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Review

Leather sustainability, an industrial ecology in process

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Abstract

Leather production is a historic industry that still has an economic influence throughout the world. Leather making is done following a sequence of complex chemical and mechanical steps, using energy, quantity of water and chemicals, and generating waste. For several decades, many organizations have been working toward a cleaner tannery industry resulting in better practices, saving energy and water, and increasing wastewater treatment efficiency. Solid waste management remains a big issue. Another question posed today is the use of chromium in tanning. It is why a lot of research is now dedicated to metal-free tanning solutions. Chromium alternatives exist but none can actually rival all the advantages of chromium and a balance must be found with environmental issues. To measure the environmental performance of leather, several tools are available. The LWG (Leather Working Group) audit is one of them. On the side of consumers, some reliable leather ecolabelings exist. Finally, life cycle assessment (LCA) is the most exhaustive tool for characterizing leather's environmental performance. Numerous LCA studies done in the past two decades underline the difficulty in obtaining general results, considering the large variety of processes used depending on tanneries, localization, and raw materials. In addition, the data available for LCA are still poor in regard to the specific data needed for leather chemicals. The best methods associated with new technologies, audit, and labeling lead leather production into a cleaner and environment-friendly industry.

KEYWORDS

clean technology, industrial ecology, leather environmental impact, leather processing, sustainable leather production, tanning processes

1 | INTRODUCTION

Leather is one of our earliest and most useful discoveries, adding value to a high-quality renewable natural resource coming from food needs. The first record of tanning leather formulas is credited to Sumerian pictographs around 750 B.C., using oil, alum stone, and vegetable tannins. Even then, it is known that it has existed for a long time (Halasz Csiba, 2001). Vegetable tanned leathers still exist today, and above all, vegetable tannins are active components in the modern tanning process (especially in retanning operations). The 19th and 20th-century industrialization led to a

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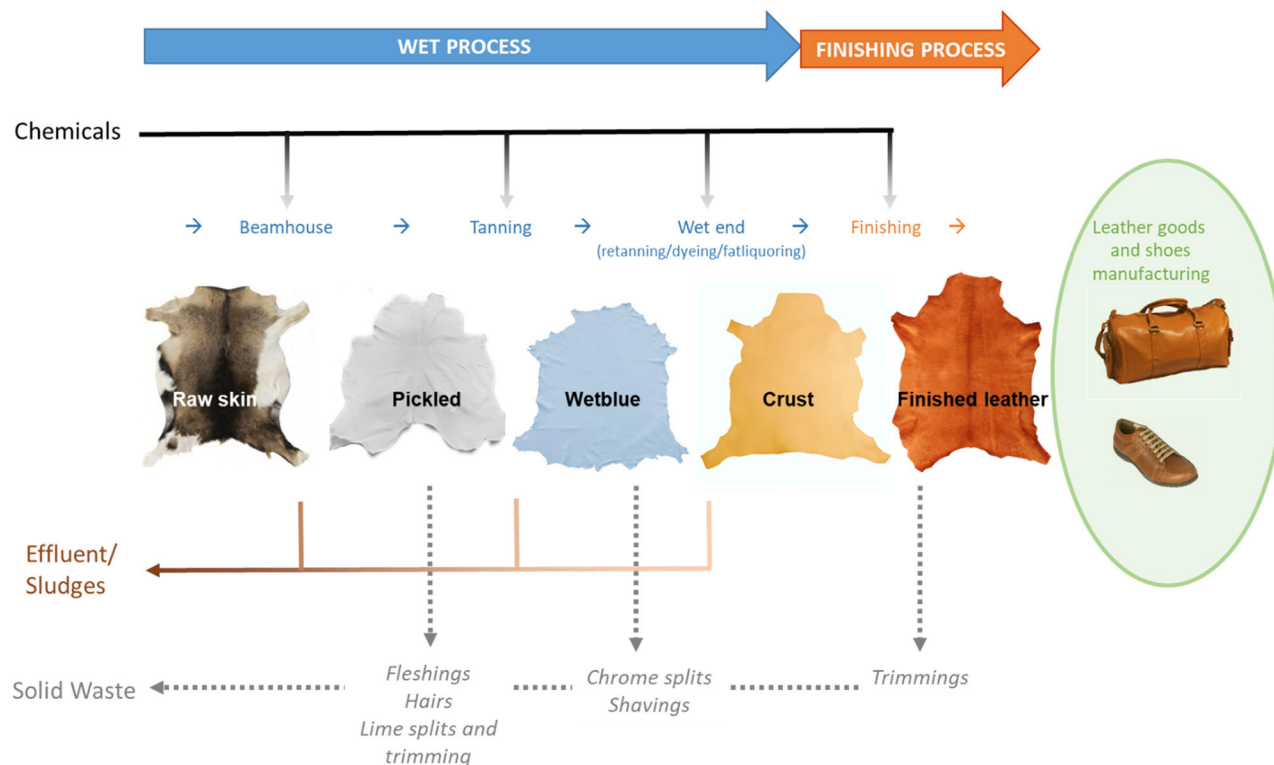


FIGURE 1 Leather processing schema.

demand for softer, lightweight leathers with a fashionable appearance, fulfilled by chromium salt technology, now the industry standard for modern leathers. Leather continues to be a material of choice; it is one of the most widely traded commodities in the world, with a global trade value of approximately US\$100 billion per year (leather and leather products industry). The world population continues to grow and the demand for meat increases, keeping the supply of leather raw material fairly constant (UNIDO, 2010).

Historically, the global tanning industry centered on small- to medium-sized family businesses near slaughterhouses. In the last three decades, leather production shifted to cheaper labor markets, leading to the decline of European tanners. The tanneries that have remained viable in Europe have built clever business models, some of them entering into international alliances and others whole or partly integrating luxury brand groups with very high levels of creativity and quality. With 25% of the world's leather production, Europe remains an important player in the international leather trade, with a turnover of nearly US\$8.5 billion, and with over 3000 companies and some 50,000 people directly employed in the sector (COTANCE, n., d.).

Advances in technology, legislation, standards, corporate social responsibility, and consumer demands must be now taken into account for the restructuring of the sector toward environmental improvements. At the same time, "synthetic leathers" improve and there are no more sectors in which leather cannot be more or less replaced by other materials. It is why, today more than ever, research and development are of extreme importance (Meyer et al., 2021).

The leather industry faces environmental challenges, but there is a need for comprehensive reviews that synthesize existing knowledge on best practices and environmental impact. It is important to clarify that our aim is not to conduct new studies but rather to synthesize existing knowledge and provide insights to support future research endeavors in this field. The calculated data presented in this review are largely based on the BAT reference document (best available techniques) from The European Commission (JRC Reference Reports, 2013). To have a more representative idea, some data were converted to refer to one square meter of finished leather (see Supporting Information S1).

2 | LEATHER PRODUCTION PROCESS

The transformation of raw hides into leather involves an intricate series of chemical and mechanical steps, with each step representing a distinct process in itself (cf. Figure 1). The initial stage in the tannery occurs in the beamhouse and encompasses curing, storage, sorting, trimming, soaking, dehairing, liming, fleshing, deliming, and bating. The goal of such operations is to deep clean the raw material to get a clear collagen structure and give softness and flexibility to the hide. Then, in the tanyard, skins are pickled and tanned. The pickling makes the hide fibers more receptive to

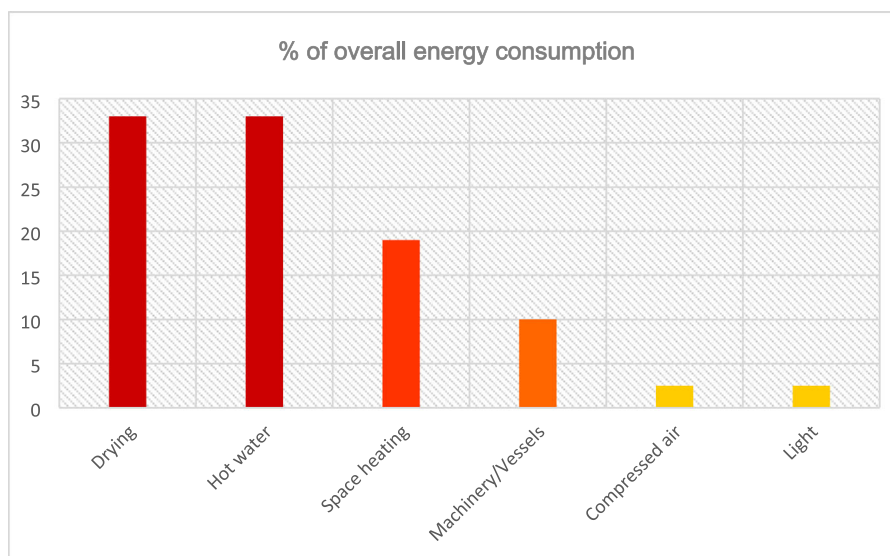


FIGURE 2 Distribution of tannery energy consumption based on “The framework for sustainable leather manufacture” (UNIDO, 2019); see Supporting Information S4.

tanning by increasing the acidity and enabling chromium and synthetic tannins to enter the hide. The tanning stabilizes the collagen ensuring rot-proof properties and making leather suitable for a wide variety of end applications. For this tanning operation, mineral, synthetic, and/or vegetable tanning agents are used. Basic chrome salt (chromium III) remains the most frequently used, and more than 80% of leather in the world is produced this way (Joseph & Nithya, 2008). The wet-end operations involve fatliquoring (to get soft leather), dyeing, and adding extra tanning agents to make the leather’s feel and physical properties uniform, matching the consumer demand. Finally, the finishing operations consist of a colored varnish applied at the surface to upgrade material by covering defects, protecting the surface (increasing properties such as light, rub, and perspiration fastness), and bringing fashion to the leather (color and color effects, structure and grain, glossy or dull, touch) (Tasca & Puccini, 2019).

3 | ENVIRONMENT IMPACT OF LEATHER PROCESSING TECHNOLOGIES

Tanning, criticized by environmental NGOs for its use of harmful chemicals, has drawn attention through reports, TV features, and web publications (Pure Earth, Green Cross, 2016). While this scrutiny mainly focuses on a segment of the industry in low- and middle-income countries lacking robust environmental regulations, it underscores the imperative to effectively manage the tannery sector for consumer confidence in leather products. Obtaining an “average” or indicative measure proves challenging due to diverse raw materials, end uses, and leather-making approaches. However, literature, especially on chromium-tanned bovine hides, indicates that processing 1 m² of finished leather entails substantial water and chemical usage, alongside significant solid waste generation (UNIDO et al., 2019).

3.1 | Energy consumption

The energy consumption, using thermal and electric sources can vary greatly between tanneries and the category of the energy source is also very relevant—fossil fuel, nuclear, renewable, or self-generated renewable. The total consumption of the entire process for 1 m² of bovine-finished leather can reach 0.31 GJ. The drying operation of leather at the end of the wet process and the production of hot water consume generally most of the energy in the entire plant (cf. Figure 2).

3.2 | Solid waste

Concerning raw material, around 7.4 kg of salted bovine hide is needed for 1 m² of finished leather weighing around 1.5 kg. This means that more than 75% of the raw material becomes waste during the tannery process. It means that each year, around 4 million tonnes of solid wastes are generated by leather industries throughout the world. Around 40% of raw material mass is constituted by salt for preservation, which is eliminated during the first step of the process in wastewater. Hair and natural fats are generally dissolved and end up in wastewater and sludge. The other solid

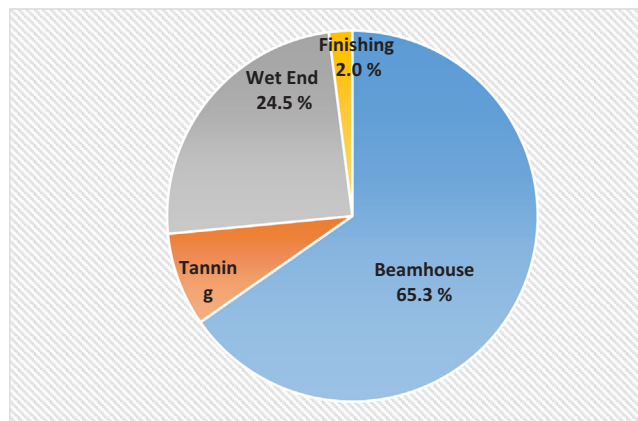


FIGURE 3 Distribution of tannery water consumption based on “The framework for sustainable leather manufacture” (UNIDO, 2019); see Supporting Information S4.

wastes include lime fleshings, split and trimmings, then wet-blue split, trimmings and shavings, and finally mixed waste such as finished and dyed cuttings. All these solid wastes are mainly landfilled or incinerated, but some local solutions could exist (Koppiahraj et al., 2019).

3.3 | Water and chemicals consumption

All the wet process operations are performed in water. Hides soak in chemical baths in the form of drums (rotary vessels) using mechanical agitation between hides and liquids. In this way, a huge quantity of water is required during the entire process. Up to 370 L of water can be used for 1 m² of bovine finished leather. Unsurprisingly, the majority of this consumption is coming from the beamhouse, as illustrated in Figure 3.

Leather processing involves a diverse array of chemicals, some used for treatment and others penetrating the skin, persisting in the final product. UNIDO & Buljan J calculated a mass balance revealing that out of 1000 kg of raw skins, 452 kg of chemicals are added. Only 72 kg remain in the finished leather, with the rest contributing to waste, yielding around 420 kg of sludge with a 30% solid content (UNIDO & Buljan, 2000).

The resulting wastewater is characterized by elevated levels of chemical oxygen demand (COD), biological oxygen demand (BOD), total dissolved solids (TDS), total suspended solids, chromium (III), and phenolic concentrations. This wastewater exhibits a high pH, strong odor, and dark brown color. Primary pollutants include chromium, tannins, phenolic compounds, phthalates, and azo dyes, with varying toxicity to humans, animals, or plants (Saxena et al., 2016). Due to high concentration and low biodegradability, tannery wastewater poses a significant environmental concern, necessitating proper treatment before final discharge. For perspective, wastewater from 1 tonne of raw bovine hides includes about 240 kg of COD, 100 kg of BOD, 150 kg of suspended solids, 170 kg of sodium chloride, 80 kg of sulfate, 10 kg of sulfide, and 5 kg of chromate (Tasca & Puccini, 2019). Pollution is not evenly distributed, with the beamhouse and tanning steps being major contributors.

4 | THE CURRENT SOLUTIONS FOR A CLEANER TANNERY INDUSTRY

Numerous agencies, organizations, and industry players at global, European, and national levels have dedicated decades to enhancing practices and mitigating environmental impacts (cf. Figures 6 and 7) (Dixit et al., 2015).

BREF or “BAT reference document” (best available techniques) is published by The European Commission. This document is drawn up for the tannery industry, by “describing applied techniques, present emissions and consumption levels, techniques considered for the determination of best available techniques as well as BAT conclusions and any emerging techniques” (JRC Reference Reports, 2013; UNIDO, 2011, 2016). Another player is the International Union of Leather Technologists and Chemists Societies, IULTCS, a worldwide organization of professional societies. Its IUE (International Union of Environment) Commission with representation from nearly 30 countries has developed technical guidelines for environmental protection aspects based on the field developments and experiences in different countries (CSIR, 2021; IULTCS, 2017, 2018d). BAT and IUE documents are globally referred to for guidance on what can be considered a cleaner tanning industry. The United Nations Industrial Development Organization (UNIDO), a specialized agency of the United Nations that promotes industrial development with environmental sustainability, is also an important player in this area, increasing the dissemination of the BAT and IUE reports, supplementing them with field studies and data from outside the European Union (UNIDO et al., 2019). All these organizations are actively engaged in addressing the major areas of concern, which include water and energy consumptions, effluent treatment, and solid wastes management.

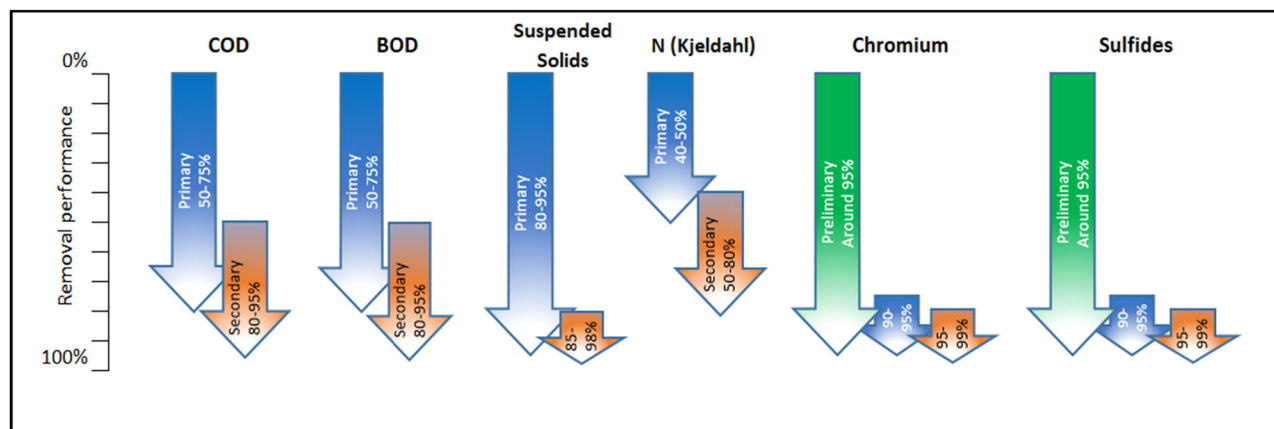


FIGURE 4 Typical performance for tannery waste water treatment based on IULTCS (International Union of Leather Technologists and Chemists Societies) reports (IULTCS, 2018e).

Reduced water and energy consumption can easily be obtained by better management and installing permanent metering in the workshops. Concerning energy, correct mechanical dewatering (sammig) can decrease substantially the quantity required. For water consumption, some practices must also change. Running water washes are one of the major sources of water wastage and must be replaced by batch washes. With modern equipment, it is possible also to work with a short float technique (reduction in water and chemicals with better mechanical action). A combination of batch washing and short floats can generate up to 70% savings during the first steps, compared with a conventional process. To reach beyond these guidelines, it is possible to manage the reuse of individual floats or treated wastewater. Lime washes, water from pickle/chrome tan, can be recycled with specific equipment for collecting, cleaning, and monitoring them (CSIR, 2021; Daniels et al., 2019; IULTCS, 2018c; Kanagaraj et al., 2008) When the water consumption decreases, wastewater decreases, but it means that effluent will become more concentrated and the treatment could be more difficult, and an appropriate balance must be found.

Concerning effluents, the treatment of tannery wastewater is by now a well-established technology (Zugno, 2022). It is a multi-stage process to purify wastewater before discharging it back into natural water bodies or on land, or reusing it. In general, wastewater is treated by a preliminary treatment (to remove large particles and to reduce the content of chrome and sulfides), a primary (physical-chemical) treatment (to remove settleable organic and inorganic solids by sedimentation, and floating materials by skimming), and then a secondary (biological) treatment (to remove biodegradable dissolved and colloidal organic matter using aerobic biological treatment processes). An advanced (tertiary) treatment can be added to reduce residual COD load and/or to remove some specific components. Always tailored to the requirements of a specific site, each effluent treatment plant must adhere to discharge standards promulgated by the relevant environmental authority. This is why, despite the existence of highly optimized processes, the lack of regulations in some countries could cause serious environmental damage. In developed nations, wastewater treatment plants are quite efficient as illustrated in Figure 4. However, two issues still pose serious challenges: the high TDS (salinity) content, unaffected by treatment (desalination by reverse osmosis is possible but is still very expensive), and the disposal of treatment plant sludge, the same issue as with other solid wastes. It should however be noted that some industrially proven low-waste advanced methods exist: using salt-free preserved hides, hair-saving liming, low levels of ammonia or ammonia-free deliming and bating, and using advanced chrome recycling systems. This way, the pollution load before treatment could be significantly reduced: COD/BOD by more than 30%, sulfides by 80%–90%, ammonia nitrogen by 80%, total Kjeldahl nitrogen by 50%, chlorides by 70%, sulfates by 65%, and chromium by up to 90% (CSIR, 2021; IULTCS, 2018a; Kanagaraj et al., 2015; Sivakumar et al., 2005; Sundar et al., 2013; UNIDO, 2016).

Another issue for the cleaner tannery industry concerns solid wastes management (cf. Figure 5). Today a large proportion of the total leather waste is still sent to landfills or incinerated, and this results in significant economic and environmental losses (Koppiahraj et al., 2019). This is why a lot of research is currently aimed toward material or energy recovery. The leather recovery method is often dependent on the stage in the life cycle at which the waste is generated. Indeed, waste coming from un-tanned leather (trimmings, fleshings, and limed splits) is generally more easily recycled. Several recovery options exist. These include methane production, grease and protein recovery, composting and fertilization, and gelatin production. After tanning, and especially after chromium tanning, the presence of metallic components and the risk of the release of harmful chemicals limit the recovery solutions. One of them is a mechanical method, such as the fragmentation of wastes into small particles for incorporation into natural or synthetic polymers to produce recycled materials, such as leatherboard. Another way is the thermal method, including brick manufacturing or cement and asphalt production.

Anyway, existing commercial lines based on current recycling technologies are not sufficient for processing waste generated by the production of leather. There are two possibilities to overcome this challenge: to develop new recycling ways for leather or to adapt leather for an easier recovery (CSIR, 2021; IULTCS, 2018b; Pringle et al., 2016; Shaw et al., 2022; UNIDO, 2017a)

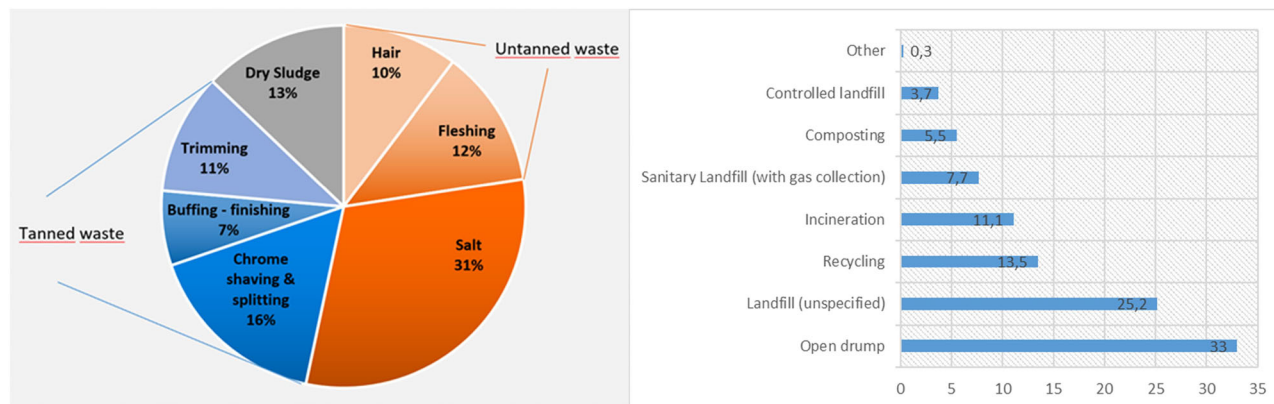


FIGURE 5 Example of distribution (%) of tannery waste during process and worldwide distribution (%) of treatment and disposal for tannery waste (Koppihraj et al., 2019); see Supporting Information S4.

Solid waste treatment is connected to many discussions on leather biodegradability. Several standards exist to check biodegradability. The standards ISO 16929 and ISO 20200, usually used for plastics, could determine the degree of disintegration of leather under defined composting conditions in a pilot-scale test or a laboratory-scale test (ISO 2021, 2023). The result for such experiences on leather is a relative biodegradation for all kinds of leather with a commonly quoted time of 0.05 to 45 years. The type of tanning, the finished composition, and the thickness affect leather disintegration. Several studies highlight a better disintegration of synthetic tanned leather, even if chromium leather has relatively good results. Vegetable leather needs a longer time to disintegrate (Lety, 2021; Lety & Bezon, 2021; Zugno, 2022). A specific leather standard exists, ISO 20136, based on the determination of degradability by microorganisms (CO₂ release) (ISO, 2020). Nevertheless, an important aspect of biodegradability is the quality of the compost obtained. In the plastic industry, for example, the standard EN 13432 requires that materials do not contain elements such as chromium (AFNOR, 2000). The standard ISO 18763 determines the toxic effects of pollutants on germination and early growth of higher plants, but no results on leather are currently available (ISO, 2016). New biodegradability studies are being carried out now, and some new data will be provided in the current years (Dhayalan et al., 2007; Guida et al., 2019; INESCOP, 2022).

5 | FINDING ALTERNATIVES TO CHROMIUM: FUTURE CHALLENGE FOR THE LEATHER INDUSTRY

Chrome tanning remains a dominant leather processing method due to its efficiency in forming robust bonds with collagen, creating durable leather for various applications. The tanning agent, basic chromium sulfate, is derived from chromite ore, posing challenges in waste treatment and recovery due to its metallic components (Clare & Flowers, 2022). At the same time, public awareness of the environmental and health impacts associated with hexavalent chromium (Cr VI) exposure has led to regulations in the European Union, the United States, China, and other nations (Fontaine, 2017). Despite Cr VI not being intentionally used in leather production, its formation through the oxidation of chromium III compounds in the tanning process raises concerns (Lenntech, n., d.; Panda et al., 2016).

In response, efforts are underway to explore alternatives to chromium tanning, with a focus on vegetable and non-chrome methods. However, terms like “chrome-free,” “metal-free,” “biodegradable,” or “natural” require scrutiny, as some communications lack a rational scientific basis (Laurenti et al., 2016). An overview of industrial or under-development chromium alternatives will be presented here.

5.1 | Vegetable tanning

Vegetable tannins are present in wood, bark, leaves, and the fruit of plants (Diaz, 2000; Franca, 2001; Silvateam, n., d.). Vegetable tanning is an old technology, but lots of changes have been made, and many new features have been added. Today several processes coexist. A very small part of the production is still completely “vegetable.” Most vegetable leathers are in reality made with a mix of synthetic and vegetable tanning agents. Indeed, traditionally, the time required for processing pure vegetable leather is around 18 and 24 months. The use of extracts in place of barks and processes in rotary drums instead of or in addition to static tanks makes the production quicker, 1 or 2 months (Simon, 2002). It is still too long to be competitive for a large-scale usage of leather. Another problem is the huge quantity of vegetable tannins required to get a correct tanning. While about 8 g of chromium salt is enough quantity to tan 100 g of leather, 30 g at least is required with vegetable tannins. Eventually, the main way to get vegetable leather is a synthetic pre-tanning step. In this way, the process does not exceed 48 h. In this case, tanning agents such as glutaraldehyde, polyphenolics, or naphthalene are currently used (Simon, 2002). Concerning vegetable agents, the most frequently used are black






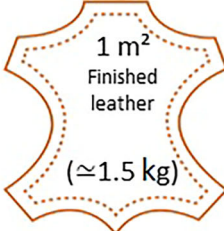




Input	Conventional process worst-case scenario	→ Advanced existing tannery
	≈ 7.41 kg of raw salted hide	→ To reduce or remove the salt quantity
	≈ 370 liters of water	→ ≈ 163 liters
	≈ 3.7 kg of chemicals	→ ≈ 3.1 kg Replacement of hazardous
	≈ 0.31 GJ	→ ≈ 0.07 GJ
		
Output	Conventional process	→ Advanced existing tannery
	 1 m ² Finished leather (≈ 1.5 kg)	
	≈ 370 liters of wastewater ≈ 3.71 kg of sludge	→ ≈ 163 liters → ≈ 2.05 kg sludge
	Solid wastes: ≈ 5.41 kg	→ To increase recycling 
	≈ 70 g organic solvent	→ ≈ 10 g

FIGURE 6 Estimation of pollutants generated in conventional and advanced leather processing based on BAT (best available techniques) (JRC Reference Reports, 2013); see Supporting Information S1.

wattle, quebracho, and chestnut. Black wattle comes mainly from South Africa and Brazil, quebracho from South America, and chestnut mainly from Europe. These resources are more or less renewable. For example, quebracho raises questions concerning environmental issues. This is because tanning agents are found within the core of trees that are a minimum of 80 years old and for which the felling is required (Gori, 1999). Apart from the fact that properties of vegetable leather are very specific and cannot match all fields covered by leather, the replacement of chromium by classic vegetable tannins seems difficult due to the insufficient availability of these resources and higher prices than equivalent synthetic molecules (Covington, 2019; International Trade Centre, n., d.).

New vegetable tannins, particularly those derived from waste produced by the agro-food sector such as apple, mango, grape, banana bunch, bagasse, or rhubarb waste, are emerging in the market. While these products react with collagen similarly to traditional tanning agents, their use could potentially reduce the overall environmental impact due to their origin from waste materials. Wastes from the olive oil industry are a special case. Indeed, oleuropein is a natural product, a secoiridoid glycoside, found in privet and olive vegetation, where its function is part of the self-defense mechanism against infections and herbivores. After activation, oleuropein can react with collagen as a synthetic aldehyde tannin (Antunes

Area of concern	The proposed actions	Sources
Water consumption	Permanent metering in workshop	JRC Reference Reports, 2013 IULTCS, 2018a UNIDO et al., 2019 CSIR, 2021
	To replace running washes by batch washes	JRC Reference Reports, 2013 UNIDO et al., 2019
	To work with short float technique	JRC Reference Reports, 2013 IULTCS, 2018a UNIDO et al., 2019
	To reuse of individual floats	JRC Reference Reports, 2013 Daniels R. et al., 2019 IULTCS, 2018b, 2018a UNIDO et al., 2019 Sivakumar V et al. CSIR, 2021
	To treat and to reuse wastewater	JRC Reference Reports, 2013
Chemicals consumption	To obtain a better exhaustion	JRC Reference Reports, 2013 IULTCS, 2018a UNIDO et al., 2019 Sundar V.J. et al., 2013 CSIR, 2021
Effluent	To use salt-free preserved hides (to decrease TDS)	JRC Reference Reports, 2013 Kanagaraj J et al., 2008 IULTCS, 2018b, 2018a CSIR, 2021
	Mechanical or manual removal of salt from hides	JRC Reference Reports, 2013 IULTCS, 2018b, 2018a CSIR, 2021
	To do hair-saving liming (to decrease the load of effluents)	JRC Reference Reports, 2013 IULTCS, 2018a UNIDO et al., 2019 CSIR, 2021
	To use advanced chrome recycling systems	JRC Reference Reports, 2013 IULTCS, 2018a UNIDO et al., 2019 Kanagaraj J. et al., 2015 CSIR, 2021
Energy consumption	Mechanical dewatering before drying	JRC Reference Reports, 2013 UNIDO et al., 2019
	To use renewable energy	UNIDO et al., 2019
Waste management	Methane production	JRC Reference Reports, 2013 IULTCS, 2018c UNIDO et al., 2019
	Grease and protein recovery	JRC Reference Reports, 2013 IULTCS, 2018c, S. Shaw et al., 2022 Pringle T et al., 2016 UNIDO et al., 2019
	Composting and fertilization	JRC Reference Reports, 2013 IULTCS, 2018c, S. Shaw et al., 2022 Pringle T et al., 2016 UNIDO et al., 2019
	Gelatin production	JRC Reference Reports, 2013 IULTCS, 2018c S. Shaw et al., 2022 UNIDO et al., 2019 CSIR, 2021
	keratin extraction	S. Shaw et al., 2022
	Recycled materials, leatherboard	JRC Reference Reports, 2013 IULTCS, 2018c S. Shaw et al., 2022 Pringle T et al., 2016 UNIDO et al., 2019
	Thermal transformation: brick or asphalts production	IULTCS, 2018c S. Shaw et al., 2022

FIGURE 7 Table summarizing the initiatives for a cleaner tanning industry.

et al., 2008; Zhang et al., 2011; Covington, 2019; MB-HOLDING GMBH & CO.KG (Allemagne), 2016). However, there are still very few of these products on the market.

5.2 | Synthetic tanning

Synthetic tannins have been used industrially for years, especially glutaraldehyde. Glutaraldehyde is often used in industrial, laboratory, agricultural, and medical settings. It has numerous uses, including disinfection and sterilization (Fearheller & EASTERN REGIONAL CENT., 1980). Since the introduction of modified glutaraldehyde for leather 30 years ago, the volume of chromium-free leathers produced in this way has steadily increased. In the automotive leather field, this kind of tanning has reached a 37% market share (CE, 2018). The process is very close to the chromium process, and more or less the same amount of chemicals is required as that of the chromium one, even if a retanning operation is essential to get performance. Glutaraldehyde toxicity remains a problem for tanners. Even if it is not classified as a carcinogenic chemical, it is an irritant, a corrosive agent, and a "health hazard" (provoking allergic skin reactions and breathing difficulties). The European Chemicals Agency has approved the addition of glutaraldehyde to the REACH (registration, evaluation, authorization and restriction of chemicals) Candidate List for Substances of Very High Concern. However, it should be noted that no glutaraldehyde residue is detectable on finished leather, so there should be no risk for the end consumer. However, at the same time, glutaraldehyde is in the process of being included in Annex XIV of REACH ("Authorisation List"), which would likely put an end to its use in the European leather industry (Agency for Toxic Substances & Disease Registry ATSDR, n., d.; Dipankar Chakraborty et al., 2008; Gabagnou et al., 2016).

An international patent was filed in June 2010 for a tanning process using another synthetic tannin, a derived triazine agent, following a large series of laboratory and industrial tests (Clariant International LTD (CH), 2010). Major benefits highlighted by the producer are the quality of wastewater, the safety of the product and of the leather, and the ease of processing solid wastes (EChEA, n., d.). In this tanning process, no pickling is necessary, so salt and water are saved. Tanning operation takes place in a drum and needs good control of temperature (modern equipment is required). As with synthetic tanning, a retanning operation is necessary to achieve leather performance. The toxicity tests conducted on both the chemical tanning agent and the resulting leather appear to be satisfactory. Concerning solid wastes, the absence of metallic components suggests some easier ways for recovery. After 10 years, there is no official data yet on the representation of this product in leather tanning.

5.3 | Other tanning possibilities

Using zeolite as a tanning agent is another new way to obtain leather. The product and its process are based on a mineral tanning technique using compounds from Al, Si, and natural polycarboxylic acids. More similar to the chromium process, it is quick and easy. The tanning agent has no toxicity identified except for the corrosive effect of the acid content. This kind of tanning process is possible using some trade references recently available (Kemira OYJ (FI), 2013). The hindsight necessary to draw definitive conclusions is not here yet but some studies produced encouraging results, achieving leathers as robust as synthetic ones (Bacarit et al., 2014, 2016). Aluminum is not considered a heavy metal, but it does not allow this kind of leather to be labeled as "metal-free."

A new tanning system based on phosphonium has been developed as a chrome-free process. The chemical agent is the tetrakis-(hydroxymethyl)-phosphonium sulfate, THPS, coming from the biocide industry (Albright&Wilson UK limited, 1992; Rhodia Consumer Specialties (GB), 2003). Some studies demonstrate good results with performant metal-free leather achieved. The process, similar to chromium tanning, is easy to manage and there is an improvement in the wastewater quality (Aravindhan et al., 2015; Nishad Fathima et al., 2005, 2006; Plavan et al., 2017). Regrettably, this type of tannin releases formaldehyde within the leather, which is not completely eliminated and remains within the material, making it potentially toxic.

Isocyanates are some collagen cross-linkers too. A trade reference based on this reactivity proposes a poly(carbamoyl sulfonate) chemical since 2011 (BAYER (Allemagne), 1997; Lanxess GmbH, 2011). No pickling is required in this process. This saves salt and water. The final leather is metal-free, presumably without hazardous elements. Wastes and wastewater can be easily treated (Lanxess GmbH, 2011), but the tanning agent is reprotoxic and tanners must be vigilant about the precautions of use. Up until now, it seems difficult to manage this process and achieve good results.

To conclude chromium alternatives, some possibilities exist but neither could achieve the same mechanical performances (ISO, 2015) and versatility of chromium-tanned leathers. A balance between leather performance, toxicity concerns, and environmental issues should be necessary.

6 | ESTIMATION OF THE ENVIRONMENTAL PERFORMANCE OF LEATHER

A number of tools and methods are already available to evaluate industrial environmental performance.

6.1 | Environmental audits

The carrying out of an environmental audit is one of these methods (ECO2L, 2013; LWG, 2022). In the leather industry, the most significant is the "LWG Environmental Audit Protocol." The international non-profit organization "Leather Working Group" (LWG) was founded in 2005. It is a multi-stakeholder group made up of brands, retailers, leather manufacturers, suppliers, and technical experts who have focused on the importance of the sustainability of leather in the world. Over time, more than 1300 members from across the supply chain have joined this program. The LWG Environmental Audit aims to improve the environmental impact of the leather industry by assessing the environmental performance and practical capabilities of companies. Then, based on compliance with the LWG environmental standards, companies obtain a certain level of certification. In addition, LWG aims to engage with members of the leather supply chain and provide them with the necessary knowledge to make informed and sustainable choices in their businesses. Now on version 7.2.2 of the protocol, the audit assesses the most important areas of the manufacturing process. Even if some part of the audit could be controversial, it has significantly contributed to raising environmental standards, primarily in developing countries. Gold, silver, and even bronze ratings improve the overall image of the company and create better marketing potential (LWG, 2022).

Unlike audits, some eco-labels are created to focus on end consumers. For a description of the eco-labels applied for leather, see Supporting Information S2.

6.2 | Life cycle analysis

Finally, life cycle assessment (LCA) is certainly the most advanced tool for sustainability evaluation, and most of the above-cited audits or ecolabels are built with this method. LCA techniques have emerged in the last 30 years and are now well established.

Concerning leather, a lot of LCAs are studied since 2000 (Bacarit et al., 2020; Chen et al., 2019; Chen et al., 2014; Deselnicu et al., 2014; EPD, 2017; Giannetti et al., 2015; Kiliç et al., 2011; Mahdi et al., 2021; Mila et al., 2002; Notarnicola et al., 2017; OECD, n. d.; Puccini et al., 2014; Rivela et al., 2004; Shi et al., 2016; Daddi et al., 2016; Ulya et al., 2020; UNIDO et al., 2012; Yang et al., 2021; Zia Uddin et al., 2016). A table summarizing the main LCA studies reviewed is available in Supporting Information S3.

The central challenge confronting the leather industry lies in defining the boundaries of its environmental impact, specifically whether to encompass or exclude upstream processes like animal breeding and agricultural activities for feed. The characterization of animal skins as co-products, by-products, or waste in relation to the meat or milk industry complicates matters. For instance, the carbon footprint of leather can fluctuate significantly, ranging from 35 to 350 kg eq CO₂ per m² for the same product, contingent on boundary-setting approaches. Over time, a consensus has seemingly emerged, predominantly regarding leather as a by-product. This perspective is evident in the Product Environmental Footprint Category Rules (PEFCR) edited in 2018. According to PEF, there are three levels of allocation of impacts of cattle farming to leather: First, the impact of cattle farming must be allocated 88% to dairy products and 12% to the other animal outputs (meat and co/by-products). The allocation is calculated on the basis of the protein content. Second, of the animals entering the slaughterhouse, 7% by mass is raw hide. Based on an economic allocation, this 7% takes a 3.5% share of the impacts of the animals at the slaughterhouse. Third, once the raw hide enters the tannery, the impact can be allocated based on hide substance content depending on if splitting occurs and hairs are saved. As a result, an allocation of 0.5 ratio must be applied to the impact per 1000 kg of meat and co/by-products entering the slaughterhouse to obtain the impact of 1 kg of raw hide. For example, if the impact of 1000 Kg of meat cattle entering the slaughterhouse is 12,000 kg CO₂eq, 6 kg CO₂eq is the impact of 1 kg of raw hide (CE, 2018). In this case, tannery operation represents, for example, less than 20% of the total carbon footprint of 1 m² of leather and less than 1% of the water footprint (UNIDO, 2017b). The problem with such a calculation is that leather cannot environmentally compete with other materials such as fabrics or artificial leather as illustrated in Figure 8, even if the leather is a kind of waste recovery, but the debate continues. In March 2024, Dr. Greg Toma presented a US-based LCA study on cattle, showing significantly different results from the EU's, notably favoring the leather industry with a 1% economic allocation instead of 3.5% (Thoma, 2024).

Other difficulties have emerged with leather LCA. It is not possible to get real comparisons or even average data, given the many end uses and approaches there are to making leather. In most cases, each study must be considered as a system itself and it seems difficult to compare with others (Laurenti et al., 2016). Another difficulty is the chemicals data available. A lot of chemicals used for making leather are more or less specific. The international cycle inventory databases contain yet no leather-specific data available. Thus, a lot of substitutions and assumptions are made to get leather LCA, affecting reliable results, particularly for measuring and comparing tanning and retanning possibilities. This is why, in recent years, additional studies have been carried out to enhance knowledge of specific chemicals (Tasca & Puccini, 2019). With the same objective, the Environmental Footprint database 3.1 (last version 2023) is designed to support the use of PEFCR and catalogs new specific leather chemicals.

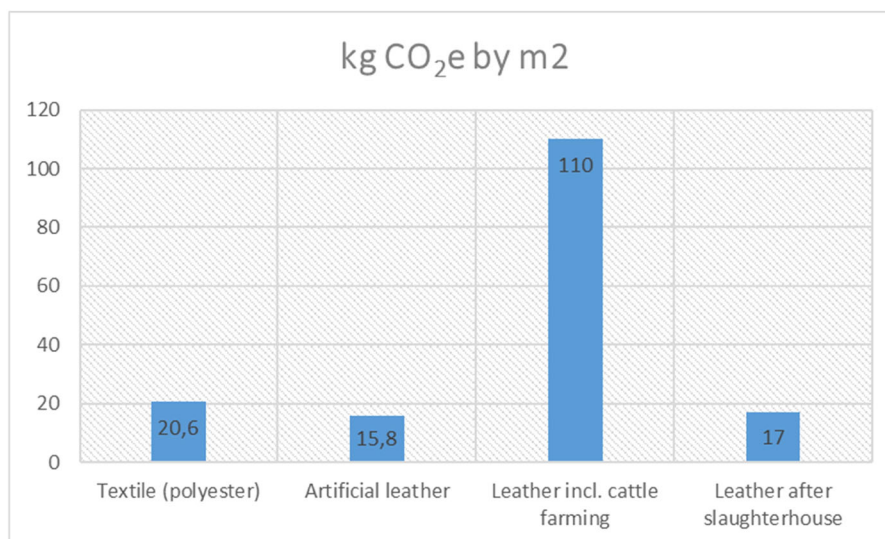


FIGURE 8 Materials carbon footprint comparison. *Source:* Based on chart by F. Schmel, derived from the presentation by J. Knoedler (UNIDO, 2017b); see Supporting Information S4.

7 | DISCUSSION

A critical review of the environmental impact of leather production, including recent improvements, reveals that despite important initial pollution some real solutions exist and are deployed in the industry thanks to the efforts put forward by several global or European organizations. The energy and water consumption could be effectively managed and reduced. The effluent treatment is now well-established and efficient for the main pollutants such as COD, BOD, suspended solids, nitrogen, chromium, and sulfides. The salinity could remain a problem because it is not possible to filter it with the current systems. However, water treatment is conditioned by discharge standards promulgated by the local authorities, resulting in sometimes problematic disparities (IULTCS, 2018e). Despite best practices, solid waste generation remains significant, with treatment varying depending on the stage at which the waste is produced, with the presence of chromium complicating treatment processes. While recycling is feasible, it is practiced in only a few countries, primarily developed nations. Solid waste treatment remains a major challenge, with current capabilities insufficient to manage the global solid waste output of the leather industry. The issue of chromium presence in sludge, leather waste, and end-of-life leather articles arises alongside solid waste treatment. Chromium is the predominant tanning method due to its favorable mechanical properties, efficiency, and versatility in producing leather. However, concerns over the difficult end-of-life treatment of chromium leather and potential toxicity from chromium VI release have spurred research into chromium-free tanning systems over the past decade. Presently, chrome tanning accounts for approximately 63% of the volume in the automotive industry, 75% in leather goods/shoes, and 100% in garment leather (CE, 2018). Other established tanning methods include glutaraldehyde tanning and vegetable tanning. Modern vegetable tanning typically involves synthetic tanning followed by vegetable tanning, offering advantages in terms of chemical safety and renewable sourcing, though the large quantity of tannin required raises questions about material availability and cost (De Nicola et al., 2004; De Nicola, Meric, Cheggour et al., 2007; De Nicola, Meric, Gallo, et al., 2007). Glutaraldehyde tanning, in use for over 30 years primarily in automotive leather, faces challenges due to its presence on the Candidate List for regulation under REACH, potentially limiting its future use.

Other synthetic tannins are being developed and marketed, varying in industrialization and environmental impact. While significant efforts are directed toward finding sustainable tanning methods, the transition from chromium tanning is slow due to the overall inferiority of alternative methods.

The pursuit of sustainable leather has led to the development of numerous tools to measure environmental impact. The number of LWG-certified tanneries is increasing steadily, with many brands considering certification when selecting suppliers. This traceability extends to eco-labels or statuses visible even to the end consumer. Given the diverse raw materials, end uses, and manufacturing approaches in leather production, a case-by-case assessment likely offers the best insight into environmental impact. This approach is supported by numerous LCAs conducted on the leather industry. However, challenges remain in choosing boundary systems and ensuring data reliability for meaningful comparisons between studies.

Over the last six years (2014–2019), approximately 30 papers on leather LCA were published, underscoring the growing environmental awareness in the industry (Navarro et al., 2020). Environmental concerns are driving much of the research and development in the leather industry, reflected in the increasing number of publications on the subject. Major stakeholders are committed to elevating sustainability standards and transitioning toward a circular economy (Brugnoli, 2017; Marchi de Almeida et al., 2020; Redwood, 2013).

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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