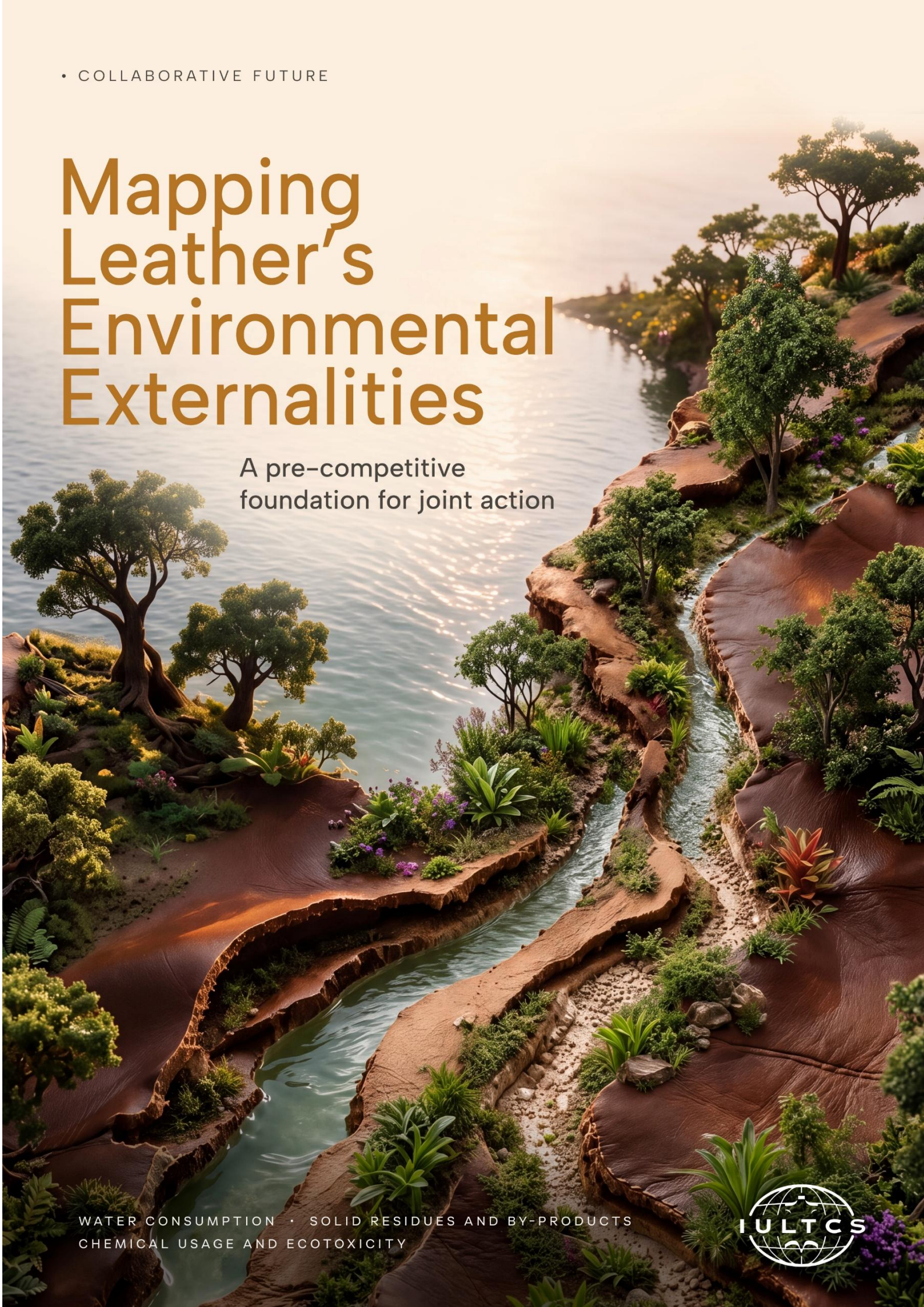
• COLLABORATIVE FUTURE

Mapping Leather's Environmental Externalities

A pre-competitive foundation for joint action



WATER CONSUMPTION • SOLID RESIDUES AND BY-PRODUCTS
CHEMICAL USAGE AND ECOTOXICITY

IULTCS

Mapping Leather's Environmental Externalities

A pre-competitive foundation for joint action

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Foreword

Anthropogenic pressures on the health of planetary natural systems are increasingly the subject of academic study given their major implications for the stability of life forms on Earth. There are numerous and distinct ways in which human beings affect the balance of planetary systems, but many of them are certainly linked to the exponential increase in consumption since the industrial revolution. Sectors producing durable consumer goods – such as footwear, accessories, furniture, or automobiles – which utilize leather and other coating materials, have complex production chains that, if not properly and holistically managed, can generate considerable impact.

Thus, deeply exploring the nature of socio-environmental impacts of a production chain proves fundamental to enabling the structuring of actions that mitigate their consequences, whether in the public or private sphere. To this end, it is essential to understand and accept the complex and multifaceted nature of impact sources, whose origins often have roots that go beyond the technical field, encompassing historical, geographical, and cultural motivations. No production chain is isolated from market, economic, and geopolitical dynamics, just as, ultimately, there is no disconnection between industrial and natural flows.

Embracing this intrinsic complexity allows us to accept the impossibility of reducing such a broad-ranging topic to simplistic actions or debates. By accepting it, we position ourselves as agents: those who have the power of action, decision-making, and promoting change. Simultaneously, we avoid flirting with the trap of reductionist idealization, which generally leads us to act on symptoms rather than causes.

It is not useful to adopt a maximalist approach that requires the simultaneous elimination of all critical issues. Instead, it is useful to optimise the process by establishing a hierarchy of mitigation measures that maintain both the application result and the improvement in environmental performance.

The leather industry has long occupied a place of high material and cultural relevance for human society. By providing a durable and comfortable material, whose raw material is widely available where animals are raised, it has always positioned itself as a versatile solution for upholsteries of all kinds. Its complex and global value chain and its plurality of applications only contribute to the myriads of technological routes and process choices with which we are confronted with.

With so many options, it becomes fundamental to establish common points of attention for the whole sector, guiding efforts and converging them into common fronts. It is known that collaboration is fundamental for the effectiveness of actions in industrial process sectors, and this series aims to offer a simplified overview of major environmental impacts to help guide pre-competitive initiatives toward cleaner leather production. This first issue aims to establish a broad framework rather than addressing every technical impact source.

IULTCS Sustainability Commission Team (IUS)

About this series

This publication initiates a series dedicated to examining key environmental externalities associated with the leather value chain. By bringing together knowledge from different parts of the chain in a neutral format supported by science-based information, the series seeks to offer a shared reference point on the environmental priorities for the sector.

Throughout this series, environmental topics are examined from a value-chain perspective, considering that environmental impacts may occur across different stages of production and require different assessment approaches depending on the nature of the subject matter. When relevant, internationally recognized methodologies, indicators, and scientific frameworks are identified to provide transparency regarding the basis of the information presented.

In this first issue, the editorial team has deliberately focused on three environmental dimensions that are material across geographies and production technologies:

(1) Water Consumption;

(2) Chemical Usage and Ecotoxicity;

(3) Solid Residues and By-products.

The selection of these themes does not, at this moment, imply a hierarchy of importance among impact categories.

The editorial approach for each topic in this inaugural edition is intentionally synthetic. The objective is not to catalogue every technical impact source or every available technology, but to provide a holistic overview of where and how impacts tend to occur, which types of indicators are more relevant, and which mitigation measures are currently being explored. The report is therefore not intended to provide an exhaustive technical assessment or prescribe specific technological pathways, but rather to establish a common understanding of the main environmental challenges across the leather value chain.

Future editions are expected to extend this framework to additional environmental externalities that are equally critical for the long-term sustainability of leather value chains. Viewed as a whole, this series aims to support informed public discussion by fostering a shared understanding of risks, trade-offs, and opportunities, providing a neutral basis for dialogue and for the development and prioritization of mitigation strategies by companies, public authorities, and civil society organizations.

1. WATER CONSUMPTION



1.1 Introduction

For upholstery and fashion material supply chains in general, water is a core resource. Needed for the production of all materials, its unavoidable nature is also a testament of its criticality. Yet, water often flows silently within supply chains. One commonly recognized challenge is that consumers are generally unaware of the total amount of water associated with the production of goods, making water use one of the most significant environmental blind spots.

As with other materials, water is a fundamental resource throughout the leather value chain. However, understanding its environmental relevance requires methodological clarity, as different water sources, uses, and geographical contexts may lead to different environmental implications. For this reason and for the purposes of IULTCS environmental assessment, water-related aspects are analyzed through a **dual framework**, considering two major stages of the leather value chain:

- **Upstream phase**: animal production and feed cultivation.
- **Industrial phase**: tanning operations and associated services.

The drivers, metrics, level of control, and environmental implications differ significantly between these two stages. Treating them separately allows for greater technical accuracy, transparency, and more effective water management strategies across the leather value chain. The main differences can be summarised as follows:

Table 1: Key Water-Related Aspects Across the Upstream and Industrial Phases of the Leather Value Chain

Aspect	Upstream phase: Animal production	Industrial phase: Tanning operations
Main water drivers	Feed production, pasture systems, livestock drinking water, and farm activities.	Processing steps such as soaking, liming, tanning, dyeing, finishing, and auxiliary operations.
Main influencing factors	Climate, agricultural practices, feed systems, land management, and geographical location.	Process efficiency, technology, operational management, wastewater treatment, and reuse practices.
Level of operational control	Mainly indirect, through sourcing practices and agricultural systems.	More direct, through industrial process management.
Main environmental considerations	Water availability, water scarcity, competition among users, and agricultural impacts.	Water consumption, efficiency, discharge quality, and treatment performance.
Main improvement opportunities	Improved agricultural practices, feed efficiency, pasture management, and sourcing strategies.	Process optimization, water reuse, efficiency improvements, and wastewater management.

When discussing water-related indicators, an important methodological consideration must be acknowledged: water use can be assessed through different approaches and expressed through different metrics.

Terms such as Water Use, Water Consumption, Water Footprint and Water Scarcity are often used in environmental assessments; however, they do not represent the same concept and should not be considered interchangeable. Their interpretation depends on the methodological framework, system boundary and geographic context applied.

To ensure consistency throughout this publication, water-related discussions are presented according to the specific methodological framework associated with each indicator. Where relevant, the underlying approach and assumptions are identified to support transparency and comparability of the information presented.

For comparative purposes, the Higg Materials Sustainability Index (Higg MSI) is commonly used by the apparel sector as the reference framework for evaluating water-related impacts across materials. Table 2 displays the Water Scarcity results for different materials, based on the Higg MSI data version 3.12.0 published in May 2026 [1]. The indicator reflects a life cycle-based assessment of potential water scarcity impacts associated with material production, enabling comparison and using a consistent methodological framework.

Table 2: Water Scarcity Impacts of Selected Materials According to the Higg MSI

Material	Water scarcity *(m^3/kg)*
Nylon	2.70
Polyester	2.77
Acrylic	2.83
Bovine Leather	6.02
Wool	6.85
Viscose	7.87
Lyocell	8.60
Cotton	124.0

1.2 Upstream Phase: Animal Production and Embedded Water

1.2.1 Conceptual Framework

In the upstream phase, water use is predominantly associated with:

- Feed crop cultivation (rainfed and irrigated);
- Pasture systems;
- Drinking water;
- Farm services.

Three distinct water sources are considered in the upstream phase:

- Green water – rainwater stored in soil;
- Blue water – surface and groundwater abstraction;
- Grey water – theoretical dilution volume associated with pollution.

For livestock systems, approximately 98% of the total water footprint is associated with feed production, while drinking and service water represent comparatively minor shares. This is true for both grass-fed and grain-fed systems, but it is important to differentiate between the types of water used: while grass-fed systems are dominated by green rainwater in pastures and roughages, grain-fed ones have higher blue and grey water components [2].

1.2.2 From Volume to Impact: Scarcity Considerations

Total volumetric indicators do not fully describe environmental pressure. The environmental significance of water use depends not only on the amount of water consumed or withdrawn, but also on where and when that water use occurs and on the availability of water resources in the surrounding watershed. The same volume of water can therefore have very different environmental implications depending on local water availability and competing demands.

This distinction is reflected in international water footprint assessment practices. **ISO 14046:2014** [3] establishes principles, requirements, and guidelines for assessing the water footprint of products, processes, and organizations based on a Life Cycle Assessment (LCA) approach. It recognizes that water-related impacts cannot be understood solely through volumetric measures and that geographical and environmental context must be considered when assessing potential impacts.

For impact-oriented evaluation, consensus literature recommends combining volumetric indicators with water scarcity footprint methods, such as AWARE [4], which account for regional water stress.

AWARE (Available WAter REmaining) is a water scarcity characterization method developed for life cycle assessment that considers the amount of water remaining available in a given watershed after accounting for the needs of humans and aquatic ecosystems. It therefore links water consumption to the local availability of water resources, allowing the potential environmental pressure associated with the same volume of water consumption to be assessed differently depending on the level of water stress in the watershed.

This distinction is essential when communicating upstream impacts. Rather than considering only the volume of water use, water scarcity indicators consider consumptive water use in relation to the availability of water resources in a specific location. As a result, the same quantity of water consumption may correspond to substantially different potential impacts depending on the level of water scarcity in the watershed where the consumption occurs [4].

Accordingly, volumetric indicators and water scarcity indicators should be understood as complementary rather than interchangeable: volumetric indicators describe the quantity of water use or consumption, while scarcity-based indicators provide an indication of the potential environmental pressure associated with that consumption in its geographical context.

1.2.3 Order-of-Magnitude Values

To illustrate the differences between water-related indicators and the magnitude of the values reported across the literature and reference databases, Table 3 presents selected global estimates of water use and water scarcity associated with cattle live weight. The values are drawn from some of the available reference sources and should be understood as indicative rather than as a single representative value for global cattle production.

Table 3: Selected Global Estimates of Water Use and Water Scarcity in Cattle Production

Source	Methodology	m^3 of water/tonne of live weight
Hoekstra & Mekonnen (2012) [2]	Water use - KPI	15400
EcoInvent v3.10 [5]	Water use - KPI	3609
EcoInvent v3.10	Hoekstra et al. (2012) Water Scarcity [4]	49.7

While studies such as Hoekstra & Mekonnen (2012) report approximately 15,400 m^3 of water per tonne of live weight, more recent sources, such as Ecoinvent 3.10 (2023), one of the world's leading life cycle inventory databases, report a global average water consumption of 3,609 m^3/ tonne of cattle live weight produced. When the same Ecoinvent

inventory is evaluated using the AWARE water scarcity methodology, the resulting value is substantially lower, at 49.7 m^3/tonne of live weight [2] [4] [5].

This substantial difference is explained by the distinct objectives of these metrics:

- Life Cycle Inventory (LCI) Water Inputs quantify the total volume of water used within the production system.
- Water Scarcity Indicators (WSI) evaluate the environmental significance of that water consumption by considering regional water availability and local water stress conditions.

These differences do not necessarily indicate inconsistencies between the sources. Rather, they illustrate the importance of clearly distinguishing between volumetric water use or consumption and water scarcity impacts, as well as between the methodological assumptions and system boundaries underlying each estimate. The figures should therefore be interpreted as different representations of the water-related implications of cattle production, rather than as directly interchangeable measurements.

Furthermore, water scarcity methodologies distinguish between the impact weight between green water, blue water, and grey water. Large water footprint values are often driven by green water consumption, particularly in grazing and feed production systems. Since water scarcity assessments focus on the potential environmental impact of water use and account for local water availability, green water generally receives a much lower weight than blue water withdrawals. This leads to significantly lower results compared to total water footprint inventories.

Therefore, a high volume of water use does not necessarily translate into a high-water scarcity impact, particularly in regions where water resources are abundant.

1.2.4 Role of the Leather Sector

Although livestock production is outside direct leather sector control, the sector can:

- Promote supply chain transparency;
- Support traceability systems;
- Encourage science-based assessment methodologies;
- Avoid simplified claims based solely on volumetric figures.

1.3. Tannery Operations: Process Water Use

1.3.1 Operational Definition

In tanning operations, water functions primarily as a process medium, facilitating diffusion and chemical reactions within the collagen matrix.

Unlike in irrigation, most water in tanneries is not consumptively lost but becomes wastewater directed to treatment. It is estimated that approximately 95% of water used in tanning is sent to wastewater treatment systems [6].

In industrial practice, "water consumption" therefore often refers to water withdrawal or use, rather than strictly non-returned water as defined in LCA terminology.

1.3.2 Key Performance Indicators

For industrial benchmarking and communication, the following indicators are recommended:

- Total water input (m^3/year), by source;
- Water intensity per unit of production:
    - L/m^2 of finished Leather.
    - m^3 per tonne of raw hides.

These metrics are used internationally in the leather sector, including by the Leather Working Group (LWG), which evaluates water use in relation to production output.

As one industry reference, Italian sector data (UNIC, 2023) report 116.7 L/m^2 of finished leather [6]. This value should be considered an industry reference rather than a universal benchmark, as water-use intensity varies according to raw material mix, leather type, process scope, technology and other production conditions.

1.3.3 Process Hotspots

Technical literature indicates that processing 1 tonne of raw hides into finished leather typically requires:

30–50 m^3 of water [7]

Indicative distribution:

Table 4: Reference Water Use Across Leather Production Stages

Phase	**Reference Water Use** *(m^3/tonne)*
Pre-tanning (beamhouse)	23–35
Tanning	3–5
Post-tanning	7–13
Finishing	1–3

These numbers can vary considerably depending on the type of leather produced and the technological approach adopted by the tannery. Generally, the pre-tanning phase represents the principal hotspot.

The Leather Working Group (LWG) recognizes water as one of the most critical resources in leather manufacturing and therefore requires tanneries to measure, monitor and report water consumption from different sources, ensuring industrial monitoring and

transparency throughout the process. The framework also promotes water reduction, reuse and recycling practices, supporting continuous improvement in water efficiency.

This emphasis on water management is made evident in the LWG Water Usage section, where water consumption is assessed as part of the facility's environmental performance and directly influences its overall LWG rating. Based on water-use benchmarks that consider the type of leather and production processes, tanneries are assessed and awarded a module rating of Bronze, Silver or Gold.

Importantly, the water module result can limit the LWG certification outcome. For example, if a tannery achieves only a Bronze rating in the Water Module, that is mostly impacted by water consumption, its final LWG medal cannot exceed Bronze, highlighting the strategic importance of effective water management in achieving higher certification levels [8].

1.4. Reduction, Recycling and Reuse

1.4.1 Process Optimization

Technological and operational improvements include:

- Low-float processing;
- Optimized drum design;
- Recipe rationalization.

Cleaner technology recommendations indicate potential reductions of approximately 30% or more, depending on baseline conditions [9].

1.4.2 Bath Recycling

Selective recycling of process baths (soaking, liming, pickling, chrome liquors) may achieve additional reductions of 20–40%, where technically feasible.

The document "IUE 1 – Recommendations on Cleaner Technologies for Leather Production" describes selective bath recycling as a technically mature practice when properly controlled [9].

Potential recyclable streams include:

- Soaking liquors;
- Liming/unhairing baths;
- Pickling baths;
- Chrome tanning liquors.

Under suitable conditions, overall water reduction in the range of 20–40% may be achieved [9].

However, IUE 1 emphasizes:

- Recycling requires monitoring of accumulated salts;

- Sulfide and lime concentrations must be controlled;
- Periodic bleed-off may be necessary.

Recycling is therefore not “closed-loop” in the strict sense, but rather a controlled partial-loop system.

1.4.3 Treated Effluent Reuse

Reuse of biologically treated wastewater is possible in selected operations, provided that the treated water meets the quality requirements of the intended application.

This fit-for-purpose principle means that the required water quality should be determined according to the specific process in which the reclaimed water will be used, rather than assuming that treated wastewater is suitable for all applications,

Reuse may be supported by treatment technologies such as:

- Advanced filtration;
- Membrane systems (including ultrafiltration and reverse osmosis).

Membrane systems may enable higher reuse rates by producing water of higher quality. However, they also generate concentrated reject streams that require appropriate management.

IUE 1 also addresses reuse of treated wastewater [9], particularly:

- Biologically treated effluent;
- Effluent after advanced clarification;
- Membrane-treated water.

Potential reuse applications may include:

- Beamhouse operations;
- Washing stages;
- Auxiliary services.

The suitability of treated water for reuse should be assessed according to the intended application and relevant water quality parameters, including:

- Residual COD;
- Total dissolved solids (TDS);
- Hardness;
- Sulfates and chlorides;
- Residual color.

This approach helps ensure that water reuse delivers environmental benefits while maintaining process compatibility and avoiding adverse effects on leather quality or processing performance.

1.5. Trade-Offs and Systemic Perspective

Water reduction is not impact-neutral. Lower process volumes may increase pollutant concentration, require more intensive treatment, increase sludge generation and shift burdens toward energy consumption.

Cleaner technology guidance explicitly highlights the potential concentration effect associated with reduced volumes [9].

Water efficiency must therefore be evaluated together with:

- Wastewater quality;
- Sludge management.

The publication "Sustainable water management in the leather industry" [10], from Leather Naturally, can serve as an instructive resource for tanneries on how to address the topic, with examples of business led cases.

1.5.1 Concentration Effect

Reducing water volume leads to:

- Increased pollutant concentration;
- Higher COD/BOD per unit volume;
- Increased salinity.

While total pollutant mass may decrease, treatment intensity per cubic meter increases.

This may require:

- Stronger oxidation;
- More Chemicals;
- Additional treatment stages.

1.5.2 Sludge Generation

Increased concentration of contaminants and dissolved solids in wastewater may lead to:

- Higher chemical dosing in treatment;
- Greater sludge production;
- More complex sludge management.

The ZDHC Sludge Reference Document [11], which provides guidance on the management and assessment of sludge generated from industrial wastewater treatment, highlights that metals and certain chemicals present in wastewater may partition into sludge fractions during treatment. This reinforces the need to consider sludge generation and composition when evaluating changes in water use and treatment practices.

Thus, water efficiency improvements must be evaluated alongside:

- Sludge quality;
- Sludge quantity;
- Final disposal or recovery routes.

Advanced reuse systems, such as membrane filtration, may reduce freshwater withdrawal but can also increase energy consumption and, depending on the energy source and system configuration, the associated carbon footprint. Water, energy, and chemical use are therefore interconnected, and improvements in one dimension should be evaluated in relation to their potential effects on the others rather than through a single-indicator approach.

This integrated perspective is reflected in sector frameworks such as the LWG and the ZDHC Wastewater & Sludge Guidelines, which consider water use, wastewater treatment, sludge characteristics, and their appropriate management as interconnected aspects of environmental performance [8] [12].

1.6. Standards and Reference Framework

Water consumption assessment in the leather sector is supported by:

- ISO 14046 – Water Footprint [3];
- ISO 14040/44 – Life Cycle Assessment [13];
- AWARE Method – Water Scarcity Footprint [4];
- EU Water Framework Directive (2000/60/EC) [14];
- Industrial Emissions Directive (2010/75/EU) [15];
- LWG Tannery of the Future [16];
- ZDHC Wastewater & Sludge Guidelines [12].

Together, these standards, methodologies, and sector-specific frameworks provide complementary perspectives for understanding and managing water-related aspects across the leather value chain. While ISO standards and assessment methods provide principles and methodological approaches for quantifying and evaluating potential environmental impacts, regulatory and sector frameworks establish requirements and practical guidance for water use, wastewater management, and resource efficiency.

If combined, they can support a more consistent and comprehensive assessment of water-related risks and opportunities, while recognizing that the appropriate indicator or framework depends on the specific purpose and context of the assessment.

1.7. Concluding Remarks

Water consumption in the leather value chain requires differentiation and contextual interpretation.

- Upstream impacts are largely feed-related and geographically variable;
- Scarcity indicators complement volumetric measures;
- Tannery water use is measurable, manageable and continuously improving;
- The beamhouse phase is typically the dominant hotspot;

- Reduction and reuse strategies must consider systemic trade-offs.

Water reduction strategies should always be evaluated using a multi-parameter approach, considering:

- Water withdrawal;
- Effluent quality;
- Sludge Generation;
- Energy demand;
- Chemical consumption.

Cleaner Technologies, as defined by IUE 1, are not merely technologies that reduce water volume, but solutions that improve the overall environmental balance of the system.

Thus, a science-based and transparent approach allows the leather sector to address water consumption with methodological rigor and institutional credibility.

2. CHEMICAL USAGE AND ECOTOXICITY



2.1 Introduction

Chemical usage is intrinsic to leather manufacture, and its environmental consequences must be interpreted through an integrated perspective that considers the nature of the chemicals used, process performance, environmental pathways and resulting environmental outcomes.

For the purposes of IULTCS environmental assessment, chemical usage and ecotoxicity should be addressed through a structured framework that considers:

- Chemical inputs and their intended process functionality;
- Environmental release pathways and potential ecotoxicological implications.

This distinction aims to support technically robust communication and avoid evaluating chemical intensity independently from treatment performance, circularity and product functionality.

To provide a comparable reference across materials, Table 5 presents the results of the Chemistry indicator in the Higg MSI. As introduced in Section 1.1, the Higg MSI is used in this publication as a reference framework for comparing environmental performance across materials using a consistent assessment approach. The Chemistry indicator represents the potential human and ecological toxicity impacts associated with the material supply chain.

Table 5: Higg MSI Chemistry Indicator for selected Materials

Material	Indicator (units)
Wool	15.2
Polyester	19.6
Nylon	19.6
Viscose	19.8
Lyocell	19.8
Acrylic	19.9
Cotton	23.0
Bovine leather	30.1

Note: The Chemistry Higg MSI indicator is measured in "units". Lower values indicate lower potential toxicity impacts associated with the assessed supply chain.

2.2 Tannery Operations: Chemical Usage and Ecotoxicity

Leather manufacturing uses chemical systems to stabilize collagen and achieve performance requirements.

Environmental relevance depends not only on the quantity and composition of chemicals used but also on uptake efficiency, recovery, treatment and exposure scenarios. Across all stages, a single tannery may use over dozens of different chemical formulations in total.

Managing this diverse chemical inventory responsibly – selecting less hazardous alternatives, handling and storing chemicals safely, and treating waste streams effectively – is critical to minimizing environmental impact.

2.2.1 Operational Definition

Chemicals are used throughout leather production to perform different functions at each stage of processing, from preparing and preserving the raw hides to transforming them into leather and imparting the required physical, functional, and aesthetic properties to the finished material. Most chemical applications take place in batch processes carried out in rotating drums, after which the process liquors are discharged to Effluent Treatment Plants for appropriate treatment.

Typical chemical families include:

- Alkalis and sulphides;
- Acids and salts;
- Chromium tanning agents and its alternatives;
- Retanning agents, dyes and fatliquors;
- Finishing polymers and auxiliaries.

From a toxicity perspective, some chemical groups are commonly prioritized for management due to the volumes used, their hazardous characteristics, and their potential environmental implications. Key examples include:

- Chromium sulphate;

- Sulfur-based beamhouse chemicals;
- Ammonium salts;
- Formaldehyde;
- PFAS/PFCs;
- Solvents, biocides and preservatives;
- Surfactant.

2.2.2 Key Performance Indicators

To support the assessment and management of chemical use and its potential environmental implications, IULTCS' IUS recommends monitoring the following key performance indicators [7]:

- Chemical intensity (kg/m^2 leather);
- Chemical uptake/exhaustion efficiency;
- Restricted substances compliance;
- Effluent ecotoxicity and discharge indicators.

2.2.3 Key Frameworks

Several established frameworks support tanneries in implementing effective chemical management systems, assessing environmental performance, and ensuring market compliance.

The most widely recognized frameworks include:

- **ZDHC (Zero Discharge of Hazardous Chemicals):**

  An industry framework focused on eliminating hazardous chemicals from manufacturing processes. Through tools such as the Manufacturing Restricted Substances List (MRSL), it helps tanneries control chemical inputs, improve chemical inventory management, and prevent environmental impacts at the source [17].

- **LWG (Leather Working Group):**

  The leading environmental auditing standard for the leather industry. LWG assesses tannery performance in areas such as chemical management, wastewater treatment, resource efficiency, and environmental compliance, while aligning with key ZDHC principles [8].

- **REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals):**

  The European Union's chemicals regulation, establishing legal requirements and restrictions for substances present in products placed on the EU market. REACH serves as a key reference for product compliance and restricted substances management [18].

While ZDHC and REACH have different scopes, they are closely connected. REACH restrictions and the identification of substances of regulatory concern are often considered

within ZDHC's risk assessment and MRSL development processes, helping align manufacturing chemical controls with evolving regulatory requirements [17] [18]. In addition, the ZDHC Chemical Watch List complements the REACH Candidate List of Substances of Very High Concern (SVHCs) by identifying substances that may represent emerging concerns and could become subject to future regulatory scrutiny, supporting a more proactive approach to chemical risk management and substitution [18] [19].

ZDHC and REACH are widely used across industries such as leather, footwear, apparel, textiles, and related material supply chains, providing a common framework for chemical management and product stewardship. Together, ZDHC, LWG, and REACH provide a complementary framework covering chemical inputs, environmental performance, and product compliance.

2.2.4 Process Hotspots

Although the different processes commonly take place in independent industrial facilities, the following hotspots can be attributed to the main production stages:

- Beamhouse operations introduce large amounts of alkaline chemicals and sulphides to clean, prepare, and unhair the hides, generally making this stage the largest contributor to COD, BOD, sulphide, and suspended solids loads.
  The resulting wastewater–has a high organic load and can reach strong alkaline conditions, with pH values of approximately 12 during liming, which can interfere with biological treatment if not properly neutralized.
  The high Total Kjeldahl Nitrogen (TKN) and suspended solids deserve special attention, implementing best practices such as:
  - Hair-saving or hair-burning, which can reduce COD and TKN by 40-60%;
  - Optimizing floats, to reduce organic loads at source;
  - Reducing salt input and maximizing its recovery;
  - Segregating high-sulphide liming liquors before mixing them with other wastewater to minimize the risk of H_2S release;
  - Ensuring adequate equalization of wastewater flows and pollutant loads to prevent sudden variations in COD and other parameters and provide more stable conditions for subsequent biological treatment.

- Chrome Tanning uses basic chromium (III) sulphate to stabilize collagen, and remains the predominant tanning technology, accounting for approximately 85-90% of global leather production [20]. In a typical chrome tanning process, considerable amounts of salt are also used, making the process a relevant source of residual chromium and salinity in the wastewater.
  Also, not all the offered chemicals are absorbed: under standard conditions, only about 55–65% of the chromium binds to the leather [21], leaving the rest in the spent tanning liquor. Tanning and pickling effluents are strongly acidic and carry high concentrations of dissolved salts (sulphates, chlorides) and residual tanning agents (chrome or natural tannins). If not treated or recycled, these effluents contribute to salinity and metal content in wastewater.
  Alternative tannages exist, such as vegetable tanning (using plant polyphenols), aldehyde tanning (e.g. glutaraldehyde, producing wet-white leather), and other

mineral or polymer systems, but these represent a minority of production and often target specific niches. To guarantee the proper management of remaining risks, special attention should be given to chemical precipitation in chromium-bearing sludge, with its proper destination being central to effective waste management.

Post-tanning (retanning, coloring, fatliquoring) adjusts the leather properties through additional treatments in drums.

Retanning uses different agents (synthetic resins, phenolic syntans, vegetable tannins) to fill and strengthen the leather structure. Dyeing imparts the desired color using dyes or pigments, and fatliquoring (oiling) adds oils or polymer lubricants to make the leather soft and flexible.

These stages of the process incorporate more specialized chemicals (surfactants, dye auxiliaries, preservatives, emulsified fats). Just like in-tanning, absorption is, by its very nature, incomplete, which contributes to high COD levels, intense color, and, at times, the presence of hazardous substances in the effluent.

Historically, some post-tanning chemicals contained harmful components (e.g. certain resin agents released formaldehyde, and some azo dyes could cleave into carcinogenic amines) but these formulations have largely been replaced or restricted by modern standards. As a result, the environmental relevance of post-tanning is increasingly associated with the diversity and quantity of post-tanning chemicals used and with the management of the resulting wastewater streams, rather than with the inherent toxicity of the process itself.

Post-tanning adds complexity to chemical management within the leather supply chain due to the wide range of process-specific chemicals and formulations used to achieve different physical, functional, and aesthetic characteristics. This diversity requires tanneries undertaking post-tanning operations to pay particular attention to the toxicological profile of the chemicals they source and use, as well as their potential environmental release pathways and compliance with applicable chemical restrictions.

In this stage, it is also essential to optimize the process to ensure the full utilization of the chemicals, making sure only the necessary amount of chemicals is used and no unnecessary COD is sent to the effluent treatment plant.

- Finishing the leather surface involves applying base coats and topcoats made of film-forming polymers (acrylics or polyurethanes), often with pigments and small amounts of additives (e.g. cross-linkers for durability). Traditionally, many finishes were solvent-based (using volatile organic solvents like toluene), resulting in significant Volatile Organic Compounds (VOC) emissions.

  Today, the industry has largely shifted towards water-based finishing systems, substantially reducing VOC emissions when comparing to historical solvent-based practices**.** In some documented cases, the transition to water-based coatings has reduced VOC emissions by more than 90% [22]. Finishing operations generally produce limited liquid effluent, while air emissions have also decreased as the use of solvent-based formulations has declined. Where solvents or spray application are still used, remaining VOC and particulate emissions can be managed through appropriate ventilation, filtration, and abatement systems.

  Despite these reductions, VOC and Hazardous Air Pollutant (HAP) emissions remain relevant environmental and occupational considerations and should continue to be monitored and appropriately managed.

2.3 Reduction, Recycling and Substitution

Cleaner chemistry strategies combine source reduction, improved exhaustion, maximization of recycling and substitution where technically justified.

2.3.1 Cleaner Technologies and Process Innovation

Encouragingly, the leather sector has made significant progress in recent decades, driven by tougher regulations as well as proactive industry initiatives.

2.3.1.1 Sectorial Progress

Key areas of improvement include:

- Stronger regulations are continuously being implemented in different countries to achieve low concentrations of COD, BOD, chromium, sulfide and other pollutants.
- Effluent treatment plants have evolved technologically, and common effluent treatment plants have been built to serve clusters of small tanneries.
- Industry standards have evolved. One major effort has been the creation of unified restricted substance lists that go beyond legal requirements such as the LWG Chemical Management Module.
- Chemical management at a tannery level has become collectively more mature. This proactive chemistry management helps prevent pollution at the source.
- Environmental auditing and certification have increased in adoption. Such programs create positive incentives (tanneries with better ratings gain business advantages) and facilitate knowledge-sharing of best practices and benchmarking. Although evolution is clear, IUS sees that there is still room for more transparency and capacity building in benchmarking tools to allow for collective sectorial progress.
- The industry has improved transparency: many leather manufacturers now publish sustainability reports, and brands often disclose their leather supply chains and progress on sourcing from certified sustainable tanneries.

2.3.1.2 Technological Innovations in the Production Process

The adoption of cleaner process technologies, often referred to as “Best Available Techniques (BAT)”, has significantly reduced the generation of pollutants during leather processing, particularly by preventing or minimizing their formation before they enter wastewater and other emission streams.

For example, many tanneries now use enzymatic unhairing or hair-save methods that drastically reduce the need for sodium sulfide and allow hair to be removed intact rather than dissolved. This innovation cuts down sulfide loading in wastewater and produces collected hair (a solid by-product that can be composted or used in other industries). Ammonia-free deliming is another improvement: using carbon dioxide gas or organic acids to neutralize limed hides in place of ammonium salts prevents ammonia emissions and lowers nitrogen content in effluent.

In the tanning process, companies have optimized conditions to achieve high-exhaustion chrome tanning (i.e. greatly increasing the fraction of applied chromium

that is absorbed by the leather). With careful pH control and masking agents, chrome uptake can exceed 90%, leaving very little residual chrome in the spent liquor. This not only reduces pollution but also saves chemical costs. Additionally, many tanneries have installed systems to recover and reuse chromium from the exhaust liquors: the waste liquor is collected, the remaining chrome is precipitated (with alkali) and filtered out as a sludge, and that sludge is then dissolved in acid to make fresh chrome tanning solution. This closed-loop recycling can be repeated for multiple cycles, dramatically cutting chrome discharge and procurement needs.

There have also been advances in alternative tanning methods. While chrome is still dominant for its superior performance, some tanneries produce chrome-free leathers using combinations of aldehydes, syntans, and vegetable tannins – especially in applications like automotive interiors where chrome allergies or disposal concerns drive demand for "wet-white" leather. These methods have improved (e.g., better control of glutaraldehyde systems, hybrid tanning approaches, etc.), though they have not fully replicated chrome's efficiency yet.

In post-tanning, chemical suppliers have reformulated many products to be safer: modern retanning resins and dyes are typically free of formaldehyde and restricted aromatic amines, and new fatliquors avoid persistent chlorinated oils.

Perhaps the most visible change has been in finishing technology: the shift from solvent-based finishes to water-based finishes across the industry has slashed VOC emissions [22]. Contemporary finishing lines also employ high-transfer-efficiency spray equipment and capture systems, so very little overspray becomes air pollution or waste.

Many tanneries that have embraced these modern techniques report substantially reduced chemical consumption and pollutant generation per hide compared to a few decades ago.

2.4 Concluding Remarks

In leading tanneries, the leather industry's approach to chemical management has evolved from compliance-driven pollution control to proactive evidence-based sustainability.

While chemical usage remains intrinsic to leather manufacture, the sector has its focus on the topic through measurable progress in reducing environmental impact through technological innovation, improved process efficiency, and clearer regulatory frameworks.

Key achievements include:

- Reductions in pollutant loads through high-exhaustion tanning, chromium recycling, and advanced effluent treatment;
- Decreases in hazardous emissions, particularly in VOCs from the shift to water-based finishing systems;
- Enhanced transparency and accountability through MRSL/RSL compliance, sustainability reporting, and third-party certification;
- Source reduction strategies via enzymatic processes, ammonia-free deliming, and optimized chemical uptake.

However, there are still numerous opportunities and gaps to be addressed. Improving chemical uptake and better characterizing the chemicals used in the processes with regards to its environmental credentials can generate considerable progress. Broadening access to sustainable chemical management concepts and tools can also help transform late movers.

The industry's willingness to acknowledge operational hotspots, adopt cleaner technologies, and engage in multi-stakeholder sustainability initiatives poses opportunities to continuously improve leather’s sustainability credentials while maintaining the functional performance that distinguishes natural leather from synthetic alternatives. Collaboration and improvement of benchmarking tools can enable collective continuous improvement, which can in turn further elevate leather’s sustainability credentials.

3. SOLID RESIDUES AND BY-PRODUCTS



3.1 Introduction

Solid residues and by-products are inherent outputs of the leather value chain. The understanding of the factors that drive and influence their generation, together with their proper management, provides the necessary tools to improve the economic and environmental efficiency of tanneries.

This document focuses exclusively on the waste generated in the tannery industrial phase, which means that waste generated from animal production, feed cultivation and related processes are not in scope. A sizable share of the directives here discussed has been based on the guidance provided by the IULTCS documents IUE 2 – "Recommendations for Tannery Solid By-Product Management" [23] and IUE 3 – "Total Dissolved Solids in Tannery Effluent" [24].

3.2. Tannery Operations: Solid By-Products and Residues

3.2.1 Operational Definition

A modern tannery can be seen as a conversion facility. Raw hides enter, and different material streams are generated and exit the tannery as several industrial outputs. Tanned

leather is one of them, but it also produces different by-product materials and residues that are strongly relevant in the mass balance.

Substances that do not leave the plant as leather appear as:

- Process-derived by-products (e.g. fleshings, trimmings, splits, shavings, hair, grease);
- Salt-bearing solids (e.g. dusted salt, evaporator concentrates, salt cakes);
- Sludges and other residues from wastewater and gas treatment.

In the IUE 2 framework, these are treated as industrial outputs that should be designed and managed for valorisation wherever feasible, with disposal reserved as the option of last resort [23].

However, these streams do not have the same environmental or economic significance. From a management perspective, priority should be given to streams that combine:

- High generation volumes;
- High treatment or disposal costs;
- Potential regulatory constraints;
- Significant pollution potential;
- Significant enviromental impact.

In most bovine tanneries, fleshings, wastewater-treatment sludge, salt-related residues and chrome-containing shavings typically account for the largest environmental and operational challenges. Consequently, effective solid-residue management requires not only quantification but also prioritisation according to risk, cost and valorisation potential.

3.2.2 Key Performance Indicators

For industrial benchmarking and communication, IULTCS recommends mass-based indicators expressed per unit of production, for example:

- Total mass of solid by-products and residues (t/year), by stream.
- Mass intensity per unit of production:
    - kg of each by-product per tonne of raw hides;
    - kg of each by-product per m^2 of finished leather, where relevant.
- Distribution of outputs by route:
    - % sent to prevention/avoidance (e.g. chilled supply chains, hair-save);
    - % reused or recycled as material;
    - % routed to energy recovery;
    - % disposed (landfill, incineration or others, without energy recovery).

While these indicators provide useful benchmarking information, waste mass alone should not be interpreted as a measure of sustainability performance. Lower quantities of highly contaminated residues may represent a greater environmental burden than larger quantities of biodegradable by-products.

Therefore, monitoring systems should consider not only volume but also:

- Hazard profile (e.g. chromium content);
- Potential for material recovery;

- Economic value;
- Treatment and disposal costs.

Indicative ranges from IUE 2 for selected streams per tonne of raw hides include [23]:

- Dusted salt from de-salting wet-salted hides: 50–150 kg/t;
- Green fleshings: 70–120 kg/t;
- Limed fleshings: 150–250 kg/t;
- Limed splits: 20–60 kg/t;
- Wet-blue splits, shavings, trimmings and buffing dust together: typically, in the several tens to over 150 kg/t range, depending on article and process design.

These values are indicative and highly dependent on product mix, beamhouse chemistry, splitting strategy and segregation practices.

3.2.3 Process Hotspots

From a solid-residue perspective, not all manufacturing stages contribute equally.

3.2.3.1 Beamhouse

The beamhouse is typically the largest source of solid outputs and often offers the greatest opportunities for reduction, reuse and recycling at source.

Major streams include:

- Dusted salt;
- Green fleshings;
- Green trimmings;
- Limed fleshings;
- Hair;
- Primary-treatment solids and sludge.

Because these materials are generated early in the process, decisions taken at this stage strongly influence downstream treatment costs and valorisation opportunities. By-products recovered in the beamhouse generally offer the highest valorisation potential, while equivalent material streams generated after tanning and retanning are frequently–directed to lower-value recovery routes or waste management due to their altered chemical composition.

3.2.3.2 Tanyard

The tanyard generates lower overall mass than the beamhouse but produces some of the most challenging residue streams:

- Limed splits;
- Wet-blue splits;
- Chrome-containing shavings;
- Chromium-bearing sludge.

Particularly for chrome-tanned leather, these residues require careful segregation and management because chromium content may restrict recycling pathways. Although they can still be valorised within circular-economy schemes, recovery typically involves greater technological complexity, stricter controls and higher costs.

3.2.3.3 Post-Tanning and Finishing

Major residual materials include:

- Trimmings;
- Shavings;
- Buffing dust;
- Finishing sludge.

Although generally smaller in volume, these streams can contain complex mixtures of pigments, polymers, syntans and residual tanning agents that may complicate recovery and recycling.

Overall, the main residue-management opportunities are usually concentrated in the beamhouse, whereas the main contamination and regulatory challenges are often concentrated in chrome-bearing streams generated in tanning and post-tanning operations.

3.3. Reduction, Recycling and Reuse

3.3.1 Process Design and Prevention

Prevention remains the most effective strategy for reducing environmental impacts associated with solid residues.

Waste treatment and recycling require energy, infrastructure and logistics, therefore, avoiding residue generation is usually preferable.

Examples include:

3.3.1.1 Alternative Preservation Strategies

Traditional wet salting remains highly effective for hide preservation but introduces large quantities of salt into the process. Excess salt can increase the salinity of tannery wastewater, complicate effluent treatment, and increase the salt content of solid residues and sludge. High salinity can also limit opportunities for water reuse and, when discharged without adequate control, may contribute to impacts on receiving water bodies and soil.

Alternative approaches include:

- Low-salt curing;
- Mechanical de-salting;
- Chilled-hide systems;
- Fresh-hide processing.

From an environmental perspective, chilled-hide and fresh-hide systems can substantially reduce salt consumption and the associated generation of dusted salt and saline residues. Their implementation, however, depends on logistics, supply-chain reliability and refrigeration infrastructure.

3.3.1.2 Co-production and Hair-save

Due to the protein/collagen rich nature of the raw material, a myriad of opportunities exist to maximize its utilization. Hair-save systems are an established approach to reducing the environmental burden associated with beamhouse operations and generating value for the tannery. Additionally, co-production practices include:

- Fleshings converted into collagen hydrolysates and tallow;
- Limed splits used for gelatine and collagen production;
- Wet-blue residues transformed into leatherboard, composites and specialised hydrolysates.

These applications generally achieve the highest resource efficiency because they optimize for a larger fraction of the original material value.

3.3.1.3 Energy Recovery

It presents itself as a core strategy to turn high-energy waste streams into usable heat, electricity or steam, providing a technologically and economically viable platform for value accrual.

Examples:

- Anaerobic digestion;
- Biogas and biomethane production;
- Biodiesel or soap production from tallow;
- Energy-recovery incineration.

While these routes reduce disposal volumes, they typically capture less value than material recycling and should therefore be considered secondary options when higher-value opportunities are unavailable.

3.3.1.4 Disposal

- Landfill;
- Incineration without energy recovery.

These alternatives remain necessary under some circumstances but should be regarded as end-of-chain solutions after prevention, reuse and recovery opportunities have been exhausted.

In all cases, IUE2 emphasises that the ranking of routes depends not only on intrinsic desirability but also on local infrastructure, market access, regulatory constraints and the maturity of each technology [23].

3.3.2 Residue Treatment and Salt-Related Solids

Certain treatment and water-management choices have direct implications for solid residues.

3.3.2.1 Chrome Recovery

Chrome recovery is among the most impactful circularity measures available to chrome-tanning operations because it simultaneously:

- Reduces chromium discharge;
- Improves sludge quality;
- Reduces consumption of fresh chromium salts;
- Expands future recycling opportunities.

3.2.2.2 Membrane Processes and ZLD (Zero Liquid Discharge)

Reverse osmosis and Zero Liquid Discharge systems can substantially improve water reuse performance. However, these technologies illustrate an important sustainability trade-off.

Rather than eliminating pollutants, they may shift them from the liquid phase into concentrated solid fractions requiring long-term management.

Furthermore, available studies indicate that the final concentration and crystallisation stages of ZLD systems can become major contributors to energy consumption, operating costs and carbon footprint [25].

Therefore, ZLD should be evaluated from a whole-system perspective rather than solely through water-reuse indicators.

3.2.2.3 Sludge Management

Sludge management routes may include:

- Anaerobic digestion;
- Composting;
- Agricultural application (where permitted);
- Thermal treatment.

The optimal route depends on contaminant profile, local regulations, infrastructure availability and life-cycle performance.

These interactions illustrate that decisions taken to manage liquid effluent can substantially reshape the solid-residue profile, reinforcing the need for integrated assessment.

3.4. Trade-Offs and Systemic Perspective

Solid-residue reduction is not impact-neutral. Measures indicate that reduce one class of output may increase burdens elsewhere in the system. Examples can be found in Tables 6 to 9.

3.4.1 Hair-Save Technology

Table 6: Benefits and Challenges of Hair-Save Technologies for Waste Reduction

Benefits	Challenges
Reduced sludge Generation	Additional segregation requirements
Reduced sulfide load	Hygiene management
Improved by-product recovery opportunities	Market dependence for recovered hair

3.4.2 High-Value Collagen Recovery

Table 7: Benefits and Challenges of High-Value Collagen Recovery Technologies

Benefits	Challenges
Significant economic value creation	Strict process-control requirements
Disposal avoidance	Restrictions on certain chemicals
Improved circularity	Higher traceability demands

3.4.3 Thermal Technologies

Table 8: Benefits and Challenges of Thermal Technologies for Residue Management

Benefits	Challenges
Reduced landfill dependence	Potential chromium-management concerns
Energy recovery opportunities	High capital and operating costs
	Residual ash generation

3.4.4 ZLD Systems

Table 9: Benefits and Challenges of ZLD Systems for Residue Management

Benefits	Challenges
Maximum water reuse	Increased energy demand
Minimal liquid discharge	Increased carbon footprint
	Generation of salt cakes with limited valorisation pathways

Consequently, environmental performance should be evaluated using a combination of indicators covering:

- Waste Generation;
- Resource efficiency;
- Energy use;
- Greenhouse gas emissions;
- Toxicity potential;
- Regulatory compliance.

Consistent with IUE 2, route selection should thereby be based on life-cycle assessment and site-specific conditions, not on single indicators such as “waste mass” solely.

3.5. Standards and Reference Framework

Solid-residue and by-product management in the leather sector is supported by a set of regulatory and technical frameworks such as:

- EU Waste Framework Directive [26] and national waste-hierarchy legislation, and comparable frameworks in non-EU jurisdictions;
- Animal by-product regulations (e.g. EU ABPR) governing the classification and permitted uses of fleshings, splits and other collagen-rich streams [27];
- The BAT Reference Document for the Tanning of Hides and Skins (TAN BREF) under the Industrial Emissions Directive, which anchors many of the by-product routes and sludge options described in IUE 2 [23];
- UNIDO guidance on tannery solid waste, chrome management, ZLD and energy aspects [28];
- ISO 59004/59010/59020 circular-economy standards, which provide a terminology and systems perspective aligned with the design-oriented approach in IUE 2 [29].

Private and voluntary frameworks such as the Leather Working Group and emerging product-passport schemes are increasingly integrating solid by-products and residue management into their assessment criteria [8].

3.6. Concluding Remarks

Solid residues and by-products in the leather value chain require differentiation and contextual interpretation, as is the case for water-related matters, while recognizing the specific drivers and management challenges associated with each type of material:

- Tanneries function as conversion facilities that generate multiple industrial outputs, many of which pose significant valorisation potential;
- The largest environmental and economic opportunities are typically associated with high-volume streams such as fleshings, sludge and salt-related residues, together with higher-risk streams containing chromium;

- Prevention remains the preferred strategy, particularly through reduced salt inputs, improved beamhouse practices, segregation of by-product streams and optimisation of chemical use;
- Chrome recovery and material valorisation are generally among the most effective circular-economy interventions available to modern tanneries;
- Material recycling should be prioritised over energy recovery whenever feasible, as it preserves more of the original resource value;
- Sustainability performance cannot be measured solely through reductions in waste mass, since many technologies may shift environmental burdens between waste generation, water use, energy consumption, and emissions;
- Robust decision-making should therefore adopt a life-cycle and systems-based perspective that considers technical feasibility, economics, environmental performance and long-term regulatory compliance simultaneously.

A science-based and transparent approach, grounded in the principles set out in IUE 2 and IUE 3, allows the leather sector to address solid-waste-related externalities with methodological rigour and institutional credibility, consistent with the mission of IULTCS.

Closing Remarks

The leather industry is, itself, a testament of complete industrial overhaul over the years. The modern industrial parks seen today bear absolutely no resemblance to the ones from the past, and so are the current environmental metrics. The sector has coordinated itself, created and implemented environmental checks, metrics and audits, innovated on technologies such as closed-loop chrome recovery, pickle-free tanning and multiple others, gave new meanings to waste and maximized co-production. These evolutions are part of the collective building of multiple minds, from India to Spain to Brazil.

Yet, the advances are not homogeneous. Many of the gains mentioned in this document are specific to leading tanneries, not the industry as a whole. Closing the gap between best-in-class performers and the broader value chain is imperative for the collective evolution of the sector. What is required for scaling is not necessarily invention, but diffusion. The same applies to shortening the gap between mandatory compliance and voluntary leadership: it was leadership that technologically transformed the industry, and only leadership can set the path towards the further sustainable revolutions we can expect for the future of the material. After all, the hide is a renewable protein-heavy platform from which nothing is lost if the supply chain is properly engineered.

The path forward requires first that the sector humbly acknowledges its inherent imperfection and room for improvement. If the sector has technologically evolved several-fold along the last years, it could potentially improve multiple times more. The substrate in its hands is a versatile, organic, renewable, compostable, and a by-product of another industry that will only grow, making it perfectly suitable to the most strict requirements for the materials of the future. But it is only with a continuous improvement focused evidence-based approach that it will assure its position as a sustainable material of the future.

Leadership requires entrepreneurship, courage and knowledge. For the latter, please always count with IULTCS to produce shared knowledge, investing on the underpinnings of a successful and sustainable leather of the future.

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