SUSTAINABILITY IN LUBRICANTS: AN ANALYSIS OF THE INDUSTRY'S EVOLUTION AND ITS GLOBAL SIGNIFICANCE OVER THE PAST FEW YEARS

1. Introduction

In modern industry, lubricants are essential for sustaining the motion of machinery and mechanical systems as they reduce friction, dissipate heat, prevent wear, and tear and ensure reliable functionality. However, the environmental impact of traditional lubricants raises questions about their alignment with the United Nations' Sustainable Development Goals (SDGs)—global objectives aimed at fostering a better world. A closer examination reveals that the low biodegradability, high persistence, and aquatic toxicity of traditional lubricants conflict with specific SDGs (#3, #6, #12, and #13), which advocate for good health and well-being, ensuring access to clean water, promoting sanitation, responsible consumption, and production, and acting on climate change (refer to Figure 1). This environmental conflict becomes especially concerning, given that approximately 50% of sold lubricants end up in "unaccounted" environmental pathways [1].

In response to the environmental concerns surrounding traditional lubricants, the lubricant industry is progressively embracing sustainability practices. Currently, measures include utilizing eco-friendly materials, optimizing production processes, extending product lifespans, and reducing waste through recycling and re-refining. Beyond considerations of biodegradability and immediate environmental impact, sustainability in the lubricant industry extends to the entire product lifecycle. This includes the product footprint in the upstream phase and contributions to dominating avoided downstream emissions (scope 3, category 11) in the use phase [3]. The relevance of this broader perspective lies in the life cycle assessments of lubricants, which commonly undergo categorization into two key phases: cradle-to-gate (upstream) and gate-to-grave (downstream, use phase) evaluations [4]. By considering the entire lifecycle of lubricants, the industry emphasizes a comprehensive approach to environmental responsibility.

The transition to sustainable measures aimed at enhancing traditional lubricants strategically aligns with environmental objectives, specifically SDGs #3 (Good Health and Well-being) and #6 (Clean Water and Sanitation). Sustainable lubricants, unlike traditional ones, contribute to cleaner air by reducing harmful emissions, thus helping to prevent respiratory issues, and promoting overall health, in accordance with Sustainable Development Goal (SDG) #3 on Good Health and Well-being. Moreover, this transition is also in alignment with SDG #6 (Clean Water and Sanitation). Traditional lubricants, if not managed properly, can contaminate water sources, posing risks to water quality. In contrast, sustainable lubricants are produced and disposed of more responsibly, contributing to cleaner water sources. Their efficient production processes and longer product lifespans also indirectly contribute to water conservation, supporting the global goal of using water wisely.

This increasing emphasis on sustainability and achieving "net zero" carbon emissions is then fueled by global resource efficiency in consumption and production, as well as a commitment to decouple economic growth from environmental degradation. This heightened environmental awareness is compelling industries to reevaluate their practices to better align with the United Nations' SDGs, driven by a combination of consumer expectations, regulatory mandates, and the need to address supply chain disruptions.

Companies now face the task of reducing their carbon footprints, curbing pollution, and minimizing waste in ways that are both cost-effective and competitive. This effort anticipates forthcoming regulations, including those concerning "Scope 3 downstream emissions" from the U.S. Securities and Exchange Commission (SEC), as well as increased scrutiny on potential

Figure 1. The 17 United Nations' Sustainable Development Goals [2].

"greenwashing" by both the European Commission and the U.S. Federal Trade Commission (FTC).

Adding to this complexity is the absence of a universal standard for sustainable lubricants. Terms such as 'biodegradability', 'environmentally friendly', and 'carbon neutral' may have been deemed deceptive in view of FTC guidelines [5]. This lack of clarity intensifies the ongoing discussion about what truly constitutes a sustainable lubricant, which is dynamically evolving. At present, there is a specific emphasis on industrial lubricants that reduce friction and extend longevity in the use phase downstream, while also being environmentally friendly and non-hazardous. Although some ambiguity remains, recent research is moving towards viable alternatives for petroleum-based lubricants that meet sustainability and green requirements to benefit the planet's future [6].

2. Recent Changes in Sustainability

Recent developments in sustainability present a myriad of perspectives and "handpicked" truths. A foundational reference point involves aligning with the 17 SDGs and 169 targets set in October 2015, which, while broad, delineates the criteria for sustainable practices. In this context, the relevance of sustainable lubricants becomes evident as they contribute directly to specific SDG targets, aligning with the broader criteria for sustainable practices.

For instance, under SDG #3, Target 3.9 emphasizes the reduction of deaths and illnesses caused by hazardous chemicals, air, water, and soil pollution [7]. Sustainable lubricants, designed with eco-friendly materials and production processes, actively contribute to minimizing these environmental hazards, thereby supporting the achievement of this target. Similarly, under SDG #6, Target 6.3 focuses on improving water quality by reducing pollution and minimizing the release of hazardous chemicals. Sustainable lubricants, through responsible manufacturing and use, help prevent water pollution, aligning directly with the objectives outlined in this target. Their characteristics, such as extended product lifespans and efficient recycling processes, further support the reduction of untreated wastewater and the increase in global recycling and safe reuse.

2.1. Advanced lubricant formulations

Recognizing the importance of lubricants in sustainable practices highlights their contribution across diverse industries. Lubricants ensure the smooth and reliable operation of mechanical systems in applications such as automotive, marine, construction, appliances, and metalworking. In particular, automobile usage stands out, constituting a substantial 55-60% of lubricant sales [4]. In the automotive sector, hydraulic and metalworking fluids make up around 10% each, while greases that are commonly used in electric and hybrid vehicles account for about 3% of the lubricant market. The latter experiences a high Compound Annual Growth Rate (CAGR), a trend attributed to the rising prevalence of electric and hybrid vehicles in the automotive industry.

The increasing demand for environmentally friendly lubricants stems from growing concerns about the ecological impact of traditional mineral oil-based products. These conventional lubricants pose significant risks due to limited biodegradability and the potential for water and soil pollution. In response to these environmental challenges, emerging trends favor natural oils as a sustainable alternative. This shift seeks to reduce dependence on conventional lubricants by emphasizing biodegradability and a low carbon footprint.

This transition addresses not only environmental considerations, but also cost and toxicity, especially in the case of environmentally acceptable lubricants (EALs). The objective is clear: a reduction in reliance on petroleum-based lubricants. A key parameter in this transition is the focus on biodegradability and maintaining a low carbon footprint. While conventional petroleum-based oils, such as mineral and white oil, typically exhibit biodegradability levels between 30% and a maximum of 65%, EALs surpass these figures. EALs boast ready/ultimate (e.g., full mineralization) biodegradation rates ranging from over 60% to as high as 95%. The importance of this lies in the environmental benefits it brings. High biodegradability means that these lubricants break down naturally over time, resulting in reduced environmental persistence. The byproducts produced during this breakdown are generally less toxic, lowering the potential harm to ecosystems. This characteristic supports healthier ecosystems, vital for biodiversity and overall environmental well-being.

2.2. Innovations in production methods

The drive for sustainability extends beyond product formulations to innovations in production methods. Manufacturers are increasingly embracing cleaner and more efficient processes (in terms of waste), aligning with circular economy principles. These practices aim to reduce waste, minimize energy consumption, and lower greenhouse gas (GHG) emissions.

At a technology readiness level (TRL) of at least seven, the innovation is linked to sourcing resources with a low carbon footprint. However, biogenic, renewable, and bio-sourced streams frequently hinder innovation, where the product's carbon footprint is elevated—especially when synthetic fertilizers are used, along with the addition of CO_2 from land use. The complexity deepens when confronted with the challenge of securing a carbon-neutral energy source. Consequently, achieving a low product carbon footprint becomes a more complex task due to these factors.

Although there is a promising shift towards environmentally friendly lubricants, the management of Used Lubricant Oil (ULO) as hazardous waste lacks a specific system in many regions. In several urban areas, ULO is released directly into the environment, either accidentally or intentionally, impacting water, sewage networks, and soils. Compounding the issue, some resort to uncontrolled burning, posing a significant problem for emissions. ULO, primarily composed of base oil, poses environmental risks when released directly into water, sewage networks, and soils, or disposed of through uncontrolled burning. Globally, the consumption of lubricating oil severely harms the environment, reaching an average of 38-42 million tons annually. Fortunately, various options, including incineration, recycling, or re-refining, present themselves for ULO management [8].

The process of re-refining used lubricants emerges as a significant solution due to its ability to achieve a substantial reduction in carbon dioxide equivalent (CO_2eq) emissions. When compared to base oils derived from crude sources, this re-refining method is effective in cutting the cradle-to-gate carbon footprint by 60-80%. CO_2eq serves as a unit of measurement, allowing for a standardized comparison of the impact of GHG emissions. The efficiency of the re-refining process, coupled with the carbon footprint of the original crude oil used, determines the extent of the reduction in CO_2eq emissions achieved through this recycling approach. The re-refining process used and product carbon footprint of the crude oil

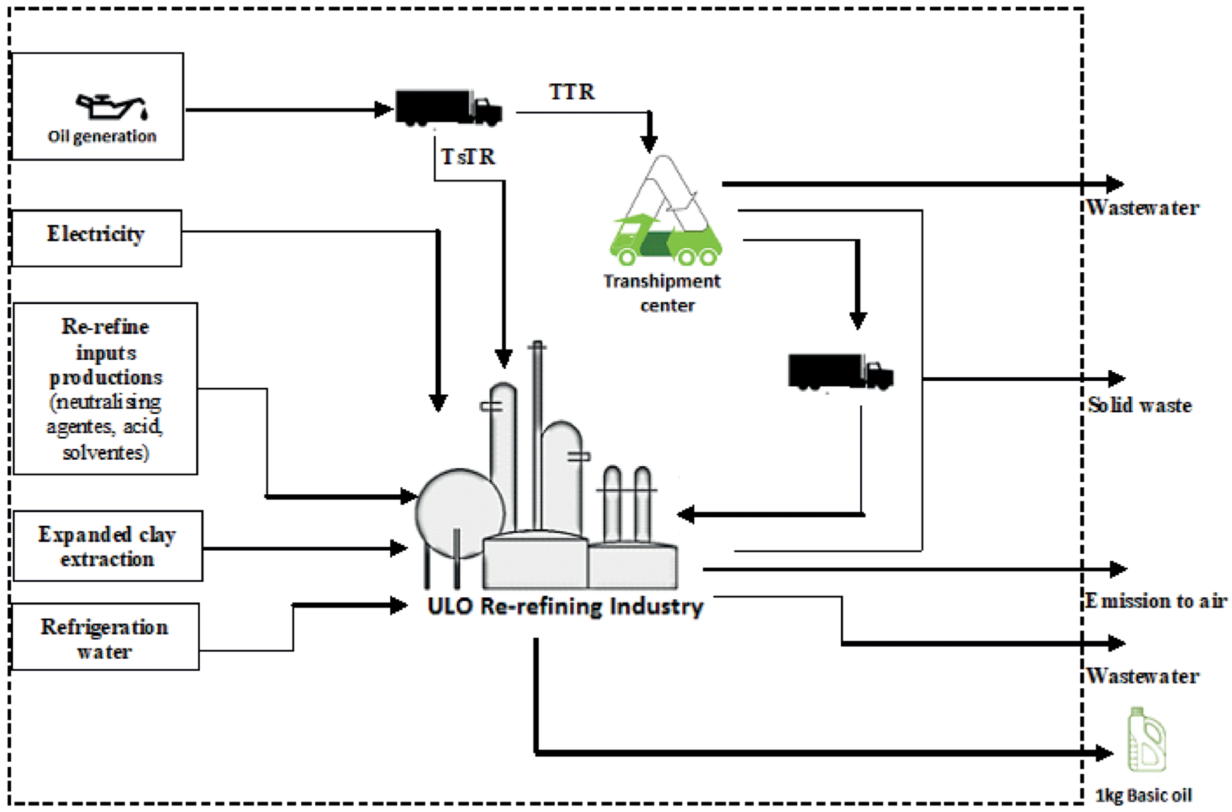

Figure 2. Approaches to Used Lubricant Oil management [10][1]

considered characterize the range in CO_2eq savings [9]. Figure 2 outlines two distinct approaches to Used Lubricant Oil (ULO) management [10].

In the first approach, known as Transportation with Trans-shipment and Re-refining (TTR), generated oil is transported from a plant to a transshipment center and then to a re-refinery for basic oil purposes. The second approach, Transportation without Trans-shipment and later Re-refining (TsTR), skips the intermediate collection point, directly transporting ULO to the re-refinery. The objective of the study by Tsambe et al. was to define the most sustainable scenario for ULO management and production, providing a foundation for future studies and process creation.

Furthermore, environmental impacts were assessed, including a quantitative analysis of carcinogen production, land occupation, and human toxicity for each scenario. Results indicated that TsTR has a more adverse impact on environmental conditions compared to the TTR scenario. For social aspects, a qualitative analysis of ULO factors, including fair working hours, worker health, and freedom of association and collective bargaining, was conducted. Workers rated each category on a satisfactory-unsatisfactory scale, with both TsTR and TTR scenarios yielding similar results, albeit with TsTR scoring slightly better overall.

Economic analyses delved into the cost-effectiveness of each scenario, with TsTR exhibiting significant economic advantages in total cost and transportation costs in Brazilian Reals (R$) per kilogram. While TsTR incurs higher environmental impacts, the TTR approach proves cost-efficient and demonstrates robust social performance. It underscores the need for sustainable practices that balance economic efficiency with social and environmental responsibility in response to the growing importance of environmental considerations in the field.

2.3. Regulatory updates and standards

The transition toward sustainability in the lubricant industry is also largely influenced by regulatory changes in climate reporting and the establishment of stringent environmental standards across value chains. These evolving regulations prompt manufacturers to embrace sustainable practices in lubricant synthesis and supply chains, including the collection and re-refining of used oils. As the lubricant landscape evolves with ongoing innovations, there is a growing need for stricter rules and bans to ensure sustainability in newly formulated products.

At the forefront of this movement is the European Union (EU), which has championed EALs since the 1990s. National labels like German RAL UZ 178 and Nordic Swan SS 155434 paved the way, followed by the introduction of the European ecolabel for lubricants in 2005 and EN16807 "Biolubricants" in 2016. It is essential to clarify, however, that "bio-no-tox" properties, while aligning with the United Nations' SDGs #3 and #6 since October 2015, are not inherently linked to sustainability. This common misconception highlights the need for a nuanced understanding; bio-no-tox or EAL criteria primarily focus on environmental protection rather than climate protection goals.

The criteria for Environmentally Acceptable Lubricants (EALs), as a specific facet of sustainable practices, center around transparent and eco-friendly labeling [11]. These measures are designed to empower consumers with a clear understanding of the environmental impacts associated with the products they use, guiding them towards approved and environmentally suitable options. The EU's commitment to sustainability extends beyond labels; it is demonstrated through governmental incentives, penalties, and specific timeline benchmarks, firmly rooted in the EU Renewable Energy Directive II (RED II). This directive outlines the EU's ambitious goal of achieving a 32% consumption of renewable energy sources by 2030 [12]. Furthermore, the EU's pledge to attain carbon neutrality by 2050 serves as a reminder of the importance of regulations and standards in propelling the lubricant industry toward a sustainable and environmentally responsible future.

3. Industry Impact

Even with a focus on sustainability in the industry, lubricants, irrespective of their source, encounter challenges in preserving their performance properties. Traditional technical requirements and "fit-for-purpose" criteria are changing. In the future, these requirements are expected to be taken for granted, with market demands shifting towards eco-toxicological, carbon-neutral, and sustainable properties.

These challenges are particularly evident under demanding conditions, such as high loads (e.g., high Hertzian contact stresses) and high temperatures, impacting lubricant performance. The oxidation reactions and potential contamination from both the environment and machine components can lead to a gradual decline in the lubricant's quality, performance, and longevity [13].

Addressing these issues requires assessing the stability and condition of lubricants over time, especially within a lifecycle assessment. Sustainable lubricant development must navigate these challenges while upholding a commitment to sustainability. This entails ensuring the preservation of antifriction properties, mechanical wear resistance, and all functional attributes throughout the entire drain period. However, a challenge persists with EALs. The most efficient options might be economically viable but prove highly toxic to the environment and organisms.

Switching to sustainable lubricants that align with the United Nations' Sustainable Development Goals (SDGs) positively impacts the industry. These lubricants meet technical specifications and environmental regulations while enabling

[1] The American Petroleum Institute recently released two documents in 2023: API TR1533, titled "Lubricants Life Cycle Assessment and Carbon Footprinting—Methodology and Best Practice," and ATIEL-UEIL, which provides the "Methodology for PCF Calculations of Lubricants and other Specialties." While the insights from these key stakeholders in the lubricant value chain are undoubtedly valuable, it raises questions about whether they hold the authoritative recognition of entities such as the U.S. SEC & FTC and the European Commission to establish standards and guidelines.

businesses to adhere to strict emission standards and sustainability objectives, thereby reducing ecological and carbon footprints. Additionally, the extended lifespan and reduced need for frequent reapplication in sustainable lubricants result in tangible cost savings, lightening the resource burden and minimizing maintenance and downtime expenses [1]. Opting for these lubricants represents a constructive and environmentally responsible choice, benefiting both business operations and broader sustainability goals.

4. Environmental Benefits

In evaluating recent changes promoting sustainability and their impact on the lubricant industry, a comprehensive approach to environmental responsibility becomes evident. The key distinction lies in understanding the difference between criteria specifically focused on environmentally acceptable lubricants (EALs) and broader goals related to climate protection. Unlike the latter, which encompasses a broader scope, bio-no-tox or EAL criteria are exclusively focused on environmental protection.

EALs, designed with environmental preservation in mind, offer several important benefits in today's global context. Their significance is highlighted by their alignment with innovative biolubricants like synthetic esters, polyalkylene glycols, and bio-olefins. These advancements adhere to United Nations' SDGs and aid industries in meeting rigorous regulatory standards [14]. Beyond their environmental contributions, these lubricants excel compared to traditional counterparts in terms of reducing carbon footprint during the usage phase. This impact fosters a more energy-efficient approach while concurrently extending the lifespan of machinery [6].

The environmental focus in the lubricant industry is closely tied to the ongoing evolution of regulatory updates and standards, marking more than just a bureaucratic shift—it signifies a positive environmental development. Dominating the global market with a 50% share in biodegradable lubricants, the U.S. leads over Europe, propelled by the mandatory 2013 Vessel General Permit requiring the use of EALs in oil-to-sea interfaces within U.S. territorial waters for vessels over 79 feet unless technically infeasible. In contrast, EU regulations on eco-friendly lubricants are non-mandatory but set criteria for biodegradability and environmental impact, aiming to mitigate harm to aquatic environments, soil, and CO_2 emissions [15]. On a global scale, a preset standard for an ultimate/ready biodegradation rate of more than 60% within a 28-day timeframe ensures that the lubricant breaks down swiftly into environmentally benign components. This rapid breakdown reduces its persistence, thereby minimizing environmental impacts [16].

Despite differences in regional regulatory approaches, there is a global commitment to promoting lubricants that undergo rapid degradation. This commitment aligns with broader environmental goals, showcasing a shared dedication to mitigating the environmental impact of lubricants worldwide. The convergence of regulatory initiatives and market dynamics emphasizes the collective effort to foster environmentally responsible practices within the lubricant industry on a global scale.

Sustainable lubricants are instrumental in addressing oil spills and leakage, which have severe negative impacts on the environment, particularly aquatic ecosystems [19]. Notably, it is essential to recognize that spills from both non-EAL and EAL lubricants are illegal. However, in the case of EALs, the consequences imposed by enforcement authorities are minimal.

While bio-based lubricant components from renewable sources may currently have limited relevance for EALs, their potential significance lies in sustainability criteria. Integrating EAL criteria into the framework of U.N. SDGs requires a commitment to using environmentally acceptable materials and practices. This commitment results in fewer leakages, extended lubricant change periods, and responsible treatment, recycling, and re-refining [1].

These sustainable practices collectively yield a reduction in environmental harm. They not only contribute to environmental protection but also enable the conservation of primary energy upstream, reduce the product carbon footprint of base oils, and advocate for the responsible use of raw materials and resources.

5. Benefits for Climate

5.1 Tribology and lubrication sciences

Sustainable lubricants emerge as key contributors to environmental well-being, effectively minimizing carbon

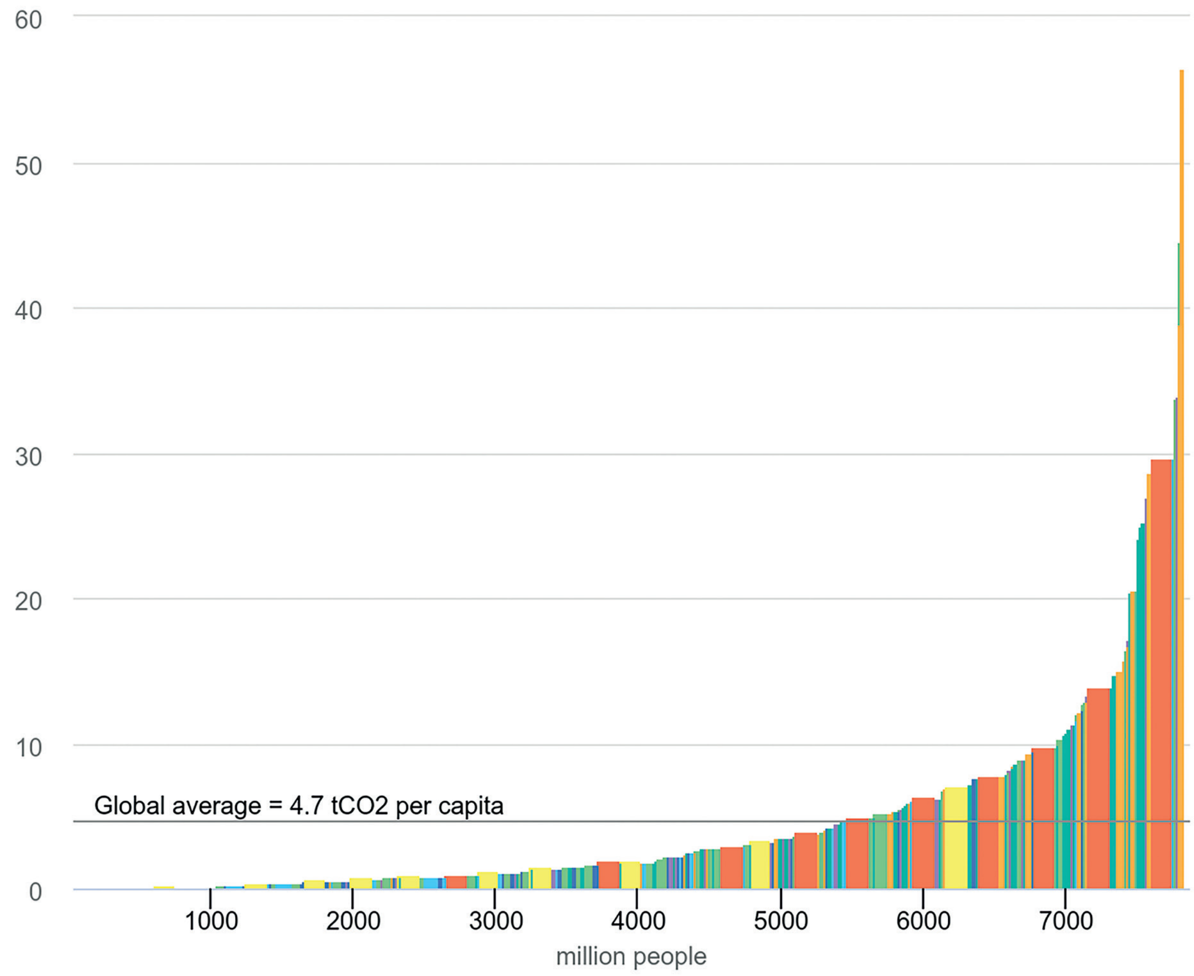

Figure 3. Energy-related CO_2 emissions per capita by income decile by regions, 2021 [17].

footprints and preventing the release of hazardous materials into the environment [5]. Opting for these eco-friendly lubricants not only reduces industry environmental impact but also demonstrates a commitment to responsible practices, aligning with global sustainability efforts.

The economic significance of tribology and lubrication sciences is often overlooked but holds immense potential for achieving climate targets. Global emissions show a stark disparity, with the top 1% of emitters producing over 1000 times more CO_2 than the bottom 1%. As shown in Figure 3, global energy-related CO_2 emissions per capita reached 4.7 tCO_2/capita in 2021 [17, 18].

Examining three recent studies by the German Society for Tribology—namely, "CO_2 & friction" (2019), "Sustainability & Wear protection" (2021), and "Tribology & Defossilization" (2023)—reveals that friction's share of direct energy-related CO_2 emissions ranges between 6.7-11 $GtCO_2$ or 0.87-1.43 tCO_2/capita [19-21]. In contrast, the estimated savings achieved by applying measures from tribology and lubrication sciences to reduce friction range between 0.3-1 tCO_2/capita. This indicates that employing techniques from these fields can significantly contribute to lowering CO_2 emissions associated with friction, presenting an opportunity for environmental improvement.

A significant contributor to CO_2eq savings stems from the conservation of resources and material efficiency. Each primary material consumed involves mining and extraction, accompanied by an associated embedded CO_2 footprint. This is where factors such as longevity, condition monitoring, and re-manufacturing come into play. Doubling the use phase inherently halves the demand for primary resources, resulting in a substantial reduction in associated emissions. Thus, prioritizing tribology and lubrication sciences is important for minimizing friction, which significantly contributes to meeting climate targets and supporting sustainability. In doing so, tribology maximizes the efficiency of resource or carbon budget utilization, leading to a reduction in downstream CO_2eq emissions. More importantly, these benefits are achieved without introducing any functional disadvantages in use.

Reducing friction and extending the longevity of machinery emerge as pragmatic and readily implementable strategies for defossilization or societal CO_2-sequestration. This is particularly significant because the CO_2eq savings generated by tribology and lubrication sciences manifest universally—occurring anywhere and anytime. Consequently, the reduction in upstream energy requirements to move machine elements downstream becomes a notable outcome. By mitigating the need for production upstream, as these elements are not consumed downstream, tribology actively contributes to a reduced environmental footprint.

A paradoxical consequence arises when considering the impact of friction reduction in the use phase of lubricants—it supersedes the existing product carbon footprint (cradle-to-gate). This means that the environmental impact of addressing friction goes beyond what is traditionally considered. To truly understand the environmental consequences, one needs to move away from simply looking at the typical carbon footprint of a product. Instead, the focus should be on aspects such as avoided emissions and considering the broader category 11 emissions within scope 3.

Extending this consideration to materials and coatings interacting with lubricants further emphasizes the significance of tribology in enhancing the longevity of tribosystems. In this context, the integration of condition monitoring and tribotronic technologies contribute to the efficient functioning of tribosystems and serve as additional mechanisms for reducing carbon emissions in the use phase of machinery.

The recent rating of lubricants as a "priority" by the Joint Research Centre (JRC) of the European Commission within the "Ecodesign for Sustainable Products Regulation (ESPR) framework" marks a significant milestone [22]. The JRC proposes key requirements under ESPR to improve the environmental impact of lubricants. These involve setting a minimum feedstock for re-refined oil, specifying the maximum friction coefficient for efficiency, and establishing a minimum durability standard for typical use. These proposed measures signify a comprehensive approach to address the environmental footprint of lubricants, ranging from the sourcing of feedstock to the operational efficiency and lifespan of the lubricants themselves.

5.2 Monetary CO_2 value

Friction reductions not only contribute significantly to sustainability but also bring tangible benefits to customers in the form of monetary CO_2 credits. These savings, represented by carbon allowances, serve as intangible assets, offsetting additional costs associated with tribological innovations aimed at mitigating CO_2 emissions. The impact of low-friction solutions can be quantified by considering the total savings, which include the monetary values derived from mitigated energy consumption and the saved CO_2 certificates (carbon allowances).

[2] These estimates of social or economic damage should not be confused with estimates of the cost required to achieve a specific emission or warming limit.

[3] SCC is an estimated monetary measure of the economic costs, i.e., climate damage, resulting from emitting one additional ton of carbon dioxide (CO2) into the atmosphere. Conversely, it represents the benefit to society from the reduction of CO_2 emissions by one ton—a figure that can be compared to the costs of emission reduction.

In the context of the European Emissions Trading Scheme (EU-ETS) in 2023, the CO_2-price corridor for compensating CO_2eq emissions ranged between 80 and 100 €/tCO_2, reaching a peak of 105.30 €/tCO_2eq in February 2023 [23]. Meanwhile, the California carbon allowance price ceiling sale for 2023 is set at 81.50 US-$/t$CO_2$, with prices fluctuating between 28-37 US-$/t$CO_2$ throughout the year. These specific price points within the carbon credit markets highlight the economic value attached to mitigating CO_2 emissions through friction reduction. Industrial customers not only experience direct savings in energy consumption but also gain from the monetizable value of reduced carbon emissions, reinforcing the economic and environmental benefits of embracing tribological innovations.

Projections indicate a forthcoming increase in the economic value of GHG avoidance costs, with expectations of a price corridor ranging between 175 and 300 €/tCO_2eq in Europe by 2032 [24]. In February 2021, the United States Government's interagency working group on the macro-economic costs of GHG emissions conducted a comprehensive assessment [25]. This evaluation focused on the social or macro-economic costs associated with carbon dioxide emissions, commonly referred to as SCC (social costs of carbon dioxide). According to their findings, the SCC for the year 2020 was determined to be $51 per metric ton of CO_2. Looking ahead, the projection anticipates an increase in the SCC, reaching $56 per metric ton of CO_2 by 2025. Furthermore, the trajectory continues to climb, with a projected value of $63 per metric ton of CO_2 by the year 2030.

These assessments not only provide a baseline understanding of the economic costs associated with carbon dioxide emissions but also offer a forward-looking perspective on the anticipated trends in these costs. Such projections are instrumental in shaping policy decisions and industry strategies to align with evolving economic considerations related to GHG emissions.

6. Conclusion

The lubricant industry has significantly shifted toward sustainability, driven by advancements in formulations, innovative production methods, the supply of renewable primary materials, adherence to stricter regulatory standards, and the imperative to meet carbon targets. This evolution benefits both the environment and businesses, with sustainable lubricants, including bio-based or bio-sourced options, playing a crucial role in reducing carbon footprints, minimizing waste, and promoting energy efficiency.

Despite these positive changes, there are challenges that need attention. One significant challenge is establishing a global and regulatory consensus on defining sustainable lubricants and developing standardized metrics for measuring sustainability. This is essential to align industry practices with broader sustainability goals.

As the fields of tribology and lubrication sciences continue to advance, there is potential to create a more eco-conscious, energy-efficient, and resource-efficient world. Implementing advancements in these areas allows the industry to strengthen its commitment to environmental responsibility and offer more sustainable products. However, this commitment must be evaluated by end-users and policymakers in terms of associated costs, considering that technologies for environmentally acceptable lubricants and climate-friendly options are available but may require regulatory mandates for widespread adoption.

The prospect of collecting and re-refining used lubricants adds to the positive outlook, offering the potential for a more circular economy, resource conservation, waste reduction, and an overall decrease in the carbon footprint. This comprehensive approach highlights the interconnected nature of sustainable practices within the lubricant industry, paving the way for a more environmentally responsible, economically viable, and socially conscious future. [26]

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