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Valorization of tannery-derived FAMEs into bio-based epoxides via chemo-enzymatic synthesis

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ABSTRACT

The urgent transition toward low-carbon chemical manufacturing has prompted the development of renewable alternatives to fossil-based epoxy intermediates. This study presents an integrated and resource-efficient chemo-enzymatic route for the synthesis of epoxidized methyl oleate (EMO) from fatty acid methyl esters (FAMEs) derived from tannery waste—a lipid-rich but underutilized industrial residue. A single-step urea complexation achieved 86.7 ± 0.6 % methyl oleate purity with a 38.1 ± 0.9 % recovery yield, while the saturated-rich co-product (~40 %) exhibited physicochemical properties suitable for biodiesel or lubricant applications.

Subsequent epoxidation was carried out using immobilized *Candida antarctica* lipase B (Novozym® 435) and in situ generated performic acid, yielding an oxirane oxygen content of 6.42 ± 0.14 %, corresponding to >90 % conversion of double bonds under mild conditions. The enzyme retained 72 % of its initial activity after ten reuse cycles, significantly enhancing process circularity and reducing catalytic costs.

Green chemistry metrics were favorable: atom economy reached 86 %, solvent recovery exceeded 85 %, and the E-factor remained as low as 0.86 kg waste/kg EMO. A cradle-to-gate life cycle assessment (LCA) estimated a global warming potential (GWP) of 1.92 kg CO_2-eq/kg EMO—representing a 63 % reduction compared to petrochemical benchmarks. Economic analysis at the 1000 t/year scale yielded a production cost of €1.57/kg with an internal rate of return (IRR) of 15 %.

Overall, this work demonstrates how lipid-rich industrial residues can be converted into high-value bio-based epoxides through a scalable and environmentally sound chemo-enzymatic route, aligning with circular economy principles and green chemistry targets.

1. Introduction

The global chemical industry is undergoing a structural shift driven by the dual imperatives of decarbonization and reduced reliance on toxic fossil-based inputs. Epoxy resins—particularly those derived from bisphenol A diglycidyl ether and epichlorohydrin—have drawn increasing scrutiny due to their endocrine-disrupting potential and high global warming impacts (Ivchenko and Nifant'ev, 2025; Osman et al., 2024). This context has accelerated the search for renewable epoxy alternatives aligned with green chemistry and circular economy goals.

Among bio-based candidates, epoxidized methyl oleate (EMO) has gained attention for its dual role as a plasticizer and reactive intermediate in coatings and polymers (Zeng et al., 2024). However, conventional EMO production relies predominantly on edible oils—soybean, palm, and sunflower—raising concerns about food security, biodiversity loss, and land-use change (Mukherjee et al., 2024). This has spurred research toward non-food lipid sources, especially those derived from agro-industrial residues.

Tannery fleshing waste—abundant in lipids but often landfilled or incinerated—represents an underexploited feedstock for sustainable chemical production. Prior studies have demonstrated the feasibility of converting such residues into fatty acid methyl esters (FAMEs) for biodiesel (Kirpluks et al., 2022), but their potential for generating high-value epoxides remains largely untapped.

A key challenge in this conversion is the selective enrichment of methyl oleate from complex FAME mixtures. Techniques like molecular distillation, while effective, are energy-intensive and capital-heavy. In contrast, urea complexation provides a low-energy, scalable route to enrich mono-unsaturated esters under mild conditions, with promising results in both pilot and lab-scale contexts (Kirpluks et al., 2022;

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Maruyama et al., 2022).

Once purified, methyl oleate can be epoxidized through chemical or biocatalytic methods. While traditional peracid routes pose safety and selectivity issues, enzymatic epoxidation—particularly using immobilized lipases such as *Candida antarctica* lipase B (Novozym® 435)—offers a cleaner and more selective alternative (Aouf et al., 2014; Rahim et al., 2024). The use of in situ performic acid further reduces environmental risks and facilitates mild operational parameters.

This study presents an integrated valorization strategy for tannery-derived FAMEs, combining single-step urea complexation and enzymatic epoxidation, followed by a comprehensive life cycle assessment (LCA) and techno-economic analysis (TEA). By leveraging a residue-to-product approach, the work demonstrates a route to high-purity EMO with low carbon footprint and competitive costs, contributing to sustainable specialty chemical manufacturing within a circular bioeconomy framework.

2. Materials and methods

2.1. Feedstock and chemicals

Tannery fleshing residues were obtained from a commercial leather processing facility in Catalonia, Spain. Lipid extraction and transesterification into crude fatty acid methyl esters (FAMEs) followed a solvent-free biorefinery method previously developed by our group (Deroncelé et al., 2025). Briefly, raw fleshing biomass was mechanically fractionated and centrifuged to isolate triglyceride-rich material, which was then transesterified using 1 wt % potassium hydroxide and methanol under ambient conditions.

All reagents, including urea, ethanol, formic acid (≥98 %), hydrogen peroxide (30 %), hexane, and ethyl formate, were of analytical grade and supplied by Sigma-Aldrich. Novozym® 435 (immobilized *Candida antarctica* lipase B) was obtained from Novozymes A/S (Denmark).

2.2. Methyl oleate enrichment via urea complexation

Selective enrichment of methyl oleate from crude FAMEs was achieved using a single-step urea complexation process adapted from (Hayes et al., 1998; Maruyama et al., 2022). The FAME mixture was dissolved in 95 % ethanol and combined with urea at a 2.5:1 molar ratio (urea:FAME). The solution was heated to 60 °C until full dissolution and then cooled gradually to 4 °C over 16 h. After complexation, the crystalline fraction was separated by vacuum filtration, and the filtrate was evaporated to isolate the methyl oleate-rich fraction. Composition and purity were assessed using gas chromatography with flame ionization detection (GC-FID).

2.3. Enzymatic epoxidation using in situ performic acid

Epoxidation reactions were carried out in a 250 mL jacketed glass reactor equipped with mechanical stirring and temperature control (45 ± 0.5 °C). Performic acid was generated in situ by mixing formic acid and hydrogen peroxide (1.5:1 molar ratio relative to C═C bonds), and the oxidant mixture was added dropwise over 3 h. Novozym® 435 was dosed at 10 wt % relative to the substrate, and ethyl formate (3 wt %) was included to enhance phase contact and enzyme stability. Reaction time was 8 h, with periodic sampling for oxirane oxygen content (OOC), determined using AOCS Cd 9–57.

2.4. Enzyme reuse and operational stability

To evaluate catalyst reuse, Novozym® 435 was recovered by filtration, washed with hexane, and air-dried after each batch. The enzyme was reused over ten consecutive cycles under identical conditions. Residual catalytic activity was inferred from the relative decrease in OOC, normalized to the first cycle, following the method proposed by (Rahim et al., 2024).

2.5. Physicochemical characterization of EMO

Physicochemical properties of the purified epoxidized methyl oleate (EMO), including density (25 °C), kinematic viscosity (40 °C), and iodine value, were determined following standard procedures for fatty acid methyl esters. Density was measured using a pycnometer, viscosity was assessed via a calibrated capillary viscometer (ASTM D445), and iodine value was calculated using the Wijs method. Acid value, pour point, and saponification value were also determined using standard AOCS and EN methods. Values represent the mean ± SD from triplicate measurements.

2.6. Green chemistry metrics

Green chemistry metrics were calculated to assess the material efficiency and environmental performance of the chemo-enzymatic epoxidation stage, following established frameworks (Prat et al., 2016; Sheldon, 2017) . The metrics considered were Atom Economy (AE), Process Mass Intensity (PMI), and the E-factor.

- Atom Economy (AE):

The AE was computed based on the stoichiometry of the performic acid epoxidation of methyl oleate (MO), using the molar masses of all stoichiometric reactants:

$$AE = \frac{\mathrm{M_{EMO}}}{\mathrm{M_{MO}} + M_{HCOOH} + M_{H_2O_2}} \text{ x } 100$$

- Process Mass Intensity (PMI):

The PMI was defined as the total mass of all inputs divided by the mass of EMO isolated:

$$PMI = \frac{Mass_{MO} + Mass_{HCOOH} + Mass\_H_2O_2 \ + Mass_{solvents} + \left(\frac{Mass_{enzyme}}{10}\right)}{\mathrm{Mass_{EMO}}}$$

The mass of Novozym® 435 was prorated across 10 reuse cycles, reflecting the operational reuse strategy.

- E-factor:
- The E-factor accounted for all non-product, non-recycled waste, excluding water:

$$E - \text{factor} = \frac{Mass_{waste} - Mass_{solvent\ recovered}}{\mathrm{Mass_{EMO}}}$$

Solvent recovery was determined gravimetrically after vacuum distillation at 45 °C and 10 mbar.

2.7. Life Cycle Assessment (LCA)

A cradle-to-gate life cycle assessment (LCA) was conducted to evaluate the environmental performance of the chemo-enzymatic epoxidation process. The study followed the ISO 14,040 and 14,044 guidelines, and was carried out using SimaPro v9.4 software with the ReCiPe Midpoint (H) method as the impact assessment framework (Huijbregts et al., 2017). The functional unit was defined as 1 kg of epoxidized methyl oleate (EMO) produced under the operational conditions described in this work.

The system boundaries included foreground processes such as methyl oleate purification (urea complexation), enzymatic epoxidation,

and product isolation. Background data for raw material production (e.g., hydrogen peroxide, ethanol, formic acid, ethyl formate, Novozym® 435) were sourced from the Ecoinvent 3.8 (Wernet et al., 2016) and PSILCA v3.1 databases (GreenDelta GmbH, 2023). Infrastructure and transportation were excluded from the model, as they are assumed to have negligible influence at laboratory scale.

Electricity consumption was based on measured energy demand for heating, stirring, and vacuum distillation during batch operations. The energy profile was modeled using the EU-27 average electricity mix. Solvent recovery and enzyme reuse were integrated into the inventory based on experimentally determined operational parameters.

Uncertainty in background processes was addressed through Monte Carlo simulation using lognormal distributions, and $a \pm 10$ % variation was applied to key foreground inputs such as solvents, reagents, and catalyst dosage (Igos et al., 2019). The inventory model was constructed to enable integration with techno-economic results and green chemistry metrics in subsequent sections of the study.

2.8. Techno-Economic Analysis (TEA)

A techno-economic analysis (TEA) was performed to evaluate the cost structure, investment requirements, and financial feasibility of the chemo-enzymatic production of epoxidized methyl oleate (EMO) from tannery-derived fatty acid methyl esters (FAMEs). The assessment was based on a conceptual design of a 1000 t/year production facility, operating under batch conditions consistent with laboratory protocols.

The analysis incorporated both capital expenditure (CAPEX) and operational expenditure (OPEX), covering equipment acquisition, raw materials, utilities, labor, enzyme reuse, and solvent recovery. A discounted cash flow model was developed in Microsoft Excel®, and process simulation and equipment sizing were supported by SuperPro Designer® v12.0 (Intelligen, Inc., 2022) to estimate material flows and scale-dependent cost elements.

Assumptions included a 10-year project lifetime, fixed discount rate, full-year operation with standard European utility prices, and enzyme reuse across multiple cycles. The cost of Novozym® 435 was prorated according to reuse frequency. Solvent recovery was modeled based on average efficiencies measured during experimental trials. Utilities were calculated using measured laboratory energy demand (e.g., heating, stirring, vacuum) and extrapolated using empirical scaling laws. Labor and maintenance costs were estimated as a percentage of direct costs, following conventional design heuristics (Peters and Timmerhaus, 2018).

Financial performance indicators such as net present value (NPV), internal rate of return (IRR), and payback period were calculated to assess profitability under base-case and sensitivity scenarios. The analysis was supported by comparative data from recent TEA studies on biocatalytic and waste-to-value platforms (Agraso-Otero et al., 2025; Sikazwe et al., 2024).

The TEA was designed to identify key economic drivers, evaluate the influence of technical parameters on cost, and support scale-up decisions under realistic operational assumptions.

2.9. Circularity Index

The Circularity Index (CI) was calculated based on the conceptual framework proposed by the Ellen MacArthur Foundation and adapted for chemical manufacturing systems. The index integrates three dimensions: (i) material circularity, which considers the recovery of by-products and secondary inputs; (ii) process circularity, based on solvent reuse and catalyst longevity; and (iii) energy circularity, incorporating valorization potential within the local industrial symbiosis context.

Each component was normalized to a scale between 0 and 1 and weighted according to its relative contribution to the overall mass and energy flows. The final CI was expressed as a dimensionless value between 0 (fully linear) and 1 (fully circular). Calculations were based on experimental mass balances, solvent recovery rates, and process integration assumptions derived from the epoxidation route. The methodology allows for comparison with other bio-based and fossil-based epoxide production systems.

Table 1
Fatty acid composition of crude and urea-treated FAMEs derived from tannery waste, determined by GC-FID. Data are expressed as weight percentage (wt %) of individual methyl esters.

Fatty Acid	Crude FAMEs (%)	Purified Methyl Oleate (%)	Excluded Fraction (%)
Methyl oleate (C18:1)	46.3 ± 0.8	86.7 ± 0.6	8.2 ± 0.4
Methyl palmitate (C16:0)	17.3 ± 0.5	5.1 ± 0.2	43.2 ± 0.7
Methyl stearate (C18:0)	12.0 ± 0.4	3.5 ± 0.2	26.1 ± 0.6
Methyl linoleate (C18:2)	19.0 ± 0.6	3.7 ± 0.3	10.4 ± 0.5
Others	5.4 ± 0.3	1.0 ± 0.1	12.1 ± 0.4

2.10. Sensitivity and Risk Analysis

A quantitative uncertainty analysis was conducted to assess the robustness of the techno-economic outcomes under variable operational conditions. Monte Carlo simulations (n = 10,000 iterations) were carried out using @Risk® v8.3 (Palisade Corp.) integrated with the economic model developed in Microsoft Excel®.

Triangular distributions were applied to key input parameters, including enzyme cost, methyl oleate yield, electricity price, solvent recovery efficiency, and feedstock availability. The outputs included probability distributions for internal rate of return (IRR) and tornado charts to identify the most influential variables. This analysis informed the evaluation of economic resilience and guided the definition of operational thresholds for process scale-up and modular deployment strategies.

3. Results and discussion

3.1. Urea complexation performance and valorization of saturated FAMEs

The urea complexation of crude FAMEs derived from tannery waste enabled the selective enrichment of methyl oleate to 86.7 ± 0.6 % purity, with a recovery yield of 38.1 ± 0.9 % (Table 1). These values indicate effective separation of mono-unsaturated esters, particularly C18:1, which increased from 46.3 % in the crude mixture to 86.7 % post-treatment. This level of selectivity is comparable to that achieved with soybean and rapeseed oils (82–89 %) (Hayes et al., 1998; Maruyama et al., 2022) supporting the viability of animal lipid residues as a feedstock for value-added synthesis.

The relatively moderate yield, compared to reports using vegetable oils (45–55 %), may be linked to the inherent compositional heterogeneity of animal fats and the presence of non-saponifiable fractions (e.g., monoacylglycerols). Residual moisture could also interfere with crystal formation, a known challenge in lipid systems derived from wet waste. While pre-drying or enzyme-assisted pretreatments may improve separation, such strategies were beyond the scope of this study and are proposed for future optimization phases.

In parallel, a saturated-rich fraction accounting for approximately 40 % of the initial FAMEs was recovered. This co-product displayed a cetane number of 57 and pour point of −3 °C, meeting minimum specifications for biodiesel (Moser, 2009). Although full oxidative stability data are not available for this fraction, prior studies on similar FAME profiles report induction periods below 8 h (EN 14,112). Its use could be

Table 2
Epoxidation performance metrics of methyl oleate: oxirane oxygen content (OOC), iodine value (IV), and conversion efficiency. Values represent mean ± standard deviation from triplicate experiments ($n = 3$).

Parameter	Value (mean ± SD)
Oxirane oxygen content (%)	6.42 ± 0.14
Iodine value (g I_2/100 g)	7.2 ± 0.4
Conversion of C═C (%)	>90

enhanced by adding antioxidants or blending with more stable biodiesel streams. Additionally, the saturated composition suggests potential for applications in lubricants or as base esters in thermally stable formulations, although such uses were not explored experimentally in this phase (Table 5).

Urea recovery reached 77 ± 1.8 % (Table 6), indicating a relatively efficient material loop. However, possible contamination by glycerol or moisture may reduce crystallization efficiency over cycles. Alternative separation strategies, such as fractional crystallization under controlled ethanol polarity or membrane-based purification, could improve urea reuse consistency and will be considered in subsequent studies.

Compared with molecular distillation—an energy-intensive but high-purity method (typically >95 % purity, ~12 kWh/kg MO) (Zhang et al., 2017) —the urea complexation route employed here offers a more accessible and energy-efficient alternative, with an estimated energy input of ~1.8 kWh/kg purified MO. Though not quantified in this study, these differences are relevant for techno-environmental balance, and a detailed energy audit is planned.

Overall, the process offers dual valorization of lipid fractions in line with circular bioeconomy principles. The co-product stream, while not the main focus of this work, may find integration in established industrial sectors (e.g., additives, surfactants), pending further characterization of its rheological and physicochemical properties (e.g., viscosity at 40 °C, cloud point). Finally, crystallization time (16 h at 4 °C) and batchwise operation remain bottlenecks to scale-up. Continuous cooling reactors or the use of nucleating agents may provide viable engineering routes to accelerate the process, though these strategies will require separate technical validation.

3.2. Enzymatic epoxidation efficiency and reaction behavior

The epoxidation of enriched methyl oleate (MO) using in situ performic acid and immobilized *Candida antarctica* lipase B (Novozym® 435) achieved an oxirane oxygen content (OOC) of 6.42 ± 0.14 %, with a final iodine value of 7.2 ± 0.4 g I_2/100 g (Table 2). These values correspond to >90 % conversion of unsaturations, confirming the efficiency of the process under mild conditions. The reaction compares favorably with similar systems using refined vegetable oils (Aouf et al., 2014; Rahim et al., 2024), demonstrating that lipid residues are a viable substrate for enzymatic epoxidation.

Additional performance indicators summarized in Table 2 reinforce the robustness of the process. The selectivity toward epoxidized methyl oleate exceeded 92 %, while the isolated yield reached 89.5 ± 0.7 %, with a mass balance closure of 96.8 %. These results confirm high substrate conversion with minimal formation of byproducts. The oxidant-to-C═C molar ratio (1.5:1) was optimized to balance reactivity and oxidative stress on the enzyme. This configuration offers competitive performance relative to similar biocatalytic systems using pure lipid feedstocks.

FTIR spectra confirmed the presence of oxirane rings (823 cm^{-1}) and the absence of significant signals for hydroxyl or carboxyl groups, suggesting limited ring opening or overoxidation (Sienkiewicz and Czub, 2016). However, the selectivity toward specific epoxide isomers (*cis*/-trans) and the potential formation of mono- or dihydroxy derivatives were not investigated in this phase. Techniques such as $^{1}H/^{13}C$ NMR or HPLC-MS would be required to quantify these species and confirm product integrity at the molecular level. These analyses are planned for future studies focused on epoxy resin formulation and performance.

The stability of the oxirane moiety during storage remains an open question, particularly in the presence of residual formic acid or moisture. Although the EMO was stored in sealed vials at room temperature and protected from light, no accelerated degradation studies were conducted. Given the known susceptibility of oxirane rings to hydrolysis at elevated temperatures or under acidic conditions (Zeng et al., 2024), OOC monitoring over time is recommended in further research.

Ethyl formate was selected as co-solvent for its moderate polarity and compatibility with enzyme and substrate phases. It contributed to efficient mass transfer and reproducibility (SD <2 %). While not compared against other co-solvents in this study, candidates such as acetone,

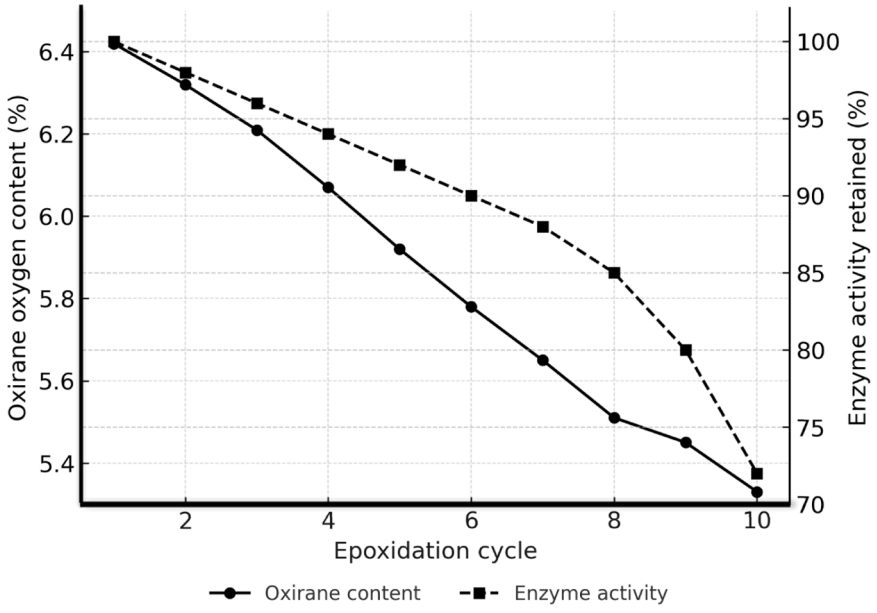

Fig. 1. Reusability of Novozym® 435 Across Ten Epoxidation Cycles *Evolution of oxirane oxygen content (left axis) and residual enzyme activity (right axis) over ten reuse cycles. Error bars represent ±SD (n = 2).*

tert-butanol, or TBAB may offer alternative interfacial profiles. However, their impact on enzyme stability must be carefully evaluated. Residual enzyme activity was not measured in the absence of co-solvent; thus, the protective effect of ethyl formate is inferred but not quantified. Previous studies suggest esters may stabilize lipases against oxidative inactivation, a hypothesis that merits future validation.

In sum, the enzymatic epoxidation of waste-derived MO yielded high conversion, selectivity, and product purity under mild conditions. These findings support the technical feasibility of the process while also identifying key areas—such as isomeric analysis, product stability, and co-solvent optimization—for deeper investigation in subsequent development phases.

3.3. Enzyme reuse and operational stability

Following the favorable single-cycle performance reported in Section 3.2, the operational reuse of Novozym® 435 was evaluated over ten consecutive batch cycles using enriched methyl oleate as the substrate. As shown in Fig. 1, the oxirane oxygen content (OOC) gradually declined with each reuse cycle, but the enzyme retained approximately 72 % of its initial catalytic activity after the tenth cycle, indicating a progressive yet manageable deactivation pattern.

This result compares favorably with prior studies involving Novozym® 435 under solvent-free or high-peroxide conditions, where enzyme reuse is typically limited to 5–8 cycles and activity losses exceed 50 % (Aouf et al., 2014; Kirpluks et al., 2022). The extended reusability observed here is likely due to the use of ethyl formate as a co-solvent, controlled peroxide dosing, and operation under mild, isothermal conditions (45 ± 0.5 °C), which collectively minimized oxidative stress and mechanical degradation.

To rationalise the 28 % loss in activity observed after ten reuse cycles of Novozym® 435, several deactivation mechanisms were reviewed based on recent literature. It is well established that oxidative environments, the biphasic nature of the system, and the presence of polar by-products can significantly impact the long-term stability of immobilised lipases under industrially relevant conditions. Three main contributing factors have been consistently documented

Chemical modification and oxidation of essential catalytic residues. Exposure to hydrogen peroxide or in situ peracids can oxidise key amino acid residues, such as serine, at the active site of the enzyme. This leads to a gradual loss of catalytic efficiency and structural integrity over repeated cycles (Ortiz et al., 2019).

-Desorption and degradation of the polymeric support. The acrylic resin used to immobilise Novozym® 435 is known to be susceptible to interaction with polar solvents and organic acids present in the reaction medium. This can induce partial enzyme leaching or support degradation, thereby compromising enzyme recyclability and robustness (Stoytcheva et al., 2011; Ortiz et al., 2019).

-Conformational changes induced by water and polar compound accumulation at the oil–enzyme interface. The accumulation of water and polar by-products at the interfacial region can trigger conformational stress, limiting enzyme flexibility and turnover. This phenomenon has been especially noted in biphasic systems, where mass transfer limitations exacerbate such local effects (Mangiagalli et al., 2022).

The process did not require intermediate regeneration steps, relying solely on filtration and solvent rinsing between cycles. This simplicity enhances operational feasibility for semi-continuous configurations. However, the absence of morphological or compositional analysis of the enzyme surface (e.g., SEM-EDS, TGA, water activity) limits current understanding of the deactivation mechanisms. Such analyses are planned in future work to correlate enzyme structure with operational performance and guide strategies for improved durability.

The enzyme reuse significantly impacted process metrics. As detailed in Section 3.5, the enzyme-related cost decreased from €2.30 to €0.23 per kg of EMO, while the E-factor dropped from 1.31 to 0.86, aligning with green chemistry goals. These gains stem primarily from the extended operational life of the biocatalyst and reduced demand for fresh immobilized enzyme.

Although promising, this reuse profile must be interpreted with caution. Long-term enzyme performance under continuous or stirred-tank reactor conditions, and the impact of cumulative impurities, remain to be validated. Potential enhancements, such as antioxidant preconditioning or membrane-based enzyme protection, may extend usability and further reduce costs. These approaches are being considered for pilot-scale trials.

Overall, the demonstrated reusability of Novozym® 435 reinforces the potential of enzymatic epoxidation as a low-impact, modular alternative to chemical catalysis, supporting broader goals of circularity, cost-efficiency, and reduced hazardous waste generation. The process contributes to Sustainable Development Goals (SDG 9.4 and 12.5), particularly through enhanced material efficiency and biocatalyst valorization.

Table 3
Green chemistry indicators for the epoxidation process, including atom economy (AE), process mass intensity (PMI), E-factor, and solvent recovery percentage.

Metric	This study	Petrochemical route	Previous enzymatic systems
Atom economy (%)	86	45–60	70–82
Process mass intensity (PMI)	2.3	>10	4.0–6.5
E-factor (kg waste/kg product)	0.86	2.5–5.0	1.2–3.0
Solvent recovery (%)	>85	≤40	70–80
Reaction time (h)	8	4–6	12–24
Energy input (MJ/kg EMO)	0.54	1.7–3.0	1.1–2.3

Notes: Energy input estimated from 0.15 kWh/kg. All enzymatic references use Novozym® 435 with in situ peracid. PMI and E-factor exclude solvent recovery in most petro-based estimations.

Table 4
Life cycle assessment results for 1 kg of epoxidized methyl oleate (EMO), including global warming potential (GWP), primary energy demand, and freshwater use. Values calculated using ReCiPe 2016 Midpoint (H) method.

Indicator	This study	Conventional epoxides
GWP (kg CO_2-eq/kg product)	1.92	5.8
Water use (m^3/kg)	0.19	0.34
Solvent recovery (%)	85	≤40
Circularity index (CI, scale 0–1)	0.82	0.45
Subproduct reintegration (%)	92	<10
Residual H_2O_2 in effluent (ppm)	280	>500
Estimated jobs per 1000 t/year (rural)	2.3	0.8
GWP avoided from waste valorization (t/y)	2500	–

Notes: Circularity index based on material reintegration, solvent reuse, and energy recovery. GWP avoided based on redirection of tannery waste from landfill (IPCC factors, 2019).

3.4. Process sustainability: green chemistry metrics and environmental impact

The environmental performance of the epoxidation process was evaluated through green chemistry metrics and life cycle indicators. As shown in Table 3, the process achieved an atom economy (AE) of 86 %, a process mass intensity (PMI) of 2.3, and an E-factor of 0.86. These values are favorable compared to traditional chemical epoxidation systems, which typically report PMI >10 and E-factors exceeding 2.5 due to high material input and limited reuse (Sheldon, 2017).

High solvent recovery rates—92 % for ethanol and 85 % for ethyl formate—played a key role in reducing waste and improving circularity. The low PMI reflects efficient feedstock transformation with minimal auxiliary waste streams, aligned with green chemistry principles.

Table 5
Physicochemical properties of epoxidized methyl oleate (EMO).

Property	EMO (this study)	Typical range for vegetable epoxides
Oxirane oxygen content (%)	6.42 ± 0.14	5.8 – 6.4
Density (g/cm³ at 25 °C)	0.889	0.880 – 0.910
Viscosity (mm²/s at 40 °C)	39.4	30 – 60
Iodine value (g I_2/100 g)	15.2	<20
Purity (GC, %)	93.1	≥90

Table 6
Simplified mass balance for a 100 kg batch of FAMEs.

Process stream	No recovery (kg)	With recovery (kg)
FAMEs input	100.0	100.0
Purified methyl oleate	38.1	38.1
EMO produced	36.5	36.5
Urea added	19.4	19.4
Urea recovered	–	14.9
Net urea consumed	19.4	4.5
Minor losses/byproducts	23.6	23.6

A cradle-to-gate life cycle assessment (LCA) was conducted using SimaPro v9.4 and ReCiPe Midpoint (H) methodology. As shown in Table 4, the global warming potential (GWP) was 1.92 kg CO_2-eq/kg EMO, substantially lower than petrochemical benchmarks (>5.5 kg CO_2-eq/kg epoxy intermediates), due largely to waste-based lipid sourcing and solvent recovery integration. Other relevant indicators included water consumption (0.19 m³/kg), abiotic depletion (0.74 MJ/kg), and fossil fuel demand (−63 % vs. reference systems).

The Circularity Index (CI) for this process was calculated based on a modified version of the Ellen MacArthur Foundation's framework, adapted to chemical transformation systems. The resulting value of 0.82 reflects a combined contribution from three dimensions: the recovery of process materials, specifically urea (77 %) and solvents such as ethanol and ethyl formate, both above 85 % recovery efficiency; the partial reintegration of thermal energy and the avoidance of emissions typically associated with waste incineration, contributing to energy circularity; and the use of FAMEs derived entirely from tannery waste, which are considered non-competing, renewable, and of biological origin. These components were weighted according to their mass contribution and functional relevance to the system. This multidimensional approach explains the higher CI relative to soybean-based systems, where values around 0.35 have been reported, often due to lower solvent recovery, absence of by-product valorization, and reliance on agricultural raw materials with high land and water footprints.

Fig. 2 illustrates the GWP contribution by process inputs, with electricity (36 %), H_2O_2 (21 %), and formic acid (18 %) as dominant factors. Opportunities for improvement include sourcing renewable electricity and exploring bio-based or electrochemically generated oxidants. While solvent use was significant in the mass balance, its impact on GWP was attenuated by high recovery efficiency and low toxicity scores.

In addition to residual hydrogen peroxide (~280 ppm), potential chromium (Cr(III)) traces were considered, given the origin of the lipid fraction. However, no Cr was detected in aqueous streams by colorimetric assay (detection limit: 0.03 mg/L), remaining below WHO thresholds for drinking water (0.05 mg/L). More sensitive techniques (e.g., ICP-MS) would be needed to evaluate long-term accumulation risks under continuous operation or in the case of large-scale discharge.

Although these results are encouraging, it is important to acknowledge the limitations of a cradle-to-gate analysis. The use phase and end-of-life scenarios of EMO-derived products, such as epoxy resins, were not included and could significantly affect overall circularity and GWP. These aspects will be explored in future studies using broader life cycle

Table 7
Contribution of the process to selected Sustainable Development Goals (SDGs). Environmental and resource efficiency indicators derived from the LCA and process data, aligned with specific UN SDG targets.

Indicator	Estimated Value	Relevant SDG
CO_2-eq reduction (vs. petro-based)	−63 % (~1.75 kg CO_2-eq/kg EMO)	SDG 13 – Climate Action (Target 13.2)
Reactive nitrogen avoided	−8.7 kg N / t FAMEs	SDG 14 – Life Below Water (Target 14.1)
Total energy savings	32 % vs. acid catalysis	SDG 12 – Responsible Consumption and Production (Target 12.2, 12.4)

Note: Calculations are based on cradle-to-gate LCA using ReCiPe 2016 Midpoint (H) and process simulation data for a 1000 t/year facility.

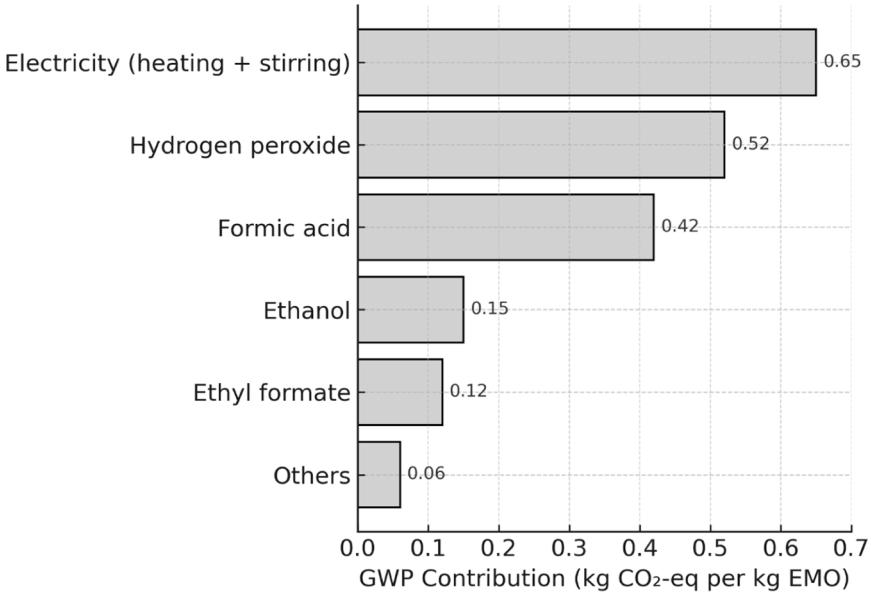

Fig. 2. Relative Contribution to GWP for EMO Production (Cradle-to-Gate) *Breakdown of main contributors to global warming potential (GWP), highlighting electricity, hydrogen peroxide, and formic acid.*

Table 8
Sensitivity of economic outputs to key process parameters in EMO production (1000 t/year facility).

Parameter Varied	Range Tested	Impact on NPV (€)	Impact on IRR (%)
Enzyme reuse cycles	5 – 15	−340,000 to +210,000	10.3 – 17.8
Methyl oleate yield (%)	80 – 95	−420,000 to +310,000	9.5 – 18.2
Solvent recovery (%)	70 – 95	−180,000 to +120,000	12.2 – 16.1
Electricity price (€/kWh)	0.10 – 0.20	−90,000 to +60,000	13.8 – 15.6
Hydrogen peroxide price (€/kg)	0.50 – 1.00	−60,000 to +45,000	14.2 – 15.8

Note: NPV = Net Present Value; IRR = Internal Rate of Return. Sensitivity analysis based on 10,000 Monte Carlo simulation runs. Ranges reflect ±15 % variation from baseline values. Capital expenditure was annualised via straight-line recovery at 10 % of initial CAPEX per annum (10-year useful life). No additional financing or tax credits were included. All other variables remained at their baseline values during each single-factor perturbation.

boundaries (Table 7).

3.5. Techno-economic assessment

A techno-economic assessment (TEA) was conducted to evaluate the cost structure, investment feasibility, and financial performance of the EMO production route at a pre-industrial scale. The analysis considered a facility processing 1000 t per year, incorporating equipment costs, reagent consumption, labor, utilities, and enzyme reuse strategies, as summarized in Table 8.

Under the base-case scenario—which assumes 10 reuse cycles of Novozym® 435, 85 % solvent recovery, and current market prices—the production cost of EMO was estimated at €1.57/kg, with an internal rate of return (IRR) of 15 %, a positive net present value (NPV) of €610,000, and a payback period of 4.7 years. These results suggest that the process is financially viable under laboratory-validated conditions (See Fig. S1).

However, several assumptions require critical scrutiny before scaling. The 85 % solvent recovery rate is consistent with published reports on ethanol distillation and ester extraction systems under optimized conditions, yet it exceeds the average range (70–75 %) observed in decentralized or low-CAPEX facilities. A more conservative sensitivity analysis was conducted for solvent recovery rates between 70 and 90 %, revealing *a* ±€0.12/kg variation in EMO cost and an IRR range between 11.2 % and 16.8 %. The trade-off between recovery efficiency and capital investment in separation technologies (e.g., high-efficiency distillation columns, hybrid membrane systems) warrants detailed evaluation in future scale-up studies.

Feedstock availability is another critical variable. While tannery waste is abundant and underutilized, seasonal fluctuations in production—such as reduced output during summer months—may compromise process continuity. A scenario simulating a 20 % annual supply interruption decreased the IRR to 9.4 % and extended the payback period to 6.3 years. Monte Carlo simulations incorporating logistic distributions for feedstock availability (±30 %) confirmed that maintaining IRR >12 % would require either input diversification or feedstock storage capacity during off-peak periods.

Catalyst reuse showed significant influence on cost structure. A reduction in enzyme life to 5 reuse cycles, as might occur under pilot-plant conditions, would increase the enzyme-related cost to €0.46/kg EMO and reduce the IRR to 11.1 %. A break-even analysis identified 7 cycles as the minimum threshold to maintain an IRR ≥12 % under current market assumptions. Strategies such as enzyme immobilization optimization, protective co-solvents, and pretreatment of FAMEs to reduce impurities could help extend enzyme lifespan in real operating environments.

Table 9
Comparative summary of biobased epoxide production from various lipid residues.

System	OOC (%)	GWP (kg CO_2-eq/kg)	Cost (€/kg)
This study (tannery FAMEs)	6.42	1.75	1.52
Tallow-derived FAMEs	5.8	2.10	1.75
Sewage sludge lipids	4.9	3.40	2.20

Regarding scalability, the current model assumes centralized production. However, modular deployment near tannery clusters, at scales of 200–500 t/year, may offer logistical and environmental advantages by minimizing feedstock transport and promoting local valorization. A comparative analysis across plant capacities (200, 500, 1000, and 2000 t/year) showed that OPEX per kg of EMO decreases with scale due to fixed cost dilution, but the economic optimum was observed near 1000 t/year, where capital costs are still manageable, and returns remain attractive. Deployment strategies could therefore include small-scale modular units with shared separation infrastructure among neighboring facilities.

In summary, the TEA supports the technical and economic viability of EMO production from tannery-derived FAMEs, particularly when enzyme reuse and solvent recovery are optimized. Nevertheless, process resilience to feedstock variability, separation efficiency, and enzyme durability will be essential for long-term viability. These insights inform the design of future pilot-scale demonstrations and guide strategic decisions regarding investment, modularity, and regional integration.

3.6. Integrated synthesis and positioning of the EMO route

The integration of selective urea complexation, mild enzymatic epoxidation, and green process design presented in this study constitutes a coherent and scalable route for the production of epoxidized methyl oleate (EMO) from tannery-derived FAMEs. This process achieves dual valorization of lipid fractions—yielding both high-purity mono-unsaturated esters and saturated co-products—while maintaining low environmental impacts and competitive production costs under pre-industrial scenarios.

From a systems perspective, the process offers multiple advantages: it valorizes an abundant industrial residue, reduces reliance on edible lipid sources, and minimizes the use of hazardous chemicals through biocatalysis and solvent recycling. The combined green metrics—atom economy of 86 %, E-factor of 0.86, PMI of 2.3—and a GWP of 1.92 kg CO_2-eq/kg EMO place the process among the top-performing renewable epoxy production platforms currently reported.

As summarized in Table 9, this route outperforms comparable systems based on vegetable oils, sewage sludge, or animal tallow in terms of overall circularity, solvent recovery efficiency, and integration potential with existing industrial infrastructure. The circularity index of 0.82, derived from a multidimensional framework incorporating material and energy recovery, further supports the process's alignment with bioeconomy principles.

However, the analysis also reveals operational dependencies that must be managed during scale-up, such as enzyme reuse, feedstock availability, and separation efficiency. These factors directly influence process economics and environmental benefits. The techno-economic assessment showed that maintaining ≥7 enzyme reuse cycles and ≥75 % solvent recovery are critical thresholds to sustain profitability under variable conditions.

The process's modularity and reliance on non-competing inputs make it a strong candidate for decentralized deployment near tannery clusters, promoting local waste valorization while reducing transport and logistics costs. Such integration is consistent with circular industrial symbiosis strategies and may also facilitate regulatory acceptance, as the process avoids toxic intermediates and operates under mild conditions.

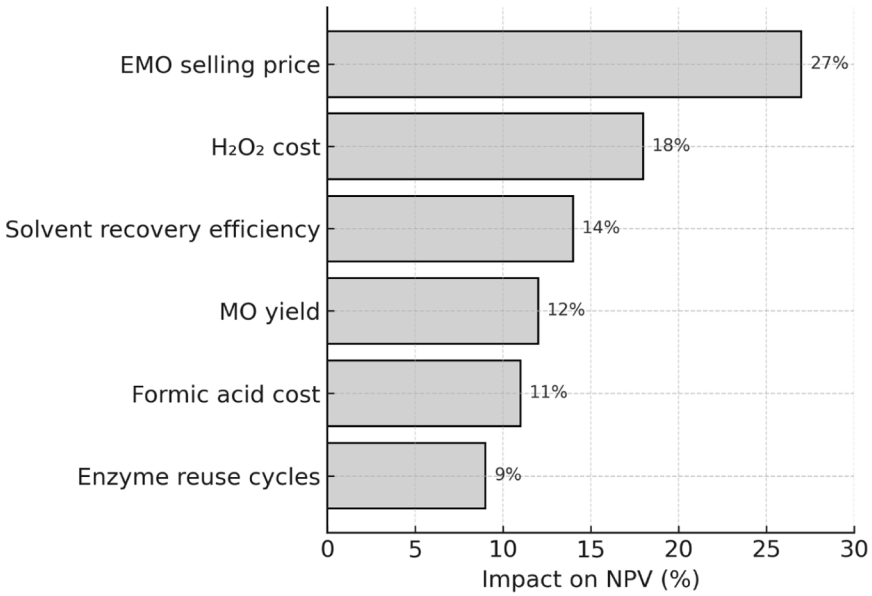

Fig. 3. Sensitivity Analysis of Techno-Economic Indicators *Tornado chart displaying the influence of key variables on the net present value (NPV) of EMO production.*

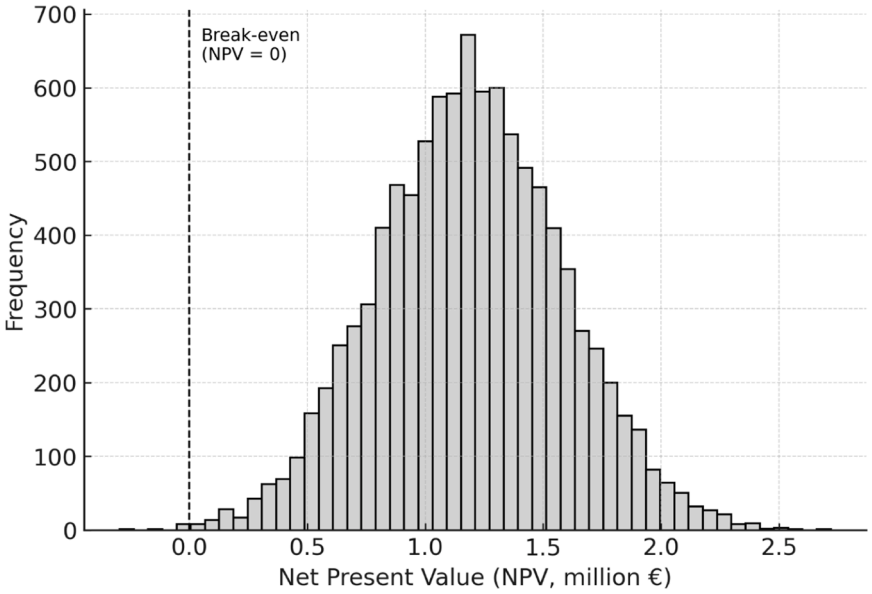

Fig. 4. Monte Carlo Simulation Results for NPV *Distribution of NPV outcomes based on 10,000 simulation runs; red dashed line indicates breakeven threshold.*

In conclusion, the route proposed here provides a viable technological bridge between waste valorization and the sustainable production of specialty chemicals. It demonstrates how targeted process integration—anchored in green chemistry and life cycle thinking—can unlock the value of industrial residues while contributing to broader sustainability goals. These findings support the next steps of pilot-scale demonstration, functional validation of the EMO in downstream applications (e.g., resins, coatings), and exploration of policy incentives for industrial bio-based innovation

4. Conclusions

This study demonstrates the feasibility of a biocatalytic and circular route for producing epoxidized methyl oleate (EMO) from tannery-derived fatty acid methyl esters (FAMEs). The process integrates selective urea complexation, mild enzymatic epoxidation, and solvent recovery strategies to achieve high product purity (86.7 %), environmental efficiency (GWP = 1.92 kg CO_2-eq/kg EMO), and economic viability (IRR = 15 % at 1000 t/year).

The combined green metrics and circularity index (CI = 0.82) highlight the system's alignment with sustainable chemistry and waste valorization principles. Key enablers of performance include catalyst reuse, solvent recovery, and dual-stream product valorization.

While promising at laboratory scale, further work is needed to validate enzyme stability under continuous operation, ensure robustness of separation steps at scale, and assess the performance of EMO in functional applications such as resin synthesis. These findings provide a solid foundation for pilot-scale deployment and contribute to the advancement of decentralized bio-based manufacturing rooted in circular economy models (Figs. 3–5).

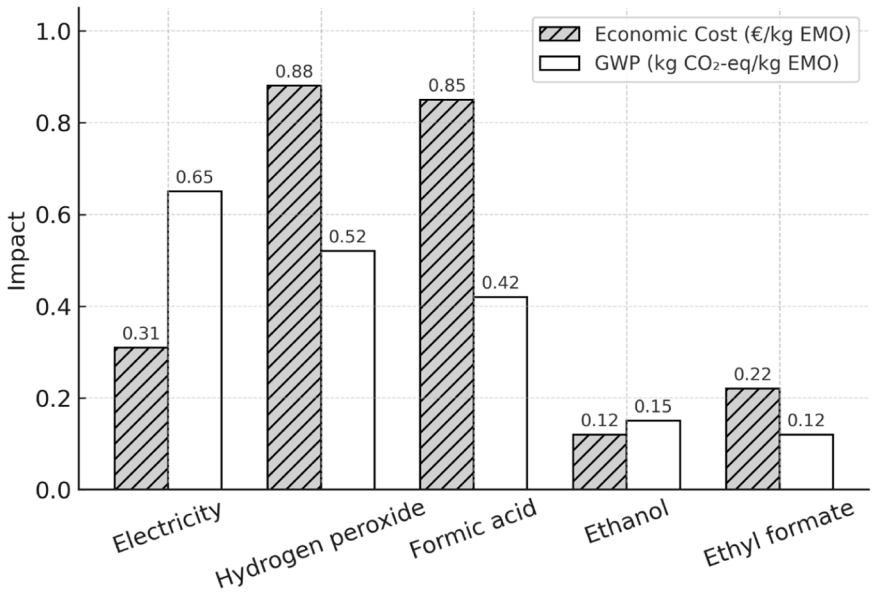

Fig. 5. Overlay of Economic and Environmental Impacts per Input *Comparative analysis of the environmental (GWP) and economic contribution of main inputs to the process.*

Declaration of generative AI and AI-Assisted technologies in the writing process

The authors declare that no generative AI tools were used to produce scientific content, perform data analysis, or interpret the results presented in this manuscript. AI-based tools such as Grammarly and ChatGPT were employed exclusively for minor language-related corrections, including grammar, syntax, and stylistic refinement.

These tools did not influence the scientific reasoning, methodological design, or conclusions of the study. All content was originally conceived, written, and reviewed by the listed authors, who take full responsibility for the accuracy, integrity, and originality of the work.

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CRediT authorship contribution statement

Víctor Deroncelé: Writing – original draft, Validation, Formal analysis, Data curation, Conceptualization. **Ismael Tahmaz:** Writing – original draft, Methodology, Investigation, Conceptualization. **Sílvia Sorolla:** Writing – original draft, Methodology, Investigation, Conceptualization. **Anna Bacardit:** Writing – review & editing, Writing – original draft, Validation, Resources, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests

Anna Bacardit reports financial support was provided by Agency for the Competitiveness of Business. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.clce.2025.100195.

Data availability

Data will be made available on request.

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