Wastewater CLI-Mate: A sector-specific Digital Platform for Carbon Footprint Assessment and Decarbonisation Pathways in Leather Manufacturing Impact of Tannery Effluents on Aquatic Biota: Fish as Bioindicator for

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CLI-Mate: A sector-specific Digital Platform for Carbon Footprint Assessment and Decarbonisation Pathways in Leather Manufacturing

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Abstract

India’s national commitment to achieve Net-Zero carbon emissions by 2070 places significant responsibility on resource-intensive sectors such as leather manufacturing to adopt transparent, standardised, and scientifically robust greenhouse gas (GHG) assessment frameworks. Conventional carbon accounting tools often lack the process-specific granularity required to capture the complex biochemical and physico-chemical transformations inherent to leather processing, leading to uncertainty and inconsistent reporting. To address this limitation, CLI-Mate, an exclusive digital platform, has been developed to assess the carbon footprint of leather manufacturing operations and associated wastewater treatment systems with high precision and reproducibility. By quantifying emissions, tanneries can better understand their environmental impact and identify opportunities for emission reduction.

CLI-Mate employs a modular architecture covering: (i) raw material and chemical inputs; (ii) beamhouse, tanning, post-tanning, finishing, and utility consumption; (iii) solid-waste generation, handling, and potential valorisation pathways; and (iv) ETP/ CETP operations, including sludge treatment. Each module captures detailed operational, chemical, and energy parameters to generate accurate and reproducible carbon footprint estimates.

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The platform incorporates a life-cycle-based approach

encompassing all stages of leather production, from raw material acquisition to final product distribution.

Key parameters such as energy use, chemical consumption, waste generation, and transportation are

systematically analysed. In addition, CLI-Mate enables scenario analysis and optimisation to support

identification of emission hotspots and resourceefficiency improvement pathways.

Field deployment in Indian and African tanneries

demonstrated the applicability and robustness of the system. Initial results indicate that tanneries can

identify significant carbon hotspots and evaluate decarbonisation pathways across key processing

stages. By offering a science-driven, sector-specific digital framework, CLI-Mate supports alignment with

Climate Action 2070 and global sustainability goals for 2050 and beyond.

Keywords: Carbon Footprint Assessment; Leather

Manufacturing; Tanning Industry; Climate Action 2070; Life Cycle Assessment; Digital Sustainability Tools

1 Introduction

Climate change mitigation has emerged as a central

priority for industrial development worldwide, with greenhouse gas emissions accounting and reduction

becoming integral to policy, trade, and regulatory

frameworks (Chen et al., 2014). In this context, India's commitment to achieve net-zero carbon emissions by 2070 has placed renewed emphasis on transitioning resourceintensive manufacturing sectors toward low-carbon and climate-aligned production pathways (Carcione et al., 2023).

The global leather industry is recognised as a significant contributor to environmental degradation, ranking among the most polluting industries due to its intensive use of water and chemicals (Islayem et al., 2025; Brugnoli et al., 2025). Leather manufacturing involves a complex sequence of biochemical and physico-chemical transformations, including beamhouse operations, tanning, post-tanning, finishing, and associated waste management processes (Daddi et al., 2024; Laurenti et al., 2016). Each stage contributes differently to energy consumption, chemical usage, waste generation, and indirect emissions linked to utilities and logistics (Ardolino et al., 2024).

However, existing carbon footprint assessment tools are largely generic and insufficiently tailored to capture the process-specific dynamics of leather processing . As a result, emission estimates often suffer from aggregation bias, inconsistent system boundaries, and limited representation of waste management and wastewater treatment systems such as Effluent Treatment Plants (ETP) (Kiliç et al., 2018). The absence of a dedicated, sector-specific digital framework restricts the industry's ability to reliably quantify emissions, identify carbon hotspots, and design effective decarbonisation strategies . Furthermore, increasing global market requirements for sustainability disclosure, product environmental footprints, and compliance with international standards necessitate a transparent and reproducible approach to carbon accounting in the leather sector (Yang et al., 2021).

In response to these challenges, the present study aims to develop and demonstrate a tool namely "CLI-Mate", an exclusive digital platform for comprehensive carbon footprint assessment of tanning operations and associated wastewater treatment systems. The objectives of this study are to:

establish a structured, process-level framework

for carbon accounting in the tanning industry;

 integrate operational, chemical, energy, and waste-

management data within a life-cycle-based boundary; and

 provide a scientifically robust and reproducible

tool to support decarbonisation planning and policy alignment.

The scope of CLI-Mate covers the entire leather manufacturing chain from raw material and chemical inputs through beamhouse, tanning, post-tanning, finishing, and waste management operations. This helps the leather industry to progress toward Climate Action 2070 and the broader sustainability vision of Leather 2050.

2 Methodology

2.1 Conceptual Framework of the CLI-Mate Tool

The CLI-Mate tool is founded on the premise that accurate carbon footprint assessment in the tanning industry requires process-level resolution supported by standardised emission accounting within an integrated digital framework. In contrast to generic organisational carbon calculators, CLI-Mate adopts a sector-specific, process-oriented approach that reflects the characteristic material flows, chemical transformations, energy demands, and waste management practices of leather manufacturing.

The framework enables systematic quantification of carbon emissions across all major stages of leather processing, including raw hide storage, beamhouse operations, tanning, post-tanning, finishing, and associated environmental management systems. Key contributors such as energy consumption, chemical use, water intake, wastewater generation, and solid-waste handling, are explicitly incorporated to ensure comprehensive carbon profiling. Particular emphasis is placed on emissions arising from Effluent Treatment Plants (ETP) and Common Effluent Treatment Plants (CETP), which are frequently underestimated in conventional carbon assessments.

CLI-Mate is designed to be scalable and adaptable across different operational contexts, ranging from small and medium tanneries to large industrial units. This flexibility recognises variations in process intensity, resource efficiency, and sustainability potential associated with production scale and technological maturity. By integrating process-specific operational data within a life-cycle-based system boundary, the CLI-Mate framework provides a robust basis for identifying carbon-intensive operations and supporting informed decision-making toward low-carbon and sustainable leather manufacturing.

Fig. 1. Home Page of CLI-Mate Tool

2.2 System Architecture and Module Description

The CLI-Mate platform is developed with a modular and scalable system architecture to enable transparent, process-level carbon footprint assessment across diverse tannery configurations. The architecture integrates data capture, emission computation, and result visualisation within a unified digital framework, ensuring traceability and consistency of carbon calculations. Functional modules cover raw material and chemical inputs, core process operations, utilities and energy use, solid waste and by-

product management, and wastewater treatment through ETP/CETP systems. Each module independently converts activity data into carbon dioxide equivalent (CO_2e) emissions, which are subsequently aggregated to generate process-wise and facility-level carbon footprints. A central aggregation and reporting layer consolidates results and presents them in structured tables and graphical formats to support benchmarking and sustainability reporting. Overall, the modular design ensures flexibility, adaptability, and practical applicability of CLI-Mate for strategic carbon management in the leather industry.

2.3 Data Inputs and Calculation Approach

The accuracy and reliability of carbon footprint assessment in CLI-Mate are primarily governed by the quality of input data and the robustness of the emission calculation methodology. Accordingly, the tool adopts a structured data input framework combined with internationally recognised emission accounting principles to ensure transparency, reproducibility, and comparability of results.

2.3.1 Data Input Framework

CLI-Mate captures data at the process-unit level, ensuring that all major sources of emissions are systematically accounted for. The principal categories of input data include:

 Material Inputs: Quantity of raw hides/skins, curing agents, tanning chemicals, auxiliaries, dyes, and finishing chemicals consumed at each processing stage.

 Energy Inputs: Electricity consumption (gridbased) and fuel usage in boilers, generators, and thermal systems, recorded in appropriate units (kWh, kg, or litres).

 Water and Wastewater Data: Freshwater intake, recycling and reuse, wastewater generation volumes, and treatment flows through ETP/CETP systems.

 Waste and By-product Data: Quantities of solid wastes such as hair, fleshings, shavings, trimmings, and treatment sludge, along with handling and disposal methods.

 Operational Parameters: Production capacity, operating hours, batch size, and process duration, enabling normalisation of emissions on a functional unit basis (e.g., per tonne of finished leather or per sq. ft of finished leather).

Data are primarily collected from plant-level operational records, utility meters, chemical consumption logs, and treatment plant monitoring reports. Where direct measurements are unavailable, conservative default values are applied to maintain consistency.

2.3.2 Emission Calculation Methodology

‘Emission calculations in CLI-Mate follow an activitybased approach, wherein each activity data point is multiplied by an appropriate emission factor to derive carbon dioxide equivalent (CO_2 e) emissions. The general calculation principle is expressed as:

$$\text{GHG Emissions } (CO_2e) = \sum (\text{Activity Data} \times \text{Emission Factor})$$

Emission factors are sourced from IPCC Guidelines, national electricity grid factors, and internationally accepted life-cycle databases, ensuring methodological alignment with ISO 14064 and GHG Protocol principles.

2.3.3 Scope-wise Emission Classification

CLI-Mate categorises emissions into:

 Scope 1: Direct emissions from on-site fuel combustion and process-related activities.

 Scope 2: Indirect emissions from purchased electricity.

 Scope 3: Upstream emissions associated with chemical production, material transportation, and waste handling.

This classification facilitates standardised reporting and supports compliance with evolving sustainability disclosure requirements.

2.3.4 Normalisation and Output Generation

Emissions are normalised against defined functional units, typically per tonne of leather or per sq. ft of leather or per m2 of leather, enabling benchmarking across different production scales and process configurations. Aggregated and module-wise results are generated to identify carbonintensive operations and support decision-making.

Through this structured data input and calculation framework, CLI-Mate delivers scientifically robust and industry-relevant carbon footprint assessments tailored to the tanning sector.

3 Results and Discussion

The results obtained from the development and application of the CLI-Mate software tool are presented and discussed in this section, with emphasis on its modular architecture, functional performance, and capability to generate detailed carbon footprint and carbon credit assessments for the tanning industry. The software framework is organised around three major analytical categories that represent the principal sources of greenhouse gas emissions and mitigation potential within leather manufacturing systems: (i) processes, including leather production and waste management; (ii) infrastructure facilities; and (iii) renewable production and biological carbon sequestration. This categorisation enables a structured and holistic evaluation of emissions and offsets across the entire production and environmental management chain.

3.1 Infrastructure Database Module: Machinery and Chemical Inventory

The Infrastructure Database Module establishes the operational baseline of the tannery by capturing detailed information on machinery, process equipment, utilities, and chemical inventories. Data related to installed capacities,

operational status, and chemical consumption across different processing stages are systematically recorded. This module supports consistent activity data generation and improves the reliability of emission calculations by linking infrastructure configuration with process performance. The infrastructure database also enables differentiation of carbon profiles across tanneries of varying capacities and technological maturity.

Fig. 2. Snapshot of “Infrastructure Database Module”

3.2 Carbon Footprint Determination Module : Process Operations

The Process Operations Module of the CLI-Mate platform enables detailed quantification of carbon emissions associated with core leather processing operations, providing high-resolution insights into processspecific climate impacts. Energy consumption, fuel usage, and process-specific inputs are evaluated at the unitoperation level. A key strength of this module is its ability to evaluate carbon footprints across different leather types and processing routes, reflecting the diversity of products and technologies employed within the tanning industry.

The module allows users to define and select various process pathways by incorporating the type of leather being produced (e.g., bovine, ovine, or speciality leathers) and the corresponding processing sequence adopted by the industry. Each process is assigned a unique Process ID, linked to the name of the leather, type of leather, and the specific unit operations involved. This structured identification ensures traceability and facilitates comparison of carbon performance across multiple products and process configurations.

Fig. 3. Snapshot of “Infrastructure Database Module”

CLI-Mate further supports assessment of newly developed or modified processes, enabling users to evaluate the carbon implications of process innovations prior to large-scale implementation. By entering processspecific operational data such as energy consumption, chemical inputs, and processing duration, the tool computes the associated carbon emissions using standardised emission factors.

For each defined process, carbon emissions are normalised and reported as CO2e per unit of production, expressed

either per square foot of leather or per kilogram of finished leather, depending on the selected functional unit. This dual normalisation enhances comparability across different leather categories and market segments. The resulting process-wise emission values allow identification of carbon-intensive operations and provide a quantitative basis for benchmarking existing processes against alternative or improved technologies.

Overall, the Process Operations Module transforms carbon footprint assessment from a facility-level exercise into a process- and product-specific evaluation, supporting informed decision-making, process optimisation, and strategic planning for low-carbon leather manufacturing.

3.3 Carbon Footprint Determination Module : Waste Management (Solid and Liquid)

The Waste Management Module of the CLI-Mate platform is designed to comprehensively quantify carbon emissions associated with the handling, treatment, and disposal of solid and liquid wastes generated during leather manufacturing. Recognising that waste management represents a significant yet often underestimated contributor to the overall carbon footprint of tanneries, this module explicitly captures emissions beyond core production operations.

3.3.1 Solid Waste Management

Solid wastes arising from leather processing including hair, fleshings, trimmings, shavings, buffing dust, and treatment sludge, are systematically quantified within the module. For each waste stream, CLI-Mate records the quantity generated, mode of collection, storage practices, transport distance, and final disposal or utilisation pathway. Emissions associated with these activities are calculated using activity-based emission factors, reflecting fuel consumption, handling energy, and disposal-related impacts.

By distinguishing between different solid waste categories, the module enables identification of waste streams with higher carbon intensity and supports evaluation of alternative handling or utilisation pathways. This granular

assessment allows tanneries to understand the climate implications of their waste management practices and supports informed decisions toward emission reduction and improved sustainability performance.

3.3.2 Liquid Waste Management and Effluent Treatment

Liquid waste emissions are addressed through explicit integration of Effluent Treatment Plant (ETP) and Common Effluent Treatment Plant (CETP) operations. The module captures influent volumes, energy consumption, chemical dosing, sludge generation, and treatment efficiency associated with wastewater processing. Emissions arising from electricity and fuel use in treatment systems, as well as sludge handling and

disposal, are quantified and expressed in CO_2e

Unlike generic carbon assessment approaches that treat wastewater management as a peripheral activity, CLIMate incorporates treatment-related emissions as a core component of the overall carbon footprint. This approach ensures realistic accounting of emissions associated with compliance-driven environmental management systems.

3.3.3 Integration with Process-Level Emissions

While process-related emissions are addressed through the Process Operations module, the Waste Management module functions as a complementary component that captures downstream impacts of production activities. The integration of solid and liquid waste emissions enables a comprehensive assessment of the carbon footprint across the entire production and treatment process.

Overall, the Waste Management Module enhances the completeness and credibility of carbon footprint assessments generated by CLI-Mate. By explicitly accounting for emissions associated with waste handling and treatment, the tool supports identification of carbonintensive waste streams and enables targeted strategies for emission reduction within the tanning industry.

Fig. 4. Snapshot of “Waste management Module”

3.4 Carbon Credit Module: Renewable Energy and Tree-Based Sequestration

The Carbon Credit Module of the CLI-Mate platform is designed to quantify emission offsets arising from renewable energy generation and biological carbon sequestration, thereby enabling assessment of net carbon emissions for tanning operations. This module complements the emission-generation modules by integrating mitigation measures within the same analytical framework.

3.4.1 Renewable Energy-Based Carbon Credits

Renewable energy-based carbon credits are calculated by accounting for electricity generated from renewable sources that displace conventional grid electricity. CLIMate captures data on the type of renewable energy system employed (such as solar or wind), installed capacity, energy generation, and operational duration. Carbon credits are estimated using nationally accepted grid emission factors, reflecting avoided emissions due to the substitution of fossil-fuel-based electricity.

This approach allows tanneries to transparently quantify the climate benefits of renewable energy adoption and evaluate its contribution toward reducing net emissions at the facility level.

3.4.2 Tree-Based Carbon Sequestration

The module also quantifies carbon sequestration resulting from tree plantation and growth, recognising biological sinks as an important component of long-term climate mitigation strategies. CLI-Mate records information related to tree species, age or size class, and number of trees, and applies standard carbon absorption coefficients to estimate annual carbon sequestration in terms of CO2e

By incorporating bioremediation, the module supports evaluation of afforestation and green-belt initiatives commonly undertaken by tanneries as part of environmental compliance and corporate sustainability programmes.

3.4.3 Integration for Net Carbon Assessment

Carbon credits from renewable energy and tree-based sequestration are aggregated and offset against total emissions generated from process operations and waste management modules. The resulting net carbon footprint provides a comprehensive and balanced representation of the facility's climate impact.

Overall, the Carbon Credit Module enhances the analytical depth of CLI-Mate by moving beyond emission quantification to include mitigation accounting. This integrated assessment supports strategic planning, sustainability reporting, and alignment with long-term climate action targets in the leather industry.

3.5 User Architecture: Admin and User Interfaces

The user architecture of the CLI-Mate platform is designed to ensure data integrity, controlled access, and ease of application across diverse tannery environments. The system adopts a role-based access framework, comprising admin and user interfaces, which supports efficient data management while maintaining methodological consistency in carbon footprint assessment.

3.5.1 Admin Interface

The Admin Interface serves as the control layer of the CLI-Mate platform. It is responsible for managing master datasets, including emission factors, process libraries, chemical databases, and system configuration parameters. The admin module ensures that calculation logic and reference data remain standardised and aligned with recognised guidelines, thereby preventing inconsistencies across different users and facilities. In addition, the admin interface manages user authentication, access permissions, and periodic updates to methodological assumptions, ensuring transparency and traceability of changes within the system.

3.5.2 User Interface and Company Profile Management

The user interface is designed for tannery-level application and supports the creation of company-specific profiles. Users can enter operational data related to production volumes, process configurations, energy consumption, waste generation, and renewable energy initiatives. The interface is structured to facilitate intuitive data entry while minimising complexity, enabling adoption without requiring specialised expertise in carbon accounting.

The company profile functionality allows each tannery to maintain a historical record of data submissions, enabling yearon-year comparison of carbon performance. Users can generate process-wise and facility-level assessments while retaining confidentiality of sensitive operational information.

Overall, the user architecture of CLI-Mate balances usability with data governance, enabling consistent application of the tool across multiple facilities and supporting reliable carbon footprint reporting, internal review, and sustainability benchmarking within the leather industry.

3.6 Generation of Final Carbon Footprint and Carbon Credit Reports

A key functional outcome of the CLI-Mate platform is the automated generation of a comprehensive final carbon

assessment report, integrating emissions from process operations, waste management systems, and carbon credits within a single, standardised reporting framework. The report is designed to support technical interpretation, management decision-making, and sustainability disclosure requirements.

The final report presents carbon emissions at multiple hierarchical levels, including unit-operation-wise emissions, process-category-wise emissions, and total facility-level carbon footprints. Emissions are expressed in terms of carbon dioxide equivalents (CO2e) and classified under Scope 1, Scope 2, and selected Scope 3 categories in alignment with international carbon accounting practices. Normalisation of results is carried out using defined functional units, such as per square foot of leather or per kilogram of finished leather, enabling comparability across leather types and production scales.

In addition to emission quantification, the report incorporates results from the Carbon Credit Module, summarising emission offsets achieved through renewable energy generation and tree-based carbon sequestration. These credits are reported alongside gross emissions to derive net carbon emissions, providing a

balanced representation of both emission sources and mitigation measures.

The report structure includes graphical summaries and tabulated outputs that highlight carbon-intensive unit operations, contributions from waste management and effluent treatment systems, and the relative impact of renewable and sequestration initiatives. This presentation enables rapid identification of carbon hotspots and supports prioritisation of mitigation strategies.

Overall, the final report generated by CLI-Mate serves as a decision-support document, facilitating internal benchmarking, progress tracking, and transparent communication of carbon performance. By consolidating emissions and credits into a single, traceable output, the reporting module strengthens the practical applicability of CLI-Mate for decarbonisation planning and sustainability reporting within the tanning industry.

4. Conclusion

The CLI-Mate platform provides a structured, sectorspecific approach for comprehensive carbon footprint and carbon credit assessment in the tanning industry. By integrating process-level emissions, waste management impacts, and mitigation measures within a single digital framework, the tool overcomes key limitations of generic carbon accounting methods. The modular architecture enables quantification of emissions at the level of individual unit operations and leather types, supporting practical application across varied production scales.

The inclusion of ETP/CETP-related emissions and carbon credits from renewable energy and tree-based sequestration enhances the completeness and credibility of the assessment. CLI-Mate thus serves as an effective decision-support tool for identifying carbon hotspots, tracking performance, and supporting decarbonisation strategies.

Overall, the platform strengthens the leather industry’s capability to align operational practices with India’s Climate Action 2070 commitment and the long-term sustainability vision of Leather 2050, contributing to a measurable transition toward low-carbon leather manufacturing.

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