc. 2019;114:194–203.
28. Yang H, An D, et al. Life Cycle Assessment of Processing Chrome Tanned Cowhide Upper Leather. Leather Footwear J. 2021;21(2):75–86. https://doi.org/10.24264/lfj.21.2.1.
29. EPD® System 3.1, EPD International AB, Valhallavägen 81, SE-11427 Stockholm, Norway; 2019.
30. ISO14040 (2006) Environmental Management - Life cycle assessment - Principles and framework (ISO 14040:2006).
31. Spin 360. LCA Consulting Company, Piazzale Luigi Cadorna, 9, 20123, Milano, LOM, Italy. Available online: https://spin360.biz/ (Accessed on 28 December 2023)
32. Santonja G, Karlis P. Developing environmental standards for the food, drink, and milk industries: key environmental issues and data collection. Environ Sci Eur. 2020;32:152. https://doi.org/10.1186/s12302-020-00431-5.
33. Carretero A, Rosa J, Sánchez-Rodas D. Applying statistical tools systematically to determine industrial emission levels associated with the best available techniques. J Clean Prod. 2016;112(5):4226–36. https://doi.org/10.1016/j.jclepro.2015.06.037.
34. ILCD Handbook: General guide for Life Cycle Assessment - Detailed guidance, JRC, EUR 24708 EN – 2010
35. Carlo Brondi, Cnr-STIIMA, https://www.researchgate.net/profile/C_Brondi
36. Our World in Data: https://ourworldindata.org/grapher/electricity-production-by-source