Environmental Impact Analysis of Different Leather Tanning Methods to Optimize Eco-Friendly Process Selection

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ABSTRACT

In response to growing demands for environmental transparency in the leather industry, this study compares three tanning processes—chrome, vegetable, and triazine—through a harmonized Life Cycle Assessment (LCA). Based on primary data from laboratory and industrial scales, results show that chrome tanning has the lowest carbon impact, while vegetable and triazine systems perform better in toxicity-related categories. Sensitivity and uncertainty analyses reveal that leather thickness, chemical formulation, and production scale are key drivers of impact variability.

Keywords: leather, tanning, Life Cycle Assessment, chrome-free, uncertainty, variability

1. Introduction

Environmental performance is becoming a central concern in leather goods, where production processes must align with sustainability without compromising product quality. Among these processes, tanning has a major influence on the environmental profile of leather due to its use of water, energy, and chemicals. While chrome tanning remains dominant, alternatives such as vegetable and triazine-based systems are gaining attention. However, comparing their environmental profiles remains complex due to differences in formulations, process scales, and data quality.

Life Cycle Assessment (LCA) is a standardized tool for evaluating environmental impacts. Previous studies have highlighted the potential of LCA to inform more sustainable leather production (Daddi et al. 2016; Laurenti et al. 2016; Pasquale et al. 2024). Yet many assessments lack consistency in system boundaries, impact indicators, or data transparency, limiting their comparability. This study addresses these gaps by applying a harmonized LCA approach to three tanning systems, integrating industrial and lab-scale data and including both deterministic and probabilistic sensitivity analyses.

2. Materials and Methods

2.1 Goal and Scope

The objective is to compare the environmental performance of three tanning technologies and to identify the main factors affecting the robustness of LCA results. The technologies studied are:

- Chrome tanning (mineral-based)
- Vegetable tanning (plant extracts, with a synthetic pre-tanning)
- Triazine tanning (synthetic)

2.2 Functional Unit and Boundaries

The functional unit is 1 m^2 of finished bovine leather used in leather goods, with a 10-year lifetime (Thomasset and Benayoun 2024). The system boundaries start from pickling and include tanning, wet-end processes (dyeing, fatliquoring, retanning), and related inputs/outputs. Beamhouse and finishing stages are excluded.

2.3 Inventory Data

Primary data were collected over two years from five industrial tanneries and one lab. All chemicals were recorded with dosage, type, and active content. Water and energy use were measured separately for process and technical uses.

2.4 Impact Assessment

The EF 3.1 method and database were used, as recommended by the PEFCR Leather guidelines (CE 2018). Impact categories include 16 environmental impact categories such as climate change, fossil and mineral resource use, human toxicity, water use... Calculations were performed in SimaPro (PRé Sustainability 2023).

3. Results and Discussion

3.1 Environmental Profiles and Breakdown by Category

It is not possible to rank the three tanning systems based on their global environmental score because the minimum and maximum values overlap significantly across technologies, making any general conclusion unreliable. When disaggregating the results by individual impact categories, chrome tanning performs best in terms of climate change and fossil resource use due to shorter process duration and lower chemical load, but it has higher impacts in mineral resource use and toxicity. Conversely, vegetable and triazine tannings show lower toxicity scores but higher climate and energy-related impacts. These patterns are consistent with those reported in earlier studies (Bacardit et al. 2020, Laurenti et al. 2016; Daddi et al. 2016). Table 1 shows minimum, average, and maximum values for the tanning/wet-end steps, and Table 2 presents the impact distribution by damage category for each technology.

Table 1. Impacts (µPt) in global score by tanning method per 1 m² of leather

	Min	*Average*	*Max*
Chromium	357	462	577
Triazine	470	528	587
Vegetal	488	593	697

Table 2. Environmental impact scores (µPt) by category and tanning method

Catégorie de dommages	***Chrom. Aver.***	***Chrom. Min***	***Chrom. Max***	***Triazine Aver.***	***Triazine Min***	***Triazine Max***	***Vegetal Aver.***	***Vegetal Min***	***Vegetal Max***
Ressources, min. et métaux	176	101	195	17	14	20	48	43	52
Changement climatique	84	70	99	162	139	186	176	138	214
Ressources fossiles	75	66	84	139	115	163	160	127	193
Toxicité humaine, cancer	41	31	49	11	8	14	18	14	22
Particules dans l'air	31	24	41	53	46	61	51	41	61
Utilisation de l'eau	17	11	24	27	24	30	31	23	40
Écotoxicité, eaux douces	19	12	26	27	24	29	25	21	29

To further explore the results, the environmental impacts were disaggregated by process steps. Whether in laboratory or industrial settings, chemical inputs emerged as the dominant source of impacts, followed by energy consumption during processing and effluent treatment. At the laboratory scale, chemicals inputs accounted for at least 70% of the total impact, while in industrial settings their contribution ranged between 86% and 89%. These findings are consistent with those of Pasquale et al. (2024), who identified the chemical load as the principal environmental hotspot in leather manufacturing. These results underline also the importance of analyzing both tanning and wet-end steps together. Focusing on only one can obscure key environmental trade-offs between technologies.

3.2 Drivers of Variability

A deterministic sensitivity analysis was conducted to assess the influence of various parameters on the environmental results. The maximum deviations reported in Table 3 are calculated within each tanning technology (chrome, triazine, or vegetable), not across technologies.

Table 3. Maximum observed deviation (%) for global and carbon footprint scores

	Global score	*Carbon footprint*
proxy	2	4
Energy mix by country	3	6
Between industrial sites	5	4
Formulations	28	26
Uncertainties	31	24
Lab vs industrial sites	57	10
Thickness	66	63

These results confirm that, although methodological harmonization is crucial, variations in operational parameters can significantly impact results. Leather thickness stands out as the most influential factor, followed by production scale, input data uncertainty and formulation diversity. These four sources contribute most to the observed variation across global and climate scores. In contrast, inter-site variability, national electricity mix, and the use of proxy data have a relatively minor effect in this study. This reinforces the importance of clearly defining the system and reporting key variables such as thickness and production scale to ensure robust comparisons between tanning technologies.

4. Conclusion

This study provides a robust comparative assessment of three leather tanning systems—chrome, vegetable, and triazine—using harmonized Life Cycle Assessment. The results highlight the challenge of ranking technologies based on overall impact due to high variability within each system. However, a breakdown by impact category reveals that chrome tanning generally performs better on climate-related indicators, while vegetable and triazine systems show advantages in toxicity-related impacts. Sensitivity analyses identify leather thickness, formulation choices, and scale effects as primary drivers of variability.

These findings underline the importance of clear functional definitions, consistent methodological choices, and representative data sets when conducting comparative LCAs. In particular, including both tanning and wet-end steps is essential to avoid misleading conclusions. Efforts to improve environmental performance should prioritize thickness and chemical formulation optimization, as these are the most actionable and impactful levers for eco-design. Both parameters directly affect the amount of chemicals used, which represent the main source of environmental impacts in tanning and wet-end processes. In contrast, acting on production scale is less relevant since industrial conditions are the ultimate goal, and uncertainty from background data is unavoidable to some extent.

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