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## 1 INTRODUCTION

Lubricants are indispensable in industrial and transportation systems, where they reduce wear, friction, and heat in mechanical operations, and enhance energy efficiency, operational reliability, and equipment lifespan (1). In 2022, the global lubricant market reached 35.9 million metric tons and is projected to grow from USD 178 billion to USD 204 billion by 2030, underscoring this critical role in modern infrastructure and mobility systems (2–4), Even with advances in electric vehicles and precision machinery, lubricants remain essential, particularly in electrified systems, due to ongoing mechanical friction and the need for thermal management (5), however, this indispensable role is accompanied by environmental burden.

Traditional lubricants are predominantly petroleum-based, raising concerns due to their persistence in ecosystems, toxicity, and the use of fossil resources throughout their life cycle (6). Lubricant oil leaks and discharges from maritime and terrestrial systems release millions of liters of pollutants annually, threatening biodiversity, impairing aquatic environments, and incurring substantial remediation costs (7), (8). In response, regulatory frameworks such as the European Union's REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) and the U.S. Environmental Protection Agency (EPA) Toxic Substances Control Act (TSCA) have become increasingly stringent, encouraging the development and adoption of safer, more sustainable alternatives (9,10).

Environmentally Acceptable Lubricants (EALs) (11,12) have gained increasing attention as sustainable alternatives to conventional petroleum-based lubricants, particularly in applications with a high risk of leakage or environmental release. A key component of EALs is biobased base oil, derived from renewable plant- or animal-based feedstocks. Unlike fossil-derived oils, which originate from geologic carbon stores, biobased oils are sourced from carbon that is already part of the contemporary carbon cycle, absorbed through photosynthesis and returned through biological processes. While fossil-based lubricants may not always fully degrade into greenhouse gases (GHG), any degradation that does occur contributes to a net increase in atmospheric $CO_2$ by introducing geologic carbon into the biosphere. In contrast, the degradation of biobased lubricants recycles existing atmospheric carbon, resulting in a lower net climate impact, provided that sourcing, processing, and end-of-life handling are managed sustainably (13). This distinction underscores the value of EALs as a climate-conscious option for sectors such as marine and hydropower, where environmental exposure poses both regulatory and operational challenges.

Moreover, biobased base oils offer advantages in biodegradability, low aquatic toxicity, and reduced GHG emissions (8), (13). These oils are typically manufactured from vegetable or plant oil, synthetic esters (polyol), and polyalkylene glycols (14), (15), with synthetic esters being the most commonly used. Polyol

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esters synthesized from renewable resources such as tall oil fatty acids known as TOFAs (derived from the kraft pulping of pine wood, are renewable, non-food-based raw materials widely used in the production of bio-based lubricants due to their high content of unsaturated fatty acids and sustainable sourcing.) (16), coconut oil, and palm kernel derivatives are particularly promising due to their high oxidative stability, low volatility, and favorable viscosity properties (17). Although biodegradable oils tend to degrade rapidly in aquatic environments, large spills may still cause oxygen depletion and subsequent harm to aquatic life. Nonetheless, their lower toxicity compared to mineral oils typically enables faster ecological recovery (18).

Polyols are synthesized via alkoxylation, where polyhydric alcohols (e.g., glycerol, sorbitol) react with alkylene oxides like ethylene or propylene oxide in the presence of potassium hydroxide (KOH) under controlled conditions. The process is tailored to achieve specific molecular weights, followed by neutralization and purification to remove catalysts and byproducts. These refined polyols are used in applications such as lubricants and foams. The environmental impact depends on feedstock origin (bio- or fossil-based), catalyst performance, and energy use during production, making it a key factor in the sustainability profile of derived products (19,20).

The environmental sustainability of polyols must be evaluated beyond their renewable origin. While biobased carbon sources are often considered environmentally preferable, this assumption does not always hold. Biobased production systems can involve intensive land use, high energy consumption, and complex chemical processing. Therefore, life cycle assessment (LCA) serves as a valuable tool to quantify the full range of potential environmental impacts and determine whether or under what circumstances biobased base oils truly outperform their fossil-based counterparts (21).

Although LCA studies on base oils and lubricants remain relatively limited, the few that exist provide useful but sometimes inconsistent insights into their environmental performance. For example, several studies report lower global warming potential (GWP) for vegetable oil–based lubricants (6), while others highlight trade-offs such as elevated eutrophication and acidification impacts (22). These differences are often influenced not only by methodological choices but also by location-specific factors such as the regional electricity grid, agricultural practices, fertilizer use, and land management associated with vegetable oil cultivation (23). Since such parameters vary widely across geographies, the environmental profile of vegetable oils can differ substantially depending on whether they are sourced, for example, from North America, Europe, or Southeast Asia (24). Furthermore, most existing studies remain narrow in scope, typically comparing finished lubricants without disaggregating the contribution of the base oil production stage, which alone accounts for 75–90% of lubricant mass (8).

As a result, several key gaps remain in the current knowledge base:

- Carbon mitigation potential: Limited evidence exists on whether biobased base oil production can significantly reduce the carbon footprint of lubricant systems.
- Temporal foresight: Existing studies rarely evaluate future environmental performance under evolving energy systems and technological pathways.
- Geographical sensitivity: The influence of production location, especially energy grid mix and regional supply chains, remains underexplored.
- Empirical granularity: Few studies incorporating high-resolution primary data from operational industrial facilities producing next-generation biobased base oils.

To help close these gaps, we present a cradle-to-gate LCA of a novel oxygen-rich, hybrid biobased polyol ester base oils, produced in multiple viscosity grades and developed by an industrial manufacturer. Drawing on primary production data from a fully operational manufacturing facility in the United States, we quantify the environmental impacts associated with producing 1 kg of this advanced lubricant base oil. These results are benchmarked against two reference products: LIGALUB 19 TMP, a commercially available biobased polyol ester; and DITA, a petroleum-derived lubricant ester, both representing European manufacturing contexts. The analysis follows the American Petroleum Institute's technical guidance (API TR 1533) (24,25) and incorporates a full product carbon footprint (PCF) assessment following the UEIL/ATIEL framework (26–28). This approach enables a robust and transparent comparison between biogenic and fossil-based lubricant base oil and supports harmonization across international supply chains and sustainability reporting standards.

With the increasing adoption of EALs, the demand for biobased polyol esters is expected to grow, driving the need to expand production capacity. To assess the long-term environmental sustainability of these products, we conducted a future-oriented scenario analysis using the Shared Socioeconomic Pathway derived from the Integrated Model to Assess the Global Environment (IMAGE). This analysis projects potential environmental impacts under evolving technological and energy conditions through 2030, 2040, and 2050. In parallel, to support anticipated demand growth in Europe, companies are actively exploring regional manufacturing options to reduce logistics-related emissions and supply chain impacts. To assess the implications of such geographic shifts, we performed a geospatial scenario analysis that examines how relocating production to Europe, and operating under different regional electricity grid compositions, would affect the cradle-to-gate environmental impacts of biobased base oil production.

By focusing specifically on the production of biobased base oil, the cornerstone of bio-lubricant manufacturing, this study provides critical insights into the environmental trade-offs, mitigation

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opportunities, and long-term viability of renewable lubricants. The findings offer guidance for manufacturers, policymakers, and sustainability professionals aiming to align industrial lubricant systems with climate goals and ecological safety standards. The study also advances the scholarly discourse by establishing a methodological blueprint for LCA of intermediate biobased inputs in industrial applications.

## 2 DESCRIPTION OF BIOBASED BASE OIL

The *Secondary Polyol Ester* (SPE) base oils investigated herein represent a class of synthetic esters designed to achieve enhanced environmental and operational performance. These base oils are produced via esterification reactions involving secondary hydroxyl groups of polyols and fatty acids derived from renewable oleochemical feedstocks. The resulting molecular architecture is characterized by a dense network of ester and ether linkages (**Figure 1**), which imparts distinctive physicochemical properties and differentiates SPE base oils from conventional synthetic ester formulations.

A key innovation in this molecular design lies in the incorporation of secondary ester bonds, which demonstrate enhanced resistance to hydrolytic degradation. In addition, the presence of alkyl branching improves low-temperature fluidity, thereby broadening their functional application in environments subject to thermal variability. The molecular architecture also contributes to an intrinsically high viscosity index and built-in detergency, which improves deposit control and performance longevity under thermal and oxidative stress.

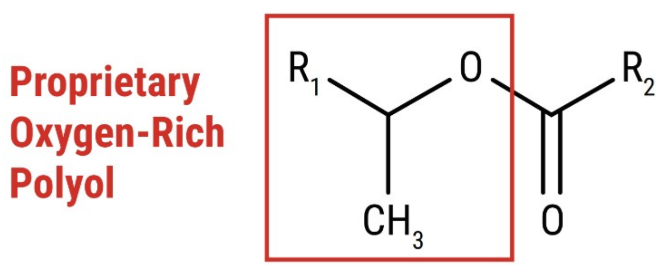


**Figure 1:** Generic Structure of SPE (29)

The SPE base oils examined across multiple viscosity grades (VG) exhibit high biodegradability (>80% according to OECD 301B) and substantial biogenic carbon content (approximately 50–76%, as determined using ASTM D6866), supporting their suitability for biobased lubricant formulations aligned with circular carbon strategies. These attributes have enabled representative SPE base oil formulations to meet the eligibility criteria of established sustainability certification frameworks, including the EU Ecolabel Lubricant Substance Classification (LuSC) list and the USDA BioPreferred Program (30,31). In addition,

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selected low-viscosity formulations are certified for incidental food contact (NSF HX-1), extending applicability to food-grade lubrication environments.

Table 1 summarizes key thermophysical and operational properties across the range of SPE base oil VG analyzed in this study. Notably, these SPE base oils achieve pour points as low as –60 °C, flash points exceeding 235 °C, and demonstrate robust performance under oxidation, thermal, and hydrolytic stability testing. Collectively, these characteristics position SPE base oils as technically advanced and environmentally compatible candidates for next-generation lubricant systems. Additional details are provided in **Supplementary Material (SM) 1**.

**Table 1:** Thermophysical, environmental, and operational performance characteristics of saturated secondary polyol ester (SPE) base oils across representative viscosity grades (VG).

| **Typical Physical Properties** | **Test standard** | **Viscosity Grades (VG)** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **VG-A** | **VG-B** | **VG-C** | **VG-D** | **VG-E** | **VG-F** |
| Kinetic Viscosity (KV) – 40ºC (cSt) | ASTM D445 | 29.5 | 44.2 | 47.8 | 69.4 | 67.0 | 96.9 |
| Viscosity Index | ASTM D2270 | 162 | 177 | 196 | 173 | 198 | 170 |
| Biodegradation (%) | OECD 301B | >80 | >80 | >80 | >80 | >80 | >80 |
| Biobased Carbon (%) | ASTM D6866 | 62.5 | 50.0 | 76.0 | 59.0 | 65.5 | 65.5 |
| HX-1 Incidental Food Contact | - | Yes | Yes | Yes | Yes | Yes | Yes |
| Digital Density 40ºC 9g/m$^3$) | ASTM D4052 | 0.97 | 0.96 | 0.97 | 0.95 | 0.95 | 0.93 |
| Pour Point (ºC) | ASTM D97 | -60 | -24 | -30 | -33 | -39 | -36 |
| Flash Point, COC (ºC) | ASTM D92A | 236 | 235 | 300 | 248 | 296 | 262 |
| Fire Point (ºC) | ASTM D92A | 262 | 264 | 324 | 276 | 322 | 280 |
| Aniline Point (ºC) | ASTM D611 | < -10 | < -10 | < -10 | < -10 | < -10 | < -10 |
| Thermal Stability | | | | | | | |
| *Cu Appearance* | ASTM D2070 | 1 | 1 | 1 | 1 | 1 | 1 |
| *Steel Appearance* | | 1 | 2 | 1 | 2 | 2 | 1 |
| *Total Sludge (mg/100ml)* | | 4.6 | 4.0 | 1.9 | 6.1 | 0.85 | 1.7 |
| Hydrolytic Stability | | | | | | | |
| *Copper Loss (mg/cm$^2$)* | | -0.08 | -0.01 | -0.05 | -0.03 | .0.06 | -0.03 |
| *Kv Change (%)* | ASTM D2619 | -3.27 | -2.14 | -0.39 | -0.16 | -2.41 | -1.79 |
| *Change in AN (mg KOH/g)* | | 0.28 | 0.13 | 0.44 | 0.20 | 0.86 | 0.46 |
| *Insoluble (%)* | | 0.02 | 0.02 | 0.03 | 0.03 | 0.04 | 0.02 |

**Note:** Viscosity grade labels (VG-A to VG-F) are anonymized. All materials were commercially available saturated SPE base oils evaluated using standardized test methods.

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### 2.1 Production process of the Secondary Polyol Ester (SPE)

The secondary polyol ester (SPE) base oils analyzed in this study are produced from polyols and fatty acids sourced from multiple commercial suppliers. The polyol and fatty acid feedstocks are transported to an industrial production facility located in South Carolina, United States, where they are converted into SPE base oils using a conventional esterification process.

The SPE base oils are manufactured utilizing a standard industrial esterification process. A proprietary polyol is carefully reacted with a free fatty acid in this process. The reaction occurs in a specialized catalyst's presence and is conducted under controlled heating conditions. This combination of polyol, fatty acid, catalyst, and heat initiates a chemical reaction that forms secondary polyol ester base fluids. Polyol and fatty acids are mixed in a reaction vessel. This vessel is equipped with an agitator to mix the reactants thoroughly. A catalyst is added to the reaction mixture to accelerate the esterification reaction. The reaction mixture is heated to the required temperature, typically between 140°C and 250°C, to promote the esterification reaction. The mixture is then maintained at the target temperature for a specified period to allow the esterification reaction to occur, forming the ester and water as byproducts. The water produced during the reaction is removed continuously to drive the reaction toward completion (The impact of disposing of the water and fatty acid was not considered due to lack of data from the waste collection company). The ester product is purified to remove unreacted starting materials, catalyst residues, and byproducts. The final ester product is cooled and then stored in appropriate containers (32,33).

## 3 MATERIALS AND METHODS

This section covers the methods and materials used in conducting the LCA. These include the LCA standards and material quantities.

### 3.1 Life cycle assessment

LCA is an established methodologies used to quantify the environmental performance of products, processes, or services. The product category rule (PCR) of the lubricant industry focuses on analyzing only product carbon footprint (PCF), however, this model considered multiple impacts. This model was developed using American Petroleum Industry (API) Technical Report 1533 (Lubricants Life Cycle Assessment and Carbon Foot Printing — Methodology and Best Practice) for Base Oils as stipulated by UEIL/ATIEL PCF guidance (34,35). The API reports were built following ISO 14040:2006, ISO 14044:2006, ISO 14067:2018, and PAS 2050:2011 (GHG Protocol, Product Life Cycle Accounting and Reporting Standard) (21,36–38).

### 3.2 Lubricant life cycle stages

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The critical stages of the lubricant life cycle are specified in **Figure 2**, including raw materials and their transportation to the manufacturing site, the production of the lubricant and its packaging, the logistics of the lubricant to the customer, the use of the lubricant, its end-of-life, recycling, and reuse after the end-of-life. According to the UEIL/ATIEL PCF guideline, PCF and LCA analysis of base oil covers mainly cradle-to-gate or cradle-to-gate + logistics (to customer gate).

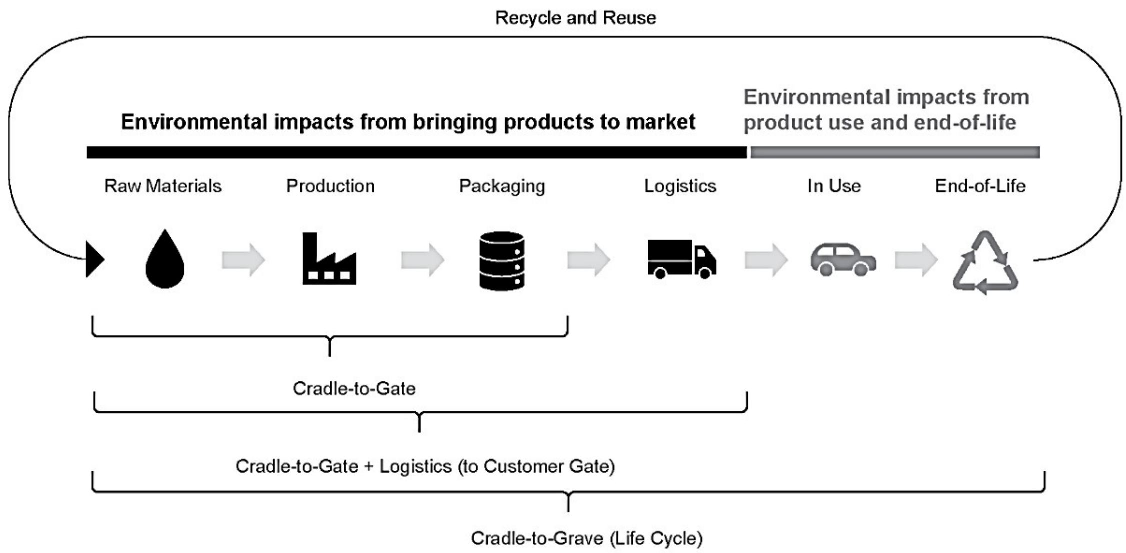


**Figure 2**: Stages of the lubricant life cycle from American Petroleum Institute (API) (34,35)

### 3.3 Secondary Polyol Ester (SPE) Base Oil LCA

This LCA aims to quantify the potential environmental impact associated with manufacturing of the SPE base oil, to identify the most impactful processes for further process development and to provide a comparison against other polyol esters and conventional petrochemical lubricant esters. An attributional LCA was selected based on existing guidelines (39).

The system boundaries for this LCA were set as cradle-to-gate**. Figure 3** shows the schematic of the SPE base oil production covering all relevant life cycle stages considered in the system boundary. Use phase and end-of-life have not been included as the applications for all base oil are similar and out of control of base oil manufacturers. The functional unit (FU) is 1 kg of SPE base oil.

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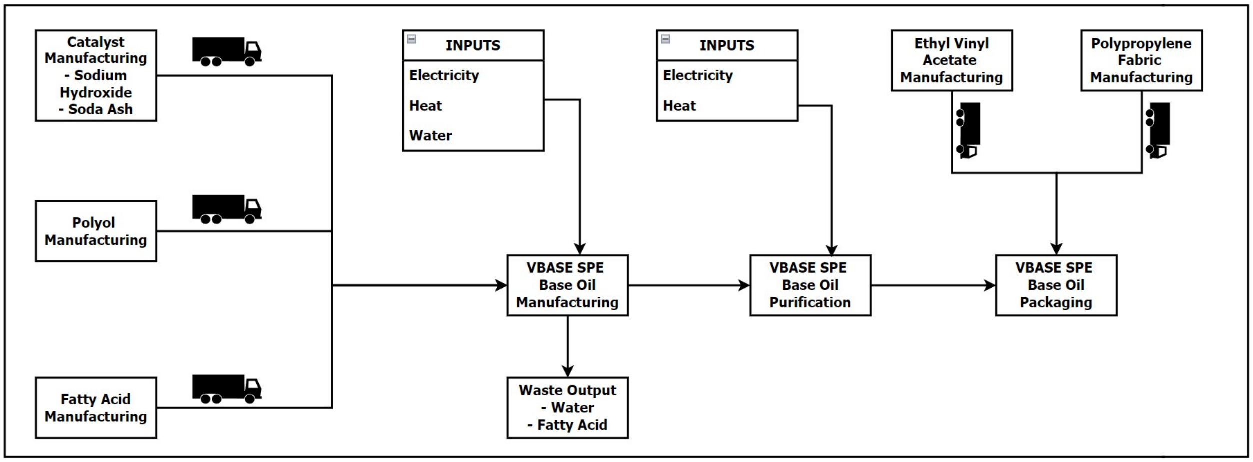


**Figure 3**: Visualization of SPE base oil manufacturing and the system boundary.

The cradle-to-gate life cycle of the SPE base oil starts with the manufacturing of raw materials at various locations, then the raw materials are transported to the SPE base oil production site and ends with the produced SPE base oil ready to leave the production site. The emissions and environmental impact associated with the generation of fatty acid, and all feedstocks are considered; however, some of the processing aids used during the base oil production were not included due to a lack of available data, but we ensured it aligned with the cut-off criteria stipulated in the API Technical Report.

While the current API PCR for petroleum products does not mandate the inclusion of indirect land use change (iLUC) in environmental product declarations (EPDs), it is important to acknowledge the significant environmental implications associated with iLUC, such as increased GHG, deforestation, and biodiversity loss. According to ISO 14067 (40), iLUC should be included in the carbon footprint of products once internationally agreed methodologies are established. Although no universally standardized approach currently exists, the scientific consensus highlights the potential scale of these impacts, particularly for biobased and land-intensive feedstocks. Therefore, companies should proactively evaluate iLUC risks as part of a comprehensive life cycle perspective, even in the absence of formal requirements, to better align their sustainability reporting with emerging international expectations and ensure transparent communication of environmental trade-offs (41).

Allocation followed the requirements and guidelines of ISO 14044:2006 and ISO 14067:2018 (37). For the production stage, individual meters were not installed. We applied mass-based allocation to assign utilities, such as electricity and steam consumption, to specific production units, batches, and products, ensuring that resource use was proportionally distributed according to product output. The following condition was followed for material cut-off: No more than 2% contribution to individual components to the overall environmental impacts and no more than 5% contribution cumulatively across multiple components

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to the overall environmental impacts. The materials excluded from the analysis were due to a lack of available reliable data, and they were cut off because they fell under the above conditions. The LCA was modeled using OpenLCA software 2.0.2 version.

### 3.3.1 Life cycle inventory

The life cycle inventory (LCI) data for SPE base oil was compiled using a hierarchical approach, prioritizing primary data measured at the production site, supplemented by existing literature and internal proprietary data. Background data were sourced from the Ecoinvent 3.9.1 cut-off database (42,43).

Raw materials were transported from various US states (e.g., Ohio, Massachusetts, Florida, Georgia, Missouri, New Jersey, and South Carolina) to the production facility located in South Carolina. Transportation distance and material weights were quantified in metric ton-kilometers. Energy inputs, including electricity and heat, were measured directly at the facility during production. At the end of production, the base oil was packaged using an Ethyl Vinyl Acetate foil and polypropylene fabric, both sourced from Michigan. The transportation distances and the life cycle impacts of the packaging materials were also included in the analysis.

The complete LCI for manufacturing 1 kg of SPE base oil is provided in the Supplementary Material (Table S1). The composition of raw materials varies by product VG (see **Table 1**). Additives were excluded, as the focus is solely on the base fluid. Inputs labeled “SPE VG” represent proprietary industrial data provided by an industrial manufacturer. This data is not publicly available but can be made accessible upon reasonable request to the authors.

### 3.3.2 Life cycle impact assessment

We use the Tool for the Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) for midpoint impact characterization in the life cycle impact assessment (LCIA) (44). TRACI was selected due to its regional relevance to North America and its compatibility with international standards, enabling meaningful global comparisons with similar lubricant studies (45). The impact categories: global warming potential (GWP) in kg $CO_2$-eq, acidification potential (AP) in kg $SO_2$-eq, eutrophication potential (EP) in kg N-eq, freshwater ecotoxicity potential (EFP) in CTUe, and smog formation potential (SP) in kg $O_3$-eq were chosen based on their relevance to lubricant and alignment with international LCA standards (46,47). To evaluate land use and land use change impacts, particularly important given the use of palm oil fatty acid and other renewable inputs, the Environmental Footprint (EF) 3.0 method was applied. This also allows direct comparisons with other polyol esters and petroleum-derived lubricant esters assessed using the same framework.

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Cumulative Energy Demand (CED) was used to quantify primary energy use, capturing direct and indirect energy flows associated with raw material extraction and manufacturing processes throughout the life cycle (48). The LCIA evaluated the magnitude and relevance of potential environmental impacts across categories, including global warming, land use, and resource depletion.

#### 3.3.3 Comparison to other studies

Our findings were benchmarked against two reference base oils evaluated by the nova-Institute: LIGALUB 19 TMP, a biobased polyol ester produced from palm kernel fatty acid and trimethylolpropane (TMP) and Disotridecyladipate (DITA), a conventional lubricant ester, whose reactants isotridecanol and adipic acid are both derived from petrochemical feedstocks (49) According to nova-institute, LIGALUB 19 TMP is produced by Peter Greven (50), a leading producer of oleochemical additives based on renewable feedstock. The system boundaries for both LCA were set as cradle-to-gate, covering all relevant stages from supply of materials (e.g. palm fruit or fossil resources) to the production of LICALUB or DITA. The use phase and end-of-life were not considered (51). For the assessment of LIGALUB 19 TMP by nova-institute, primary data was provided by Peter Greven and where no primary data was available, secondary data was taken from Ecoinvent 3.10 database and expert estimates. For the production of DITA, secondary data was used to replicate the European production of DITA (51,52). The potential environmental impact of all three studies was assessed based on the EF 3.0 method.

These comparative LCAs were selected because they represent functionally equivalent products to the SPE base oils and used consistent system boundaries. Furthermore, the LCA of LIGALUB 19 TMP underwent external peer review by a panel of three independent experts, including LCA and lubricant specialists. Nevertheless, differences in regional data and timeframes introduce some limitations to the comparability of results.

#### 3.3.4 Biogenic carbon uptake

For biobased products, accounting for biogenic carbon uptake is an important consideration in carbon footprint assessments. In this study, we evaluate two scenarios: one that excludes biogenic carbon accounting and one that includes it, applying characterization factors of –1 for $CO_2$ uptake and +1 for $CO_2$ emissions. The biogenic carbon uptake is considered as being a product property, the uptake was also calculated based on the biogenic carbon content of the product.

The SPE base oils were attributed with various biogenic carbon uptakes of 1.36, 0.73, 1.88, 1.31, 1.04 and 1.31, kg $CO_2$-eq/kg, respectively, based on its biobased carbon content shown in **Table 1**. For more information on how this was calculated, see **SM 3**. According to Nova-institute, LIGALUB 19 TMP was attributed with a biogenic carbon uptake of 2.08 kg $CO_2$/kg based on its biobased carbon content of 81% and DITA was attributed with 0 kg$CO_2$/kg based on its biobased content of 0% (51).

### 3.3.5 Sensitivity analysis

To support the growing demand for biobased base oils in Europe and reduce environmental burdens associated with transcontinental logistics, Lubricant companies are evaluating the feasibility of establishing regional production facilities. We conducted a geospatial sensitivity analysis to assess how relocating manufacturing from the current South Carolina (U.S.) facility to Europe would influence cradle-to-gate life cycle impacts of the SPE base oils. This geospatial analysis focuses on the SPE base oil VG-A, selected for its representative process characteristics shared across the SPE base oils.

Using OpenLCA software, we modeled alternative scenarios by modifying the electricity grid mix while maintaining a consistent materials supply chain based on global averages (Rest of the World). This approach isolates the effects of regional energy systems on environmental outcomes. Three scenarios were evaluated: the baseline U.S. grid (SERC region), the European average grid, and the Norwegian grid, which is dominated by hydropower and reflects high renewable energy penetration.

This analysis underscores the importance of regional energy context in determining the sustainability of biobased lubricant production. It provides actionable insights for future site selection and decarbonization strategies in the biobased materials sector.

### 3.3.6 Future-oriented analysis

We conducted a prospective LCA (pLCA) to evaluate the long-term environmental performance of the SPE base oil production under future energy and policy scenarios. This analysis employed the *premise* Python library, a tool that dynamically projects the ecoinvent database into the future using pathways from integrated assessment models (IAMs). *Premise* enables scenario-based adjustments to life cycle inventories by incorporating anticipated shifts in energy technologies, policy interventions, and market trends (53). The pLCA was conducted only on the SPE base oil VG-A production because of the similarities in the production process of the other SPE base oil grades, as described in **Section 2**.

We used the IMAGE as our reference IAM (54,55), which simulates the environmental impacts of human activities across 26 global regions through spatially explicit grids. IMAGE facilitates systems-level exploration of interactions between energy, land use, and climate, enabling the assessment of long-term environmental responses and mitigation strategies (56,57).

Two Shared Socioeconomic Pathways (SSPs) were applied, SSP1 and SSP2, for the years 2030, 2040, and 2050. SSP1 outlines a sustainability-oriented trajectory with low barriers to climate mitigation and

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adaptation, characterized by reduced material consumption, low resource intensity, and global prioritization of human well-being (58,59). In contrast, SSP2 reflects a "middle-of-the-road" development pattern marked by uneven economic growth, moderate progress on environmental goals, and declining but persistent resource and energy use. These pathways provide contrasting yet plausible futures for assessing the sensitivity of polyol ester production to systemic shifts in energy infrastructure (58).

To establish a reference baseline, we first modeled the current SPE base oil production system using attributional LCA with Ecoinvent 3.10, assuming U.S. electricity grid conditions. This current state model serves as a benchmark for comparison and an anchor to mitigate interpretive uncertainty in prospective scenarios. We then applied *premise*-modified versions of the ecoinvent database based on IMAGE-informed electricity grid compositions and adjusted every material and process in the SPE base oil production under SSP1 and SSP2. These future scenarios reflect evolving electricity mixes and changes in material supply chain directly influencing the environmental burdens associated with each kilowatt-hour used in production. By integrating this dynamic energy data into the life cycle inventory, the study captures the environmental implications of biobased base oil production over time under different policy and development assumptions. Further methodological details and future electricity grid mx, see **SM 4**.

The comparative and pLCA results offer insight into future-specific environmental trade-offs and underscore the role of geographic energy variation in guiding sustainable production strategies.

## 4 RESULTS AND DISCUSSIONS

This section covers the life cycle impacts of various SPE base oil based on different impact categories.

### 4.1. Results for SPE base oils

**Table 2** presents the cradle-to-gate LCA results for the SPE base oils across six viscosity grades (VG), revealing consistent trends in environmental impact that align with the physical and chemical properties of each product. Notably, higher-viscosity base oils exhibit lower environmental burdens per kilogram of product. This inverse relationship between viscosity and environmental impact likely reflects differences in both energy intensity and yield efficiency during production.

**Table 2**: Cradle-to-gate LCA results for the SPE base oils.

| **Impact Categories** | **SPE Base Oils Viscosity Grades (VG)** | | | | | |
|---|---|---|---|---|---|---|
| | **VG-A** | **VG-B** | **VG-C** | **VG-D** | **VG-E** | **VG-F** |
| GWP [kg $CO_2$-eq/kg] | 4.36 | 4.21 | 3.72 | 3.93 | 3.52 | 3.07 |
| GWP (with bio. uptake) [kg $CO_2$-eq/kg] | 3.00 | 3.48 | 1.84 | 2.62 | 2.48 | 1.76 |

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| | | | | | | |
|---|---|---|---|---|---|---|
| AP [kg $SO_2$-eq/kg] | 2.51E-02 | 2.17E-02 | 1.36E-02 | 1.45E-02 | 1.64E-02 | 1.33E-02 |
| EP [kg N-eq/kg] | 4.60E-02 | 3.86E-02 | 2.36E-02 | 2.41E-02 | 2.66E-02 | 1.97E-02 |
| EFP [CTUe/kg] | 83.37 | 63.08 | 23.00 | 22.68 | 36.15 | 21.37 |
| SP [kg $O_3$-eq/kg] | 2.96E-01 | 2.82E-01 | 1.83E-01 | 2.08E-01 | 2.47E-01 | 2.24E-01 |

GWP without biogenic uptake ranged from 4.36 kg $CO_2$-eq for VG-A to 3.07 kg $CO_2$-eq for VG-F. When accounting for biogenic carbon uptake, the reduction was significant, with GWP values falling to 3.00 and 1.76 kg $CO_2$-eq respectively. This improvement in net carbon footprint correlates with the higher biobased carbon content in the heavier grades, VG-D, VG-E and VG-F all exceed 65% biobased carbon according to ASTM D6866, compared to just 50–62.5% in the lighter grades (see **Table 1**).

Similar trends were observed in AP, EP, EFP, and SP, where lower values were generally associated with higher-viscosity grades. For instance, the AP dropped from 2.51E–02 kg $SO_2$-eq for 32S to 1.33E–02 kg $SO_2$-eq for VG-F, while the EP decreased from 4.60E–02 to 1.97E–02 kg N-eq. These reductions likely result from differences in feedstock conversion efficiency, processing inputs, and emissions associated with utilities. Lighter grades, due to their lower kinematic viscosities (e.g., 6.1 cSt at 100°C for VG-A), often require more extensive separation and conditioning processes to meet ASTM D445 and D2270 specifications (see **Table 1**), which may increase utility and solvent consumption.

The data also show that higher-viscosity oils generally exhibited higher flash and fire points, reflecting formulation differences that may influence processing energy requirements. For instance, flash points increased from 236 °C for the VG-A grade to 262–300 °C for the VG-F and VG-C grades, while fire points followed a similar trend (262 °C for VG-A vs. 280–324 °C for higher-viscosity grades). By contrast, pour points remained below −24 °C across all grades (see **Table 1**), indicating that cold-temperature performance was preserved even as thermal stability improved with viscosity.

The results suggest that viscosity is not only a functional attribute but also a proxy for environmental efficiency in the manufacturing of biobased base oils. Higher-viscosity products not only offer greater lubricating film strength and thermal stability, critical for demanding applications in automotive and industrial systems, but also deliver superior environmental performance from cradle to gate. These findings reinforce the potential for biobased lubricants to displace petroleum-based alternatives in a wide range of applications while minimizing lifecycle emissions and toxicity. Future work should consider system-level trade-offs in use-phase performance and end-of-life fate to further substantiate these cradle-to-gate advantages.

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The cradle-to-gate primary energy results for the SPE's base oils reveal distinct patterns tied to viscosity grade and the balance between renewable and non-renewable energy inputs. As shown in **Table 3**, the total energy demand per kilogram of product ranged from 64.9 MJ/kg for grade VG-C to 145.6 MJ/kg for grade VG-A, indicating more than a two-fold variation across the product line. Notably, lighter viscosity grades, such as VG-A and VG-B, exhibited significantly higher total primary energy use compared to higher-viscosity grades like VG-F and VG-E.

**Table 3:** Cradle-to-gate primary energy use for the manufacturing of 1 kg of SPE base oil

| **Primary Energy** | **SPE Base Oil Viscosity Grades (VG)** | | | | | |
|---|---|---|---|---|---|---|
| | **VG-A** | **VG-B** | **VG-C** | **VG-D** | **VG-E** | **VG-F** |
| Non-renewable [MJ/kg] | 72.1 | 79.0 | 48.7 | 60.1 | 70.2 | 63.2 |
| Renewable [MJ/kg] | 73.5 | 51.1 | 16.2 | 13.3 | 39.1 | 33.6 |
| Total [MJ/kg] | 145.6 | 130.1 | 64.9 | 73.4 | 109.2 | 96.8 |

The observed trends in energy use are shaped by both Scope 1 (direct fuel and steam inputs) and Scope 2 (purchased electricity) contributions, as well as the mix of renewable versus non-renewable sources. For example, lighter viscosity grades such as VG-A and VG-B exhibit the highest renewable energy consumption (73.5 MJ/kg and 51.1 MJ/kg, respectively) due to their reliance on biobased feedstocks. At the same time, these grades draw heavily on non-renewable energy (72.1 MJ/kg and 79.0 MJ/kg), leading to elevated total energy footprints. The higher demand reflects more intensive Scope 1 and Scope 2 requirements, particularly high-temperature distillation or dehydration steps.

In contrast, mid- to high-viscosity grades, including VG-C, VG-D and VG-F, demonstrate lower overall energy use. Grade VG-C has the lowest total energy demand (64.9 MJ/kg), with 16.2 MJ/kg from renewable sources and 48.7 MJ/kg from non-renewables, suggesting more efficient production or less intensive Scope 1/2 inputs to achieve the target viscosity. Similarly, VG-F shows a balanced energy profile (33.6 MJ/kg renewable, 63.2 MJ/kg non-renewable; total 96.8 MJ/kg), indicating that heavier products require fewer processing steps per unit of output.

Generally, the data reveals a clear relationship between viscosity and energy performance: lighter viscosity oils require greater Scope 1 steam and Scope 2 electricity inputs to maintain quality standards, while heavier grades benefit from simpler processing. Although renewable energy helps mitigate carbon impacts, it still carries upstream burdens from agriculture and bio-based chemical production. These findings emphasize the need to optimize both feedstock selection and Scope 1/2 processing strategies, particularly for lighter viscosity formulations, to enhance the sustainability of biobased lubricants.

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### 4.2. Contribution analysis of the SPE base oils

**Figure 4** presents the relative contribution of key inputs and process for six viscosity grades. The contribution analysis indicates that fatty acid and proprietary polyols are the primary drivers of environmental impacts across most categories, particularly GWP, EFP, and EP. In some viscosity grades, these two inputs account for over 80% of the total impact, highlighting upstream chemical sourcing as the dominant environmental hotspot in the biobased base oil production system. additional details are provided in **SM 6**.

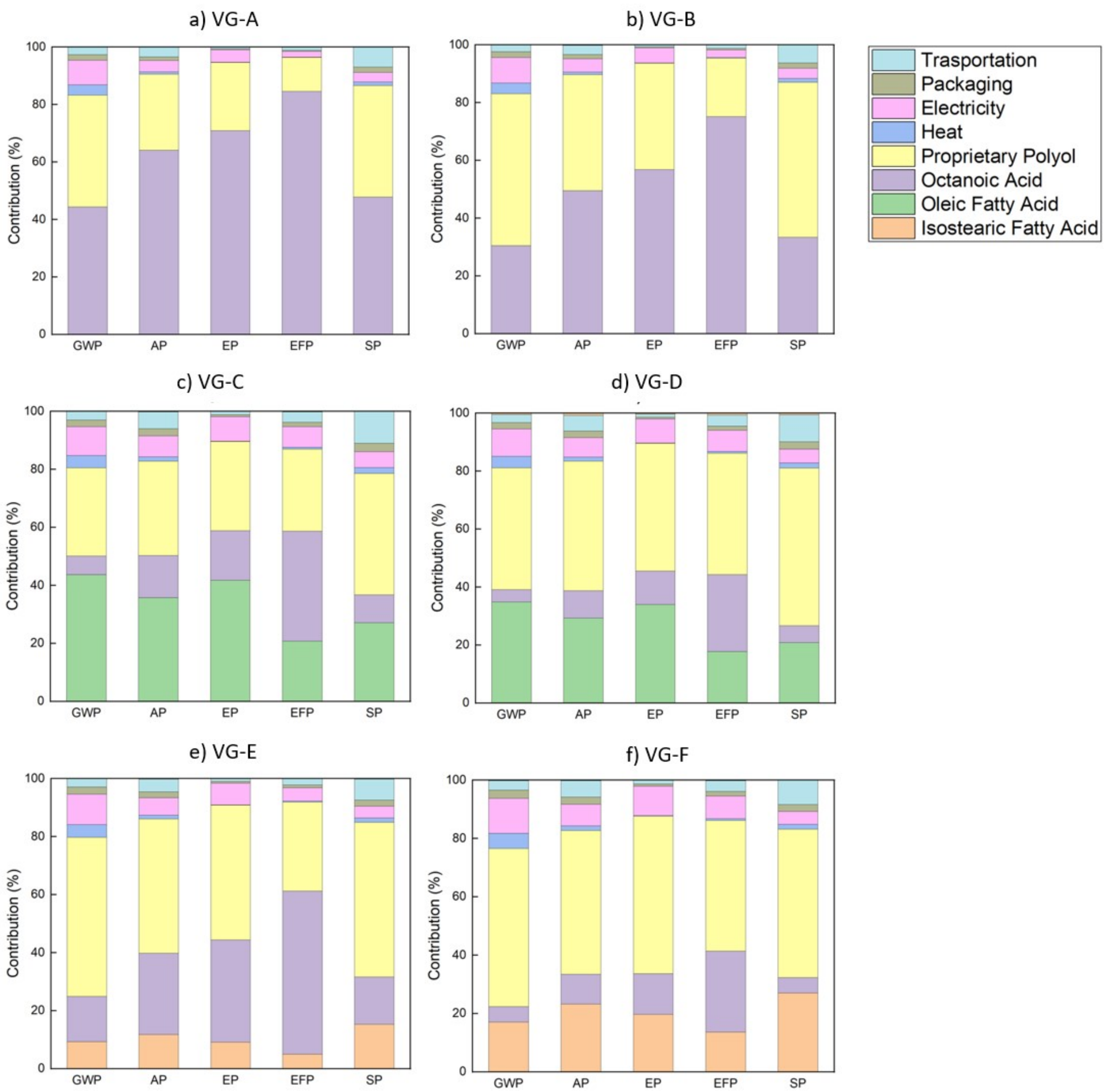

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**Figure 4:** Relative contribution of key inputs and processes to five impact categories: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), freshwater ecotoxicity (EFP), and smog potential (SP), for the SPE base oils across six viscosity grades: (a) VG-A (b) VG-B (c) VG-C (d) VG-D (e) VG-E and (f) VG-F. Only components contributing more than 2% to a given category are labeled with their respective percentages.

These insights align with broader trends in LCA literature: the transition to biobased products often shift burdens upstream from fossil resource extraction to agricultural and chemical processing. In this context, SPE base oils relatively strong performance suggests that careful supply chain curation, including certified feedstocks and optimized process design, can substantially reduce this risk. To mitigate these effects, future process development should focus on:

- Sourcing lower-impact acids and polyol alternatives, preferably from more sustainable agricultural systems or recycled biomass;
- Reducing dependency on fossil-based energy through on-site renewable energy integration;
- Improving supply chain efficiency by minimizing transport distances or switching to low-emission logistics.

By addressing these hotspots, the environmental footprint of the SPE base oils production can be significantly reduced while maintaining product performance.

## 4.3. Comparison with European base oil

**Table 4** summarizes the cradle-to-gate carbon footprint of producing 1 kg of the SPE base oils (manufactured in the United States) compared to two European lubricant products: LIGALUB 19 TMP, a commercially available biobased polyol ester, and DITA, a petrochemical-derived conventional lubricant ester. The Impacts were assessed using EF 3.0 methodologies.

The results show that for GWP, the SPE base oils exhibit cradle-to-gate emissions between 3.19–4.52 kg $CO_2$-eq/kg, which decrease to 1.88–3.64 kg $CO_2$-eq/kg when biogenic carbon uptake is considered. In contrast, DITA yields 6.97 kg $CO_2$-eq/kg, with no biogenic offset. The relative reduction in carbon footprint ranges from 41% to 84%, highlighting the strong carbon mitigation potential of these biobased formulations. Compared to LIGALUB, the SPE base oils exhibit a 4–35% lower GWP even after adjusting for biogenic carbon, suggesting meaningful performance gains rooted in upstream feedstock selection and manufacturing efficiency

**Table 4:** Cradle-to-gate product carbon footprint (PCF) and other environmental impact of the SPE base oils compared to LIGALUB polyol ester (biobased) and conventional petroleum-based lubricant ester (DITA), All absolute values are in kg of product and bio. stands for biogenic. The results are presented based on Environmental Footprint (EF 3.0) impact assessments methods.

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| Impact Categories | BASE OILS | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | VG-A | VG-B | VG-C | VG-D | VG-E | VG-F | LIGALUB | DITA |
| GWP (kg$CO_2$-eq) | 4.52 | 4.37 | 3.82 | 4.05 | 3.66 | 3.19 | 5.87 | 6.97 |
| GWP (with bio. uptake) (kg$CO_2$-eq) | 3.16 | 3.64 | 1.94 | 2.74 | 2.62 | 1.88 | 3.79 | 6.97 |

Beyond carbon footprint indicators, normalized cradle-to-gate results across all environmental impact categories reveal distinct performance patterns among the **SPE base oils**, the European biobased polyol ester (LIGALUB), and the petroleum-derived reference lubricant (DITA), as shown in **Figure 5**.

EFP impacts, reported only for SPE base oils, show a wide range of contributions. VG-A and VG-B dominate this category, jointly contributing over 40% of the total EFP impact. These impacts originate from upstream synthesis intermediates, especially octanoic acid, and residual by-products associated with fatty acid esterification (60,61). This finding emphasizes that even biobased feedstocks with low carbon footprints can exhibit elevated ecotoxicity if not sufficiently purified. Mitigation efforts should focus on improving catalyst recovery and reducing toxic effluents during refining.

In SP, which measures contributions to ground-level ozone formation, DITA exhibits the highest single contribution (16%), but several SPE base oils grades (e.g., VG-A, VG-B, VG-F) also present substantial shares. Nonetheless, no individual SPE base oil grade exceeds DITA's total impact, and collectively, the SPE base oils grades achieve a more balanced distribution, reflecting reduced volatile organic compound (VOC) and $NO_x$ emissions. These reductions likely result from cleaner processing conditions and tighter emissions control in the SPE base oils manufacturing, critical given tightening regulatory limits on tropospheric ozone precursors.

EP reveals a similar pattern; although some SPE base oil grades (e.g., VG-A and VG-B) match or exceed DITA's contribution, LIGALUB stands out with the lowest share (3%), reinforcing its advantage in nitrogen-related emissions. The SPE base oil VG-F also performs well, contributing only 5%, suggesting room for optimization through targeted energy use and catalyst efficiency adjustments.

In AP, the impact is more evenly distributed. The SPE base oil grades generally match or outperform DITA (12%), with SPE base oil VG-F again demonstrating low acidification emissions (9%). This may be attributed to the absence of sulfur-intensive inputs and better management of acidic process waste.

Across the board, while the SPE base oil formulations demonstrate competitive or superior performance across most categories, the results reaffirm a central principle in life cycle assessment: sustainability is multi-dimensional. Optimizing for one impact category (e.g., GWP) may exacerbate another (e.g., EFP),

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underscoring the importance of holistic, multi-indicator evaluation frameworks when designing next-generation lubricants. The absolute values for the result of the impact categories can be seen in **SM 4.**

The results affirm that SPE base oils, synthesized from biobased feedstocks, offer substantial carbon footprint reductions relative to both petrochemical (DITA) and biobased (LIGALUB) alternatives, positioning them as promising candidates for decarbonizing industrial lubricants. However, the findings also underscore a crucial insight: sustainability in chemical manufacturing extends beyond carbon metrics.

Trade-offs observed in categories such as EFP and EP reveal that lower GWP does not inherently guarantee a lower environmental burden across all dimensions. These trade-offs often arise from upstream processing inputs and the complexity of catalyst and solvent recovery systems, highlighting key intervention points for green process innovation. As such, manufacturers must account for side-stream emissions and material purity, especially in esterification and feedstock processing, to unlock the full environmental potential of biobased alternatives.

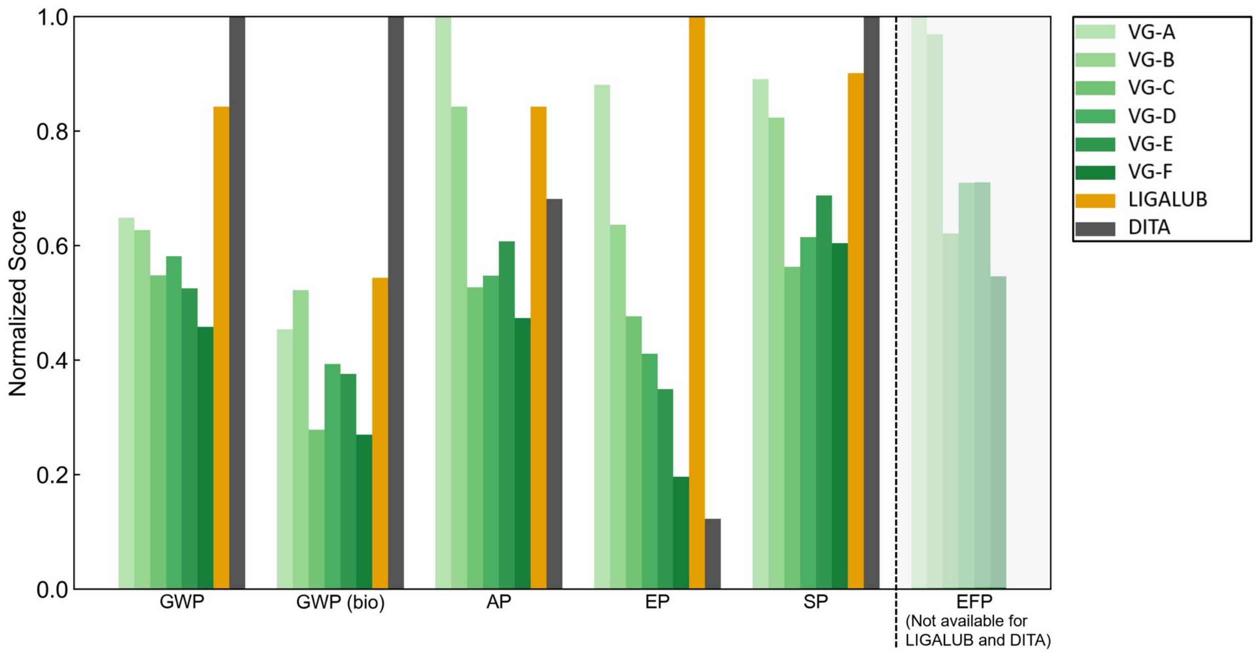


**Figure 5:** Normalized environmental impact indicators for eight base oils across six categories: global warming potential (GWP), GWP with biogenic carbon uptake (GWP (bio)), acidification potential (AP), eutrophication potential (EP), smog formation potential (SP), and freshwater ecotoxicity potential (EFP). Values are normalized per impact category across all base oils. The EFP indicator, shaded in grey, is reported only for SPE base oils due to data unavailability for LIGALUB and DITA.

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This comparative study emphasizes a systems-level approach to assessing lubricant sustainability, extending beyond greenhouse gas emissions to include impacts such as toxicity, acidification, and ozone precursor formation. While LCA databases like ecoinvent provide comprehensive inventories for conventional chemicals, publicly available data for biobased lubricant intermediates are extremely limited, making primary data collection essential. By incorporating these less-studied impact categories for biobased ester base oils, this work provides actionable insights for the lubricant and specialty chemical sectors, encouraging the adoption of comprehensive LCA strategies to guide more responsible product design, feedstock sourcing, and policy alignment.

### 4.4. Sensitivity analysis

Although electricity contributes modestly to overall cradle-to-gate life cycle impacts (**Figure 4**), a targeted sensitivity analysis was conducted to evaluate the influence of regional electricity grid composition on the environmental performance of SPE base oil production. Electricity supply scenarios were modeled using grid mixes from the Ecoinvent 3.10 database to represent three distinct regions: the U.S. Southern Electricity Reliability Corporation (SERC), the European interconnected grid (UCTE), and Norway.

These regions exhibit substantial differences in electricity generation portfolios. The SERC region is dominated by fossil-based electricity generation (approximately 65%, primarily coal and natural gas), with comparatively smaller contributions from nuclear and renewable sources. The European grid reflects a more diversified mix, including higher shares of biomass, waste-derived energy, and variable renewable resources. In contrast, Norway's electricity supply is largely hydropower-based, with more than 95% of generation derived from renewable hydroelectric sources, representing one of the lowest-carbon grid mixes globally.

Results in **Table 5** confirmed limited sensitivity to grid variations. GWP decreased by 6.8% when shifting from the fossil-intensive SERC grid to hydropower-dominated Norway, with similar modest reductions (<3%) in other indicators like CED and SP. These marginal differences reflect the relatively minor role of electricity in polyol ester production, where upstream processes (e.g., feedstock cultivation, solvent recovery) dominate environmental burdens as shown in **Figure 4**.

However, the analysis revealed subtle trade-offs. For example, EFP was slightly higher under the European grid due to increased reliance on biomass and waste-derived energy. While not decisive in isolation, such regional nuances may grow more impactful as biobased manufacturing transitions toward deeper electrification and as grid decarbonization advances.

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Therefore, while electricity sources have limited influence today, their importance will likely increase in future low-carbon production contexts, justifying continued attention to grid infrastructure when planning biomanufacturing expansion.

**Table 5:** Cradle-to-gate environmental performance of the SPE base oils: Based on plant location and their respective electricity grid mix. European average (UTCE stands for Union for the Coordination of Transmission of Electricity – European grid), USA (US-SERC stands for US Southern Electricity Reliability Corporation) and Norway grid mix. Modeled using Ecoinvent 3.10 database.

| Locations | GWP (kg CO2-q) | AP (kg SO2-q) | EP (kg N-eq) | EFP (CTUe) | SP (kg O3-eq) | CED (MJ) |
|---|---|---|---|---|---|---|
| VG-A SPE_USA | 5.01 | 0.026554 | 0.04520 | 140.97 | 0.3154 | 147.17 |
| VG-A SPE_European Average | 4.91 | 0.026815 | 0.04569 | 141.99 | 0.3150 | 145.91 |
| VG-A SPE_Norway | 4.67 | 0.025920 | 0.04419 | 139.70 | 0.3059 | 142.74 |

## 4.5. Prospective LCA result

The pLCA of SPE base oil VG-A (**Figure 6**) reveals that the environmental performance of its production is strongly controlled by the electricity grid mix projected under SSP1 and SSP2. SPE base oil VG-A is manufactured by esterifying bio-derived fatty acids with proprietary polyols. This reaction, catalyzed and conducted at elevated temperatures (140–250 °C), is energy-intensive and, therefore, highly sensitive to the source of electricity. The pLCA reveals that under SSP1, a rapid decarbonization scenario, GWP and CED for SPE base oil VG-A decline by 20% and 9%, respectively, by 2050. These improvements stem from the growing share of wind and solar in the electricity mix (67% by 2050) and reduced fossil use. In contrast, under SSP2, where fossil fuels remain prominent, GWP and CED decrease by only 7% and 6%, respectively.

EP shows similar improvement under SSP1 but stagnates under SSP2. EFP, however, increases slightly in both scenarios, indicating that non-energy-related processes, such as polyol synthesis or agricultural input production, are immune to energy transitions. This highlights the need for a dual sustainability strategy: coupling energy decarbonization with feedstock and chemical input optimization.

These pLCA indicate that electricity grid transformation is the principal driver of environmental improvement in GWP, CED, and air emissions. However, categories like ecotoxicity highlight the importance of addressing upstream supply chains and material inputs. Aligning lubricant production with low-carbon electricity, especially under pathways like SSP1, offers a clear strategy for enhancing the sustainability of biobased lubricants. Future work should also explore the optimization of feedstock sourcing and heat integration to complement electricity-driven gains.

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The pLCA approach employed here offers a forward-looking lens to evaluate the decarbonization potential of emerging bio-industrial systems. Crucially, the results underscore that achieving meaningful reductions in GWP and CED hinges on rapid electricity sector decarbonization, as envisioned under SSP1. However, gains in energy-related indicators alone are insufficient. The persistence or increase of impacts like EFP suggests that upstream inputs, such as agricultural feedstocks, catalysts, and polyols, must be improved in parallel. This highlights a broader implication for sustainable materials design, indicating that environmental benefits must be pursued through both cleaner energy and cleaner chemistry.

The forward-looking nature of pLCA inherently carries uncertainties, particularly when relying on IAM projections. While SSP1 and SSP2 provide useful bounding cases, rapid decarbonization versus moderate transition, the actual trajectory of global energy systems could diverge due to geopolitical, economic, or technological disruptions. Our conclusions are most robust for energy-driven indicators (GWP, CED, air pollutants), consistently showing sensitivity to grid mix across both scenarios. By contrast, non-energy indicators (e.g., ecotoxicity) remain relatively unchanged regardless of scenario, highlighting that these results are less contingent on IAM assumptions and more dependent on process-level choices. Future work could apply sensitivity ranges or probabilistic IAM ensembles to further quantify the stability of conclusions under broader plausible futures.

Temporal and regional differences must be considered when interpreting comparative results between SPE base oil VG-A, fossil-derived DITA, and the European biobased ester LIGALUB 19 TMP. The SPE base oil results are projected from a 2025 U.S. production baseline, embedded within future electricity pathways. By contrast, LIGALUB data reflect present-day European conditions, where the grid is already less carbon-intensive, while DITA represents a fossil-based baseline with relatively stable supply chains. While SPE base oil appears to outperform DITA under most categories, direct comparisons with LIGALUB require caution: differences may reflect regional energy mixes and temporal assumptions as much as intrinsic product performance. Highlighting these contextual differences helps ensure that comparative claims are interpreted as directional insights rather than one-to-one equivalencies.

By embedding future-oriented scenarios into life cycle modeling, this work advances the methodological frontier of pLCA and fills a notable gap in sustainability assessments of lubricant base oils. Few prior studies integrate dynamic energy pathways into base oil evaluations. By using IAM-aligned scenarios, our analysis provides clarity on the conditions under which biobased base oils can contribute meaningfully to climate goals. It also offers actionable insights for industry and policymakers: aligning production with low-carbon electricity and improving feedstock sourcing are complementary strategies for realizing the full sustainability potential of biobased lubricants.

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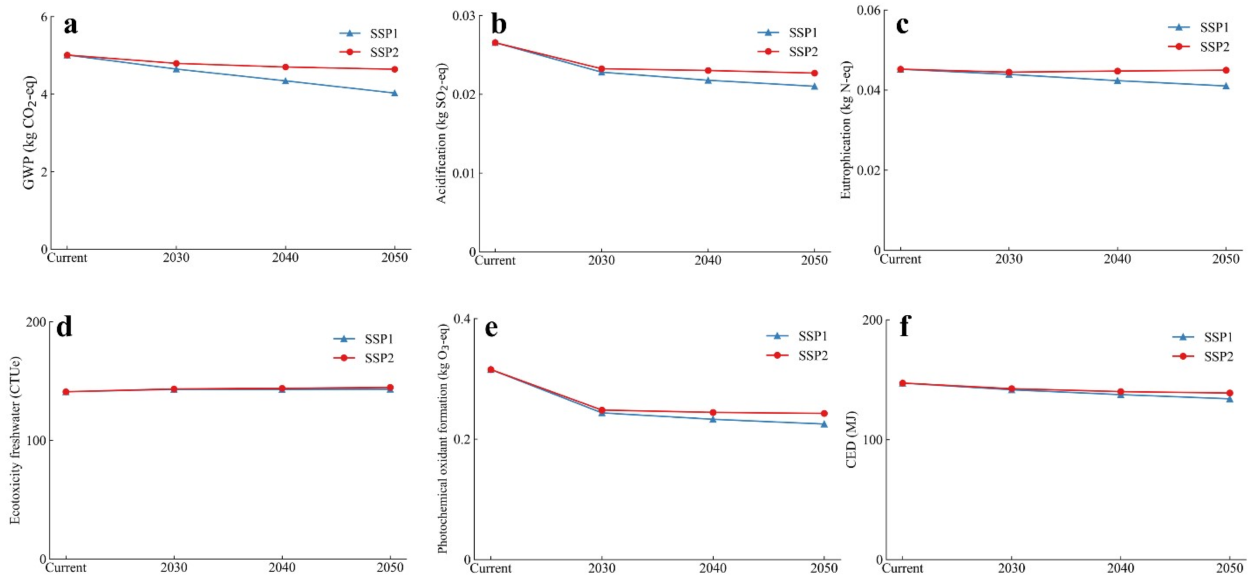


**Figure 6:** Prospective LCA environmental impact results for the SPE base oil VG-A.

## 4.6. Comparison with other Studies

**Table 6** presents a comparative summary of key LCA studies on lubricant base oils to contextualize the the SPE base oils cradle-to-gate assessment results. By comparing the SPE base oils study to previous assessments conducted by Ramboll (62), Ekman et al. (6), and Vag et al. (63), readers can better understand the methodological advancements and increased transparency that influence environmental performance outcomes.

**Table 6:** Comparative overview of LCA studies for lubricant base oils, highlighting regional differences, system boundaries, objectives, methodological approaches, and reported GWP values.

| Study | Region/Location | System Boundary | Objective | LCA Methodology | GWP Value (kg $CO_2$eq) | Year |
|---|---|---|---|---|---|---|
| SPE base oil (This study) | USA (regionalized data) | Cradle-to-Gate | Assess the environmental impacts of novel SPE biobased base oils | ISO 14040/44, ISO 14067, PAS 2050, API TR 1533, EF 3.0, TRACI 2.1 | 3.07–4.36 per kg (1.76–3.48 with biogenic Carbon uptake) | 2025 |
| Ramboll (Safety-Kleen) (62) | USA | Gate-to-Gate (2nd refining only) | Evaluate GHG emissions of re-refined base oils (second stage only) | Unspecified; limited boundary | 0.7 per liter (approx. 0.6–0.8 per kg estimate.) | 2023 |
| Ekman et al. (6) | Sweden/EU | Cradle-to-Gate | Compare mineral vs. vegetable oil-based hydraulic fluids (incl. biotech route) | ISO 14040/44 (assumed) | 1.4 per kg | 2011 |
| Vag et al. (63) | Sweden | Cradle-to-Grave | Compare base fluid manufacture for | ISO 14040/44 (assumed); limited | 1300–2200 per $m^3$ (1.3–2.2 per kg est.) | 2002 |

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| | | | |
|---|---|---|---|
| | | synthetic and biobased lubricants | methodological transparency |

This current study distinguishes itself through its comprehensive cradle-to-gate system boundary, which includes emissions from raw material extraction, energy use, and processing. In contrast, the Ramboll study of re-refined oil only covers gate-to-gate emissions from second-stage refining, omitting upstream impacts such as collection and initial refining, which limits comparability. Studies by Ekman et al. and Vag et al. are older and less transparent in their methodologies and data sources.

In contrast, our analysis applies current, regionally specific data and adheres to established LCA standards. While our study reports higher GWP values (e.g, per kg), this reflects the use of more complete accounting and updated modeling practices. This comparison emphasizes the importance of consistent system boundaries and up-to-date inventories in evaluating and benchmarking biobased and re-refined lubricants.

### 4.7. Limitations

We acknowledge several limitations in this study. One key limitation is the reliance on secondary datasets such as Ecoinvent and EPDs. These generic data sources often fail to capture regional specifics, such as variations in energy mixes, transportation distances, and feedstock cultivation practices, which can significantly influence environmental outcomes (64). Impacts related to land-use change, water consumption, and global warming potential may thus be over or underestimated. Additionally, context-specific variables such as biodiversity, land management, and regional agricultural techniques are not well represented in standardized inventories, limiting the ecological relevance of the results (65,66).

While pLCA using scenario-based frameworks (e.g., premise) enables exploration of future impacts, these rely on IAMs that incorporate uncertain assumptions about socio-economic trajectories, technologies, and policies (67,68). Key factors like electrification rates, grid decarbonization, or geopolitical shifts may not unfold as modeled, leading to discrepancies between projected and actual impacts (69–71). Therefore, pLCA results in this study should be interpreted as indicative rather than predictive. Future research would benefit from incorporating sensitivity analyses and routine updates to account for emerging trends and revised assumptions.

The system boundary adopted in this study is cradle-to-gate, excluding the use and end-of-life phases. Currently, the end-of-life management of bio-based base oils such as polyol esters and lubricants is not well standardized, with most pathways involving partial recovery, energy recovery through incineration, or uncontrolled disposal, depending on regional infrastructure and policy (72–74). Incorporating these

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downstream stages in future research would enable a more comprehensive assessment of the product's overall environmental sustainability. Although primary data was obtained from a commercial-scale production facility, the analysis relies on deterministic values. In practice, key parameters, such as emission factors, energy consumption, and material inputs, exhibit variability and occur within a range. Future studies should incorporate uncertainty analysis to enhance the robustness of environmental conclusions. Furthermore, the reliance on data from a single manufacturer limits the ability to draw generalized conclusions for other biobased base oils. Nevertheless, this study offers valuable insights into the environmental profile of the specific biobased formulation examined.

### 4.8. Broader industrial contributions, policy implications, and recommendations for stakeholders

This study advances the environmental assessment of lubricants by shifting focus from finished products to the cradle-to-gate impacts of base oils, which are a significant source of environmental burden. By using high-resolution operational data from a commercial-scale facility, the analysis brings transparency to a supply chain stage often treated as a "black box." The results confirm that base oil production decisively shapes the overall footprint of lubricants, highlighting the importance of targeted interventions at this stage.

Beyond GWP reductions, the study broadens the scope to acidification, eutrophication, smog formation, and freshwater ecotoxicity, exposing environmental trade-offs. Scenario modeling further illustrates how regional energy mixes, raw material sourcing, and future decarbonization pathways influence outcomes. These findings provide a methodological template for future LCAs of industrial intermediates and deliver timely insights for advancing climate-aligned lubricants.

#### 4.8.1. Strategic levers for decarbonization

Three intervention points stand out:

- Energy source transformation: Locating production in renewable-rich grid regions or aligning with SSP1 decarbonization trajectories can reduce GWP and CED by up to 20% and 9%, respectively.
- Feedstock and process optimization: Fatty acids and proprietary polyols dominate acidification, eutrophication, and toxicity impacts, underscoring the need for cleaner synthesis routes, catalyst reformulation, and regionally optimized sourcing.
- Product versatility: Broader viscosity range and NSF HX-1 certification support diverse applications, enhancing supply chain resilience and regulatory alignment (e.g., EAL in maritime, REACH in the EU).

#### 4.8.2. Policy Implications

Scaling sustainable lubricant inputs requires supportive frameworks:

- Expand environmental reporting standards (e.g., ISO 14067, EU PEF) to cover base oils.
- Provide incentives for regionalized biorefining in low-carbon grid zones.
- Integrate advanced biobased oils into carbon markets and EPR frameworks to reward lower-carbon products and enhance traceability.

#### 4.8.3. Recommendations for industrial stakeholders

Lubricant formulators, OEMs, and sustainability professionals should:

- Prioritize suppliers with third-party verified LCAs following industry frameworks.
- Request site-specific energy and biogenic carbon disclosures in PCF reports.
- Collaborate on feedstock optimization and renewable integration to address toxicity-related impacts.

This study demonstrates that not all biobased base oils deliver equal environmental benefits. Strategic choices in feedstock, energy sourcing, and regional siting will determine whether biolubricants achieve their full potential in advancing low-carbon, sustainable lubrication systems.

## 5 CONCLUSIONS

Lubricants play a vital role in reducing friction and wear across mechanical systems, but remain largely reliant on petroleum-derived inputs, which contribute to GHG emissions, environmental toxicity, and long-term persistence in ecosystems. This study provides a comprehensive cradle-to-gate LCA of biobased secondary polyol ester (SPE) base oils of various viscosity grades (VG) developed by an industrial manufacturer, offering a detailed evaluation of their environmental performance relative to both fossil-derived and alternative biobased lubricants.

Our results demonstrate that SPE base oils outperform conventional petrochemical products like DITA and are competitive with leading biobased alternatives such as LIGALUB 19 TMP. When biogenic carbon uptake is accounted for, GWP reductions reach up to 84%, with additional improvements in acidification and eutrophication potentials. However, contribution analysis reveals that upstream feedstocks, particularly fatty acid and proprietary polyols, are the dominant environmental hotspots across all impact categories, often contributing over 80% of total GWP, EP, and EFP. These results underscore the critical role of cleaner feedstock sourcing, more sustainable agricultural inputs, and low-impact synthesis routes in reducing life cycle burdens.

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Further analysis of the SPE base oils revealed a consistent trend: lighter viscosity grades (e.g., VG-A and VG-B) tend to exhibit both higher cradle-to-gate environmental impacts and greater total primary energy demand, while heavier grades (e.g., VG-D and VG-F) demonstrate improved energy and environmental performance. These trends are closely tied to production energy intensity, process configurations, and biobased carbon content. Lighter grades typically require extensive conditioning, higher-temperature separations, or greater solvent use to meet viscosity and volatility specifications, increasing renewable and non-renewable energy inputs.

Geospatial and prospective LCA scenarios further emphasize the pivotal role of regional energy systems and future grid decarbonization in shaping environmental outcomes. Shifting production from fossil-dominated grids to cleaner electricity mixes resulted in modest but measurable GWP and cumulative energy demand reductions. Moreover, aligning production with sustainable development scenarios like SSP1 showed additional benefits, particularly for carbon- and energy-intensive processes. However, these regional and future-oriented benefits were less pronounced in categories like freshwater ecotoxicity, where impacts stem predominantly from upstream agricultural and chemical inputs. This finding underscores the limits of energy-based strategies alone and the necessity of improving feedstock sustainability and chemical processing pathways.

The study reveals that viscosity is not only a functional specification but also a proxy for environmental efficiency. Higher-viscosity products offer thermal stability and lubricating film strength critical for industrial and automotive applications while delivering better life cycle environmental performance. These findings highlight the need for integrated product and process design, where function, performance, and sustainability are co-optimized.

Reducing the environmental footprint of lubricants requires coordinated action across the value chain. Manufacturers can lower life cycle impacts through transparent, certified feedstock sourcing, targeted formulation strategies for heavier viscosity products, and region-specific production siting that leverages low-carbon grids. Policymakers may support these transitions by implementing ecolabeling schemes, green procurement policies, and life cycle–based standards prioritizing low-GWP and biodegradable lubricants. Industry standards should evolve to incorporate environmental performance indicators alongside traditional metrics like viscosity index and oxidation resistance. For consumers and institutional buyers, selecting environmentally preferable lubricants remains challenging; third-party certifications (e.g., USDA BioPreferred, EU Ecolabel) and standardized carbon footprint disclosures are essential for supporting informed decision-making.

By quantifying both the benefits and trade-offs of biobased base oils under current and future conditions, this study delivers a science-based foundation for improving lubricant sustainability. It supports innovation in formulating high-performance, low-impact lubricants and provides a robust framework to inform decisions across policy, manufacturing, and end-user contexts. Finally, the SPE base oils exemplify the potential for biobased technologies to displace petroleum incumbents while contributing meaningfully to low-carbon, circular, and environmentally responsible material transitions.

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**Authors' Contribution**

Muzan Williams Ijeoma conducted the analysis, investigation, data curation, and visualization, and wrote the original draft under the supervision of Michael Carbajales-Dale, who also reviewed and edited the manuscript. Hao Chen and Zachery Hunt reviewed and edited the manuscript.

**Compliance with ethics guideline**

Hao Chen and Michael Carbajales-Dale declare no conflict of interest. Muzan Williams Ijeoma was employed by VBASE Oil Company during the project period but was not employed by the company at the time of publication. Zachery Hunt was employed by VBASE Oil Company at the time of publication.

**Supplementary Data**

Supplementary data would be made available upon request.

**Data Availability Statement**

The data used in the study is proprietary information.

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