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Review article

Enhancing tribological performance of electric vehicle lubricants: Nanoparticle-enriched palm oil biolubricants for wear resistance

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A R T I C L E I N F O

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A B S T R A C T

The transition to electric vehicles (EVs) calls for sustainable advancements in automotive lubricants, as traditional fossil-fuel-based products pose environmental challenges. Palm oil-based biolubricants enriched with nanoparticles present a promising eco-friendly alternative that meets the thermal and tribological demands of EVs. This paper aims to analyze the development of nanoparticle-enriched palm oil-based biolubricants, aimed at improving the sustainability and performance of electric vehicle (EV) lubrication systems. The critical findings highlight that integrating nanoparticles such as graphene, titanium dioxide, and aluminum oxide into palm oil-based lubricants significantly enhances their tribological properties. These enhancements include a 26.21%–34% reduction in coefficient of friction (COF), a 12.99%–30% reduction in wear, and improved thermal stability. The study found that nanoparticle-enriched biolubricants outperformed traditional options in terms of friction and wear under high-temperature and pressure conditions, as supported by regression analysis. The study demonstrates that nanoparticle-enriched biolubricants offer a viable eco-friendly alternative to conventional lubricants, lowering the environmental impact by reducing greenhouse gas emissions and energy consumption. This innovation has significant implications for both the environment and industry, offering a sustainable solution that reduces dependency on fossil fuels, enhances EV efficiency, and aligns with global sustainability goals. Besides, this paper discusses biolubricants drawbacks and future studies direction.

1. Introduction

The transition to electric vehicles (EVs) necessitates advancements in all aspects of automotive technology, including developing

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sustainable lubricants [1]. As the global demand for EVs continues to rise [2], the automotive industry faces the challenge of creating systems and components that align with sustainability principles and environmental stewardship [3]. Unlike traditional internal combustion engine vehicles, EVs have unique requirements for lubrication, particularly in managing thermal properties and minimizing wear in electric drivetrains and bearings [4,5].

Traditional lubricants from fossil fuels pose significant environmental challenges, highlighting the urgent need for eco-friendly alternatives [6]. These conventional lubricants contribute to environmental degradation through their production, use, and disposal processes. Additionally, used lubricants often contain hazardous substances that can contaminate soil and water if not properly managed, posing severe risks to human health and wildlife [7]. The high dependency on non-renewable resources further intensifies the unsustainability of fossil fuel-based lubricants.

As the world becomes more conscious of environmental issues, there is a pressing demand for lubricants that minimize ecological impact. Eco-friendly alternatives, particularly those derived from renewable sources such as plant oils, offer a viable solution. The demand for sustainable lubrication solutions has reached a critical juncture, driven by mounting concerns over environmental impact and the urgent need for eco-friendly alternatives across various industries, including automotive [8–10]. These biolubricants reduce the carbon footprint and provide safer disposal options, as they are typically biodegradable and less toxic. The shift towards sustainable lubricants is essential to mitigate the environmental challenges of traditional fossil fuel-based products, making it a critical component of the broader movement towards greener automotive technologies [11].

Palm oil has emerged as a focal research point in response to this demand due to its abundance and renewability. Its suitability for lubrication applications presents promising prospects for synthesizing biolubricants that align perfectly with the global transition towards sustainable and eco-friendly practices [12–14]. Incorporating nanoparticles into palm oil-based biolubricants enhances their performance, making them suitable for electric vehicles (EVs). Nanoparticles like graphene, metal oxides, or carbon nanotubes improve lubricity, thermal stability, and wear resistance by creating a protective film on metal surfaces, reducing friction and wear under high-pressure and high-temperature conditions [15]. This is crucial for EV motors and drivetrains' efficient operation and longevity. Additionally, nanoparticles improve thermal conductivity, aiding in better heat dissipation and maintaining lubricant stability under varying temperatures [16].

Nanoparticle-enriched palm oil-based biolubricants offer superior thermal stability, reduced friction, and improved wear resistance, enhancing the efficiency and reliability of electric vehicles (EVs). These lubricants remain effective under high temperatures, reduce energy losses, extend vehicle range, and minimize wear on components like gears and bearings, leading to longer maintenance intervals and lower replacement costs. Although recent studies highlight these benefits, further research is needed to optimize their formulations and applications as the demand for effective EV lubrication solutions grows [17,18]. Within this context, the combination of palm oil-derived biolubricants and nanoparticles stands out as a notable innovation, as reported by Hamdan et al. [19]. Previous researchers reported that by enhancing tribological performance and environmental friendliness, these nanolubricants hold significant promise for advancing the efficiency and longevity of electric vehicle technology [20–22].

Afifah et al. [23] reported that the optimal conditions for producing palm stearin methyl ester (PSME) include a 4:1 methanol-to-palm stearin ratio, a reaction temperature of 60 °C, an 8-h reaction period, and a 6.0% catalyst concentration, yielding 95.26% PSME. Compared to traditional mineral oil-based lubricants, PSME significantly improved viscosity, oxidation stability, and tribological performance. These findings suggest that PSME is a promising sustainable and green lubricant, especially suitable for tropical conditions, resulting in lower wear rates and longer component lifespans. According to Kalam et al. [18], the potential of biodegradable olive oil as one bio-based lubricants, with an emphasis on its physicochemical characteristics, lubrication performance, and thermal stability, as a lubricants for heavy-duty diesel engines. It emphasizes that 68.7% of biodegradable olive oil is oleic acid, which adds to its exceptional heat stability—it can tolerate temperatures as high as 390 °C. According to the study, olive oil performs better in terms of lubrication efficiency and wears fewer engine components than traditional mineral oil (SAE15W40) due to its lower coefficient of friction (COF) and wear scar diameter. The study also found that, while olive oil works well under lubrication circumstances, its oxidation stability can be improved further using additions. The conclusion underlines that olive oil's unique qualities make it a suitable bio-based lubricants choice for increasing the efficiency of heavy-duty diesel engines.

Nur Faeqah Idrus et al. [24] reported on the impact of steric hindrance on the miscibility of palm oil-derived pentaerythritol (PE) ester lubricants with HFC R134a refrigerant. While PE esters possess qualities like commercial polyol esters, their neopentyl structure hinders their mixing capabilities. The research suggests using surfactants to enhance compatibility. Additionally, the interaction between HFC R134a and lubricants can alter moisture levels, potentially reducing the efficiency of the refrigeration cycle. PE esters exhibit a lower pour point, making them suitable for refrigeration applications. The lower pour points indicate better flow properties at low temperatures, which are crucial for maintaining effective lubrication during refrigeration cycles. Given that miscibility affects oil return in refrigeration systems, ensuring compatibility between lubricants and refrigerants is essential for the longevity and efficiency of compressors.

Mohammed Aziz et al. [25] studied the kinetics and thermodynamics of the microwave-assisted transesterification of methyl ester derived from palm oil into biolubricants. The transesterification of palm oil methyl ester (PME) and trimethylolpropane (TMP) under microwave irradiation at 110–130 °C for 90 min results in high yield and quality biolubricants with excellent physicochemical properties and a high conversion rate. The activation energy for this process is significantly lower (17–17.6 kcal/mol) compared to conventional heating (33.3–33.9 kcal/mol). The resulting biolubricants demonstrate enhanced stability and performance relative to conventional lubricants. Environmentally, the microwave-assisted method reduces energy consumption, lowers the carbon footprint, minimizes the use of harmful chemicals, and promotes renewable resources.

Furthermore, Pico et al. [26] dispersed diamond nanoparticles into Polyol ester (POE) lubricant at 0.1% and 0.5% mass fractions. Tribological evaluation results indicate that adding diamond nanoparticles at mass fractions of 0.1% and 0.5% reduced wear by 4%

and 30%, respectively. The mechanism of wear reduction can be explained as follows: within the lubrication regime, diamond nanoparticles, due to their spherical or near-spherical shapes, act as nano-rollers between the contact surfaces. This rolling effect reduces friction and wear by minimizing direct metal-to-metal contact. This effect is modest at a 0.1% mass fraction, leading to a 4% reduction in wear. However, at a 0.5% mass fraction, the increased concentration of nanoparticles significantly enhances this rolling effect, resulting in a 30% reduction in wear.

Sustainable lubricants, like nanoparticle-enriched palm oil-based biolubricants, support several Sustainable Development Goals (SDGs). They promote renewable resources and reduce fossil fuel reliance, aligning with SDG 7: Affordable and Clean Energy by improving energy efficiency in electric vehicles [27]. They enhance component lifecycle and performance, supporting SDG 12: Responsible Consumption and Production by reducing waste and encouraging sustainable industrial practices. Additionally, they lower greenhouse gas emissions, aligning with SDG 13: Climate Action and mitigating environmental pollution, emphasizing their role in advancing global sustainability efforts [28].

Despite the expanding literature of research on biolubricants, especially those sourced from renewable materials like palm oil, a significant research deficiency persists in the optimization of these lubricants for electric vehicles (EVs). Although recent studies have shown the environmental advantages and tribological enhancements of nanoparticle-infused palm oil-based biolubricants, according to the authors' best knowledge there is insufficient comprehension of their long-term efficacy under the specific conditions experienced in electric vehicles, including elevated thermal loads and fluctuating operational temperatures. Furthermore, current formulations remain inadequately tailored to satisfy the specific lubricating requirements of electric drivetrains and components. This study examines how nanoparticles improve the thermal stability, reduce friction, and boost the wear resistance of palm oil-based

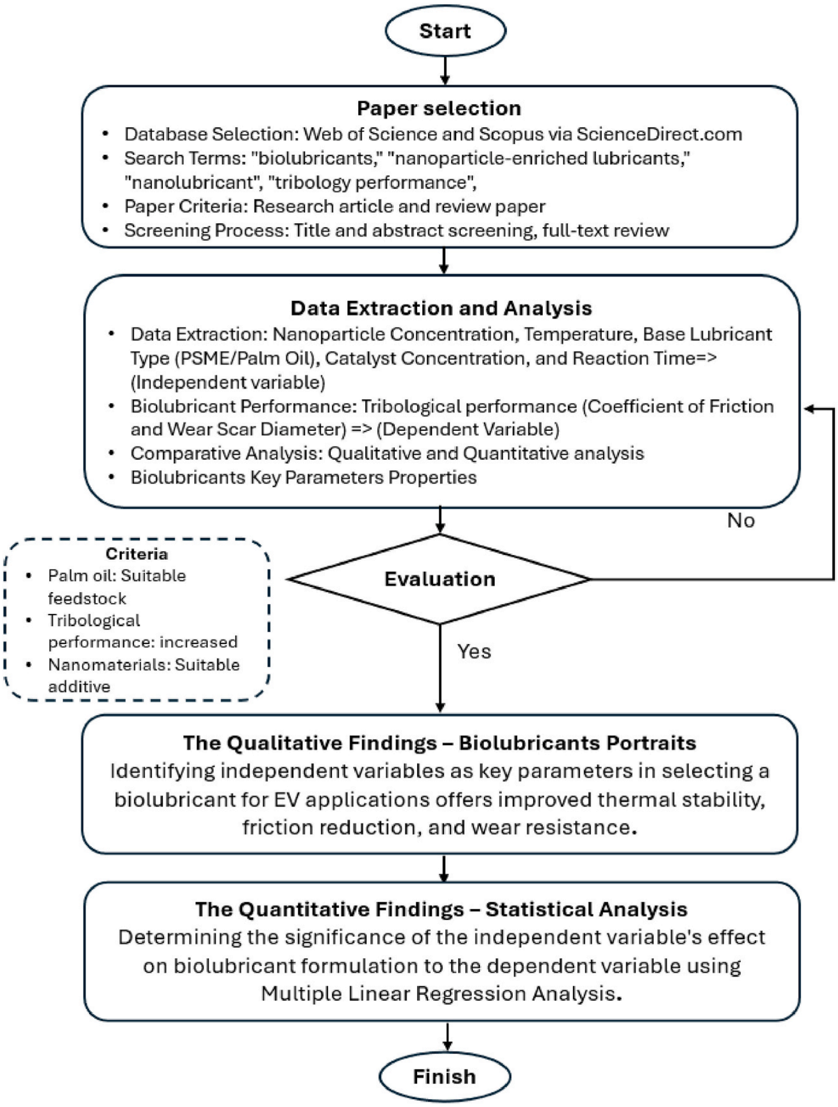

Fig. 1. Research flowchart.

biolubricants, thereby increasing their suitability for electric vehicle applications. This action fosters the advancement of sustainable, high-performance lubricants that correspond with the industry's transition to environmentally friendly vehicle technologies.

2. Methodology

2.1. Search approach

Web of Science and Scopus were searched for relevant material. The search phrases used were "biolubricants," "palm oil-based lubricants," "nanoparticle-enriched lubricants," "sustainable lubricants," and "electric vehicles." Boolean operators were employed to guarantee that all pertinent research was included in the search results. This methodical search strategy aimed to thoroughly cover the body of knowledge already available on the subject [29].

2.2. Data extraction and analysis

The present review centers on the extraction of data about independent parameters, including but not limited to feedstock types, transesterification methods, added materials, viscosity, oxidation stability, biodegradability, and nanoparticle types. The effects of these variables on tribological performance—especially wear and coefficient of friction—and on the surroundings were methodically sorted and examined [30]. Both qualitative and quantitative methodologies were used in the comparison analysis to evaluate the connection between these independent factors and the dependent outcomes. This method assures a thorough assessment of the sustainability and efficacy of biolubricants [31].

2.3. Evaluation criteria

The evaluation of biolubricants in this review was based on three main criteria: the suitability of palm oil as a feedstock, the enhancement of tribological performance, and the effectiveness of nanomaterials as additives. Palm oil was chosen due to its renewable nature and favorable chemical properties for biolubricants production. The tribological performance was assessed by measuring the friction and wear reduction coefficient, indicating improved lubrication properties [32]. The inclusion of nanomaterials was evaluated for their potential to enhance these properties further, making them a suitable additive for sustainable biolubricants. These criteria were used to systematically compare and analyze the various studies included in this review. The detailed methodology adopted in this study is presented in Fig. 1.

Based on the review's findings, it is hypothesized that palm oil is a promising option for sustainable biolubricants. By lowering the coefficient of friction (COF) and wear scar diameter (WSD), the use of nanoparticles as additives in palm oil-based biolubricants is anticipated to greatly enhance their tribological performance in EV applications. Specifically, independent variables such as nanoparticle concentration, temperature, base lubricant type (PSME/Palm Oil), catalyst concentration, and reaction time are expected to significantly impact the COF and WSD. Higher nanoparticle concentrations and optimized reaction times are likely to reduce COF and WSD, improving wear resistance. Additionally, variations in temperature and base lubricant type can influence the stability and efficiency of the biolubricant, while the catalyst concentration can affect the uniform dispersion of nanoparticles. This combination is projected to increase the lubricants' lifetime and efficiency, making them more effective and environmentally friendly. A quantitative analysis using Multiple Linear Regression was performed to validate and support the results of the qualitative analysis, which was based on a comprehensive review of relevant literature and findings from previous studies. The results suggest that optimizing these independent variables is crucial to developing enhanced lubrication solutions, which will be discussed in more detail in the following sections.

3. Literature review

3.1. Biolubricants: an overview

Biolubricants, referred to as bio-based lubricants, are made from renewable biological sources such as vegetable oils, animal fats, and other materials. Unlike traditional lubricants, often made from petroleum-based products, biolubricants are made from natural, biodegradable, and non-toxic raw ingredients, making them a more environmentally friendly option [33]. Biolubricants are made with many base oils sourced from sustainable biological sources. These base oils are frequently modified or blended with various additives to improve their performance properties, including viscosity, thermal stability, and resistance to oxidation and wear [34].

3.2. Classification of biolubricants

Biolubricants can be classed according to their base oil source and application. Vegetable oil-based biolubricants include soybean, rapeseed, sunflower, and palm oil. They are the most prevalent type of biolubricants due to their widespread availability and beneficial characteristics [35]. Despite their rarity, animal fat-based biolubricants such as lard and tallow provide unique qualities for specialized applications [36]. Synthetic ester-based biolubricants derived from natural fatty acids and alcohols have outstanding thermal stability and performance properties for high-temperature applications [37].

3.3. Application-based classification

Automotive biolubricants are used in vehicles' engines, transmissions, and hydraulic systems, providing good thermal stability, oxidation resistance, and wear protection [38]. Industrial biolubricants include machinery, compressors, and other industrial equipment designed to perform under high loads and harsh conditions [39]. Marine biolubricants are specially formulated for marine environments, requiring high biodegradability and non-toxicity to aquatic life [40]. Agricultural biolubricants used in farming equipment and machinery must be biodegradable and environmentally safe to prevent soil and water contamination [41]. Food-grade biolubricants are employed in food processing and packaging equipment, where incidental contact with food is possible, and they must meet strict safety and non-toxicity standards [42].

3.4. Palm oil-based biolubricants and their essential parameters

Recent developments in biolubricants based on palm oil have marked a significant stride toward sustainability in lubrication technology [32]. Palm oil, derived from the fruit of the oil palm tree, has become a prominent feedstock for biolubricants due to its abundance, renewability, and favorable properties. Researchers have been focusing on optimizing the synthesis processes to enhance the performance characteristics of palm oil-based biolubricants, addressing challenges related to viscosity, oxidative stability, and lubricating properties. Advanced refining techniques, such as hydrogenation and transesterification, are being employed to tailor the molecular structure of palm oil derivatives, resulting in biolubricants that offer improved thermal stability and wear resistance [43].

Palm oil is a highly significant agricultural commodity, particularly in regions like Southeast Asia, where it plays a critical role in both the economy and local industries [44]. In contrast, the impact of palm oil is less pronounced in regions such as Europe and the United States, where alternative vegetable oils are more commonly used. This regional disparity underscores the importance of considering geographic and economic contexts when discussing the global implications of palm oil production and trade [45].

USDA Foreign Agricultural Service (2023) reported that the prevailing status of Indonesia and Malaysia as the predominant global producers of palm oil, producing 59% and 24%, respectively, has significant implications for the sustainable supply of palm oil as a feedstock for lubricants [46] as depicted in Fig. 2. The substantial production volumes from these two countries underscore their pivotal role in meeting the global demand for palm oil, a key ingredient in bio-based lubricant formulations. However, the sheer magnitude of their contributions also accentuates the importance of adopting sustainable practices within the palm oil industry as the primary source of palm oil. Indonesia and Malaysia are crucial in shaping the industry's environmental and social impact. Therefore, initiatives focusing on sustainable palm oil production, such as adherence to certification standards and environmentally friendly cultivation practices, are essential.

By correlating the dominance of Indonesia and Malaysia in palm oil production with sustainable supply considerations, the bio-nanolubricants industry can contribute to environmentally responsible practices, fostering a more eco-friendly and socially conscious approach to palm oil utilization. The detailed production of each country is depicted in Fig. 3. Based on the graph, it is evident that Indonesia's palm oil production for 2022/2023 reached 46 million metric tons, while Malaysia achieved 24 million metric tons. Thailand and several other countries collectively produced up to 10.07 million metric tons. The data indicate a substantial supply for the global industry, meeting the requirements for developing bio-nanolubricants.

Fig. 4 depicts the empirical growth pattern of the palm oil industry in Indonesia from 2013 to 2022.

According to Fig. 4, despite the global challenges posed by the pandemic between 2019 and 2022, the industry exhibited a resilient and stable upward trend. Notably, there was a substantial increase in production from 42.5 to 46 million metric tons during this period, suggesting that the palm oil sector in Indonesia remained largely unaffected by the pandemic, showcasing its robust and adaptable nature. The observed compound average growth rate of 4% over the decade underscores the industry's capacity for sustained development and resilience in the face of external disruptions.

Palm oil-based biolubricants have exhibited promising attributes, including high biodegradability, low toxicity, and favorable tribological performance [32]. However, for these biolubricants to achieve widespread acceptance, it is imperative to address specific challenges [30]. The eco-friendly nature of palm oil-based bio-nanolubricants aligns with the global push toward sustainable practices

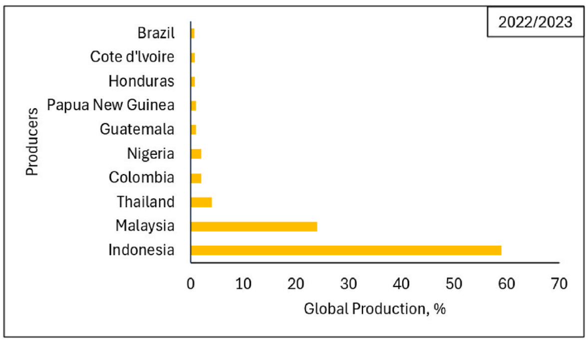

Fig. 2. The largest of global palm oil producers [46].

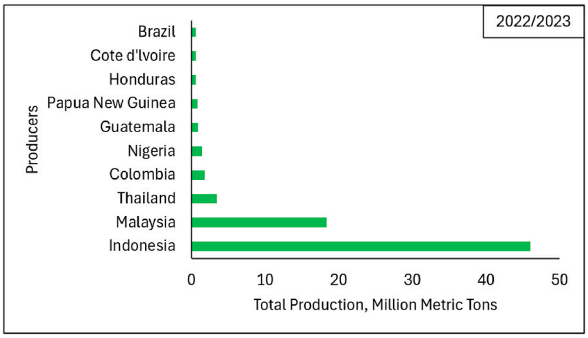

Fig. 3. Global palm oil production distribution [46].

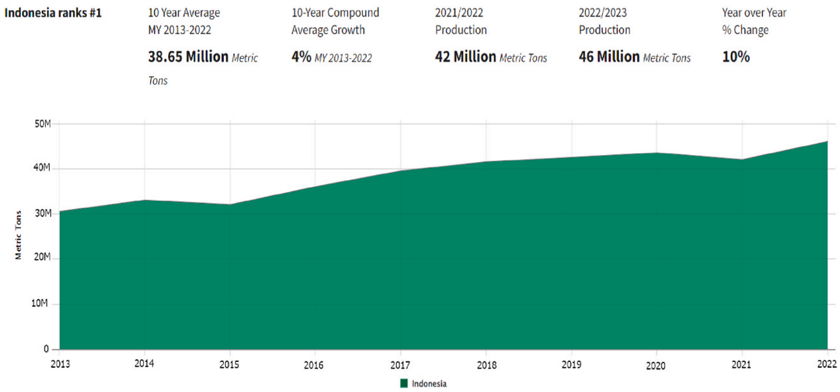

Fig. 4. Growth of the Indonesian palm oil industry over ten years (2013–2022) [46].

in various industries. This condition has led to increased attention on the life cycle analysis of these lubricants, emphasizing their overall environmental impact and carbon footprint. Integrating palm oil-based biolubricants with cutting-edge nanotechnologies, such as the incorporation of nanoparticles, further enhances their tribological performance [38]. This dual focus on feedstock improvement and nanomaterials underscores the dynamic landscape of recent developments in palm oil-based biolubricants, positioning them as versatile and sustainable alternatives in the evolving field of advanced bio-lubricants. The eco-friendly attributes of palm oil-based bio-nanolubricants are increasingly valued as industries worldwide prioritize sustainability. This heightened awareness has spurred a growing interest in conducting life cycle analyses of these lubricants, which scrutinize their environmental impact and carbon footprint across all stages of production, use, and disposal. Moreover, the incorporation of cutting-edge nanotechnologies, such as the integration of nanoparticles, represents a significant advancement in enhancing the tribological performance of these lubricants. This dual approach—addressing both feedstock enhancement and the utilization of advanced nanomaterials—reflects the dynamic evolution of palm oil-based biolubricants. It positions them as versatile and sustainable alternatives within the rapidly advancing realm of

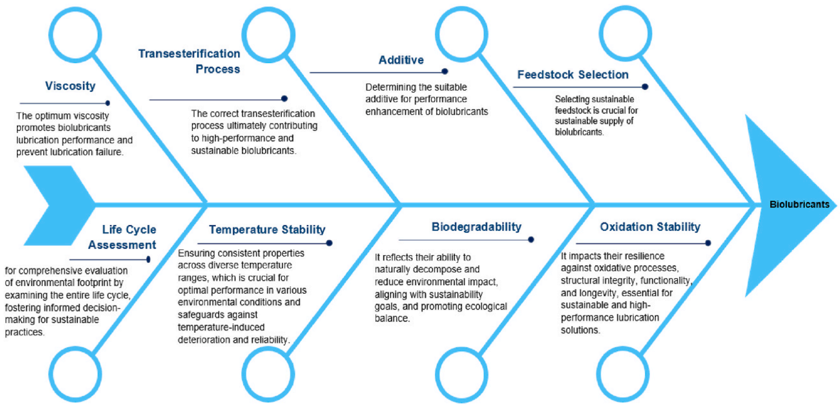

Fig. 5. Key factors influencing biolubricants.

advanced bio-lubricants, as highlighted by Shafi et al. [47]. Table provides a detailed overview of the specifications for refined palm oil, outlining its key primary physical and chemical properties to ensure quality and suitability for engineering applications.

Fig. 5 Highlights the pivotal factors influencing the production of palm oil-based biolubricants, including crucial considerations for quality, tribological performance, and sustainability, underscoring the importance of environmental responsibility in manufacturing. These parameters encompass eight pivotal factors.

3.5. Feedstock selection

Feedstock selection is a pivotal aspect of palm oil-based biolubricants production, significantly influencing the final product's overall quality, sustainability, and ethical considerations [50]. The choice of palm oil as the primary raw material holds paramount importance, and the type and quality of palm oil selected have far-reaching implications. To enhance the environmental and ethical aspects of feedstock sourcing, there is a growing emphasis on sustainable practices, often achieved through certification programs [51]. These programs, which may include certifications such as RSPO (Roundtable on Sustainable Palm Oil) [52–54], focus on ensuring that palm oil is sourced responsibly, and adhering to stringent environmental and social criteria [55]. Sustainable feedstock selection addresses concerns related to deforestation and biodiversity and promotes fair labor practices. Thus, integrating certified and sustainably sourced palm oil as feedstock aligns with the industry's commitment to ethical, environmentally responsible, and socially conscious biolubricants production [56]. Palm oil comprises three main parts: the mesocarp, kernel, and shell. The mesocarp, found in the middle layer of the palm fruit, is the primary source of oil extraction due to its high oil content. Palm kernel oil is derived from the kernel, the innermost part of the fruit, which contains the seed or nut. Lastly, the outermost layer is the shell, serving as a protective barrier for the mesocarp and kernel.

Salimon et al. [57] investigated the synthesis and optimization of green biolubricants derived from Malaysian palm kernel oil (PKO) and trimethylolpropane polyol ester by adopting in-situ generated performic acid to epoxidize the palm kernel oil polyol triester (PKO-TMPE). The findings show that the best results were obtained with a molar ratio of unsaturation, hydrogen peroxide, and formic acid of 1.00: 7.67: 5.00, a temperature of 51.85 °C, and a reaction time of 1.62 h. The optimal epoxidation process yielded a high epoxide yield of 92.5% and a relative conversion oxirane of 100%, with a low iodine value of 0.40 g/100 g I_2. The epoxidized PKO-TMPE (EPKO-TMPE) exhibited favorable lubrication properties, including a high flash point of 335 °C, oxidative stability temperature of 278 °C, a viscosity index of 187, and a pour point of −19 °C. Tribological assessments showed a small coefficient of friction (0.16 at 40 °C and 0.18 at 100 °C) comparable to commercial lubricants. This improvement is mainly because the process of epoxidation modifies the chemical structure of palm kernel oil, creating epoxide groups that enhance the lubricant's performance. These epoxide groups increase the oxidative and overall thermal stability of the biolubricants. Another aspect that affects that event is that Palm kernel oil contains a high proportion of medium-chain saturated fatty acids, contributing to a stable and consistent lubricating film under various temperature conditions. Regarding tribological performance, the specific molecular structure of EPKO-TMPE allows it to form a strong lubricating film that effectively separates moving surfaces, reducing direct metal-to-metal contact and thus lowering the coefficient of friction. The biolubricants maintain their low friction coefficient at 40 °C and 100 °C, demonstrating their ability to provide consistent lubrication under varying thermal conditions. These claims align with the previous researchers' findings [58–60]. The shell is typically removed during processing to extract palm and kernel oil, as depicted in Fig. 6.

3.6. Transesterification process

Transesterification is a critical stage in palm oil-based biolubricants production [61]. In the context of biolubricants, the transesterification process refers to a chemical reaction used to produce ester-based lubricants from palm oil. This process involves the exchange of ester groups between the triglyceride molecules present in the feedstock and alcohol molecules, typically methanol or ethanol, in the presence of a catalyst [62]. This intricate chemical reaction necessitates careful consideration of various parameters to ensure optimal efficiency and desired product characteristics [63].

The control of reaction conditions, including temperature, pressure, and catalyst type, is paramount in determining the transesterification process's success. The catalyst identified in the investigation is potassium carbonate (K_2CO_3). It is categorized as a heterogeneous catalyst, indicating that it occurs in a distinct phase (solid) from the reactants in the liquid phase. This differentiation is significant since the catalyst is isolated from the liquid mixture following the reaction through centrifugation, and the leaching experiments demonstrated minimal solubility of K_2CO_3 in the resulting products. The temperature setting influences the desired biodiesel

Fig. 6. Main parts of palm fruit.

compound's reaction rate and selectivity. Similarly, pressure conditions are crucial in maintaining the reaction equilibrium [62]. Fig. 7 illustrates the various chemical pathways and reactions in converting triglycerides into biolubricants. The process begins with the hydrolysis of triglycerides in the presence of a base catalyst, producing fatty acids and glycerol. Alternatively, triglycerides can undergo transesterification with alcohol, using a base catalyst to form fatty acid methyl esters (FAME) and glycerol. Further chemical modifications include transesterifying FAME with trimethylolpropane (TMP) using a catalyst to produce TMP tri-ester, a type of biolubricant. Fatty acids can also be esterified with alcohol to form estolides. Epoxidation of triglycerides, using peroxide and carboxylic acid, produces epoxidized triglycerides, which can subsequently undergo a ring-opening reaction to form ring-opened triglycerides. Additionally, triglycerides can be acetylated in acetic acid or acetic anhydride to produce acetylated triglycerides. These various pathways and reactions (hydrolysis, transesterification, esterification, epoxidation, ring opening, and acetylation) demonstrate the complexity and versatility of chemical modifications that can be applied to triglycerides, resulting in biolubricants with enhanced performance characteristics, such as improved viscosity and stability, for EV applications (see Fig. 8).

Each step in the process is crucial for producing high-quality biolubricants, but two steps require special attention: (1) transesterification with TMP (Trimethylolpropane). This step further modifies FAME (Fatty Acid Methyl Esters) into TMP tri-esters, known for their excellent tribological properties, high viscosity index, and thermal stability. The effectiveness of this conversion is crucial for improving the lubricity and wear resistance of the biolubricants; and (2) ring-opening reaction of epoxidized triglycerides. This reaction alters the molecular structure to enhance the film-forming ability, reducing friction and wear. This step is essential for ensuring a stable lubrication film that can withstand mechanical stresses, directly impacting the tribological performance.

Furthermore, Ceron et al. (2018) reported that the synthesis of biolubricants can be achieved through the transesterification process by adopting a schematic setup as shown in Fig. 9. Biolubricant esters were successfully produced from palm kernel oil using simulated fusel oil containing ethyl (11.2%), butyl (10.6%), and isoamyl alcohols (78.2%). The process utilized enzymatic transesterification with lipase from Burkholderia cepacia immobilized on an epoxy matrix silica-hydroxyethyl cellulose as a biocatalyst. The produced biolubricant exhibited alkyl ester contents greater than 98%, mono-glycerides (MG) contents between 0.083 and 1.28 wt%, absence of di-glycerides (DG), a kinematic viscosity of 4.41 ± 0.25 mm^2/s, and a viscosity index of 149.22 ± 2.11. The biocatalyst exhibited stability with a half-life of approximately 38 days. Additionally, the biolubricant demonstrated an oxidative stability of 23.85 $\pm$ 1.65 min, confirming its high-quality performance and potential for industrial applications [63].

3.7. Additives

Additives refer to a broad category of substances added to lubricants to improve their performance or impart specific properties. Additives can serve various functions, such as enhancing lubricity, reducing friction and wear, improving thermal stability, preventing corrosion, and extending the lubricant's service life [64]. Additives serve as integral components in the formulation of palm oil-based biolubricants, offering a tailored approach to enhance specific properties such as viscosity [65], oxidation stability [66], and anti-wear characteristics [67]. While adding additives is not universally compulsory, their strategic incorporation is often essential for optimizing and customizing biolubricants formulations to meet diverse application requirements. Viscosity modifiers, oxidation inhibitors, and anti-wear additives contribute significantly to the overall performance of lubricity and durability of the biolubricants, as depicted in Fig. 9. The decision to include additives depends on the desired performance attributes and the intended application, with careful consideration given to achieving a balanced and sustainable formulation. Thus, while additives are not strictly mandatory, their judicious use remains a common practice for achieving optimal biolubricants performance in various operating conditions.

Furthermore, according to Chan et al. (2018), in the pursuit of creating eco-friendly biolubricants formulations, researchers are

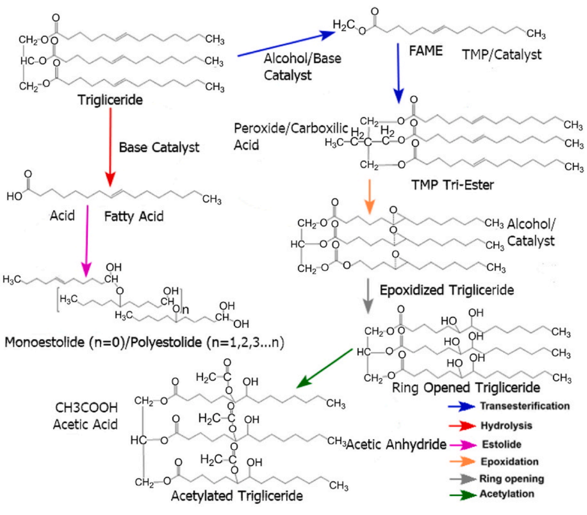

Fig. 7. Chemical modification process flow of biolubricants synthesis [42]. Reprinted with permission from MDPI under an open access Creative Common CC by license.

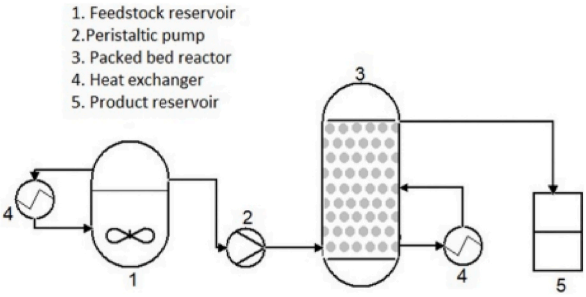

Fig. 8. Experimental configuration utilized in the synthesis of biolubricants [63]. Reprinted with permission from Elsevier.

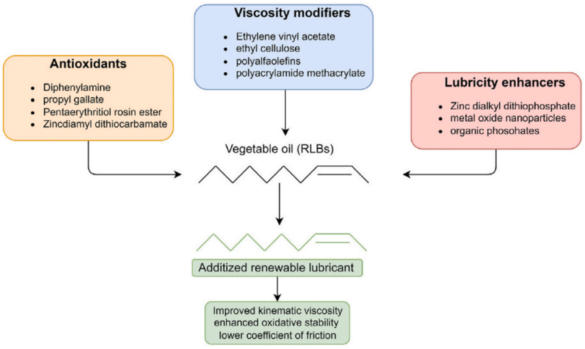

Fig. 9. Diverse additives influencing biolubricants characteristics [69]. Reprinted with permission from Elsevier.

focusing extensively on tribological additives. These additives encompass compounds and polymers from botanical origins, particulate and stratified substances, and ionic liquids. Besides, the successful formulation of biolubricants depends on selecting appropriate base stocks and biolubricants additives that match the standards for a given application. In terms of tribology, a good biolubricants base stock can be achieved by optimizing two characteristics: the stability and adhesion strength of the tribofilm it produces under lubrication conditions, provided that the lubricant's viscosity range and lubrication regime are appropriate and aligned with the application requirements. Tribological additives can then be added to improve the base stock [68]. Compounds derived from plants, like cystine Schiff base ester, can serve as additives with anti-friction, anti-wear, and anti-corrosion properties. These compounds contain disulfide groups and amine and carboxylic functionalities, which could create a surface-complex film, especially in situations involving metal-to-metal contact. Conversely, ethylene-vinyl acetate copolymer (EVA) and ethyl cellulose (EC) are viscosity modifiers. Despite comprising a small percentage of the additives in a base stock, they can increase the viscosity of the base stock by at least two-fold [69].

Previous studies have widely adopted Zinc dialkyl dithiophosphate (ZDDP) as a quintessential anti-wear additive across traditional and biodegradable lubricants. ZDDP engenders a protective film on metal surfaces, curbing friction and wear amid high-pressure scenarios [16,70,71]. Additionally, Boron-based additives, comprising borate esters and boron nitride, emerge as potent anti-wear agents, fostering protective layers on metal surfaces and mitigating metal-to-metal contact, thus reducing friction and wear as reported by previous researchers [72–74]. Moreover, Xie et al. (2022) reported that Molybdenum disulfide (MoS_2), functioning as a solid lubricant, finds utility as an anti-wear additive in biolubricants, bestowing a low-friction coating on metal surfaces, thereby curtailing wear and elongating equipment lifespan [75]. Rui et al. (2020) adopted two oil-soluble ILs (4(or 5)-methyl-benzotriazole-1-ylmethyl) -octadec-9-enyl-ammonium bis(2-ethylhexyl) phosphate and 4(or 5)-methyl-benzotriazole-1-ylmethyl)- dioctyl-ammonium bis (2-ethylhexyl) phosphate as corrosion inhibitors additive on poly-alpha-olefin (PAO) lubricant. The finding shows that Corrosion and rust tests reveal that adding merely 0.1% ILs into PAO10 can effectively strengthen the anti-corrosion and anti-rust performance of base oil [76]. Wang et al. (2023) noted the utilization of carbon dot-based ionic liquids (CDILs) in lubricants to inhibit corrosion. Evaluation findings indicate that CDILs with moderate alkyl chains in the cationic component demonstrate the best corrosion inhibition and lubrication efficacy. The quality of adsorption and formation of the lubricating film is influenced by the physical adsorption of CDILs and the structures of the cations [77].

A previous study reported by Nugroho et al. [78] revealed a common issue with conventional lubricants is their inability to maintain performance under extreme temperatures and pressures, which leads to the breakdown of the thin lubricating film and results in lubrication failure. A nanomaterial additive is needed to transform the sliding movement between two metal contacts into a rolling movement within the lubrication regime, thereby enhancing lubrication performance to address this challenge. In this regard, Vardhaman et al. [155] reported that the incorporation of zinc oxide (ZnO)/functionalized multi-wall carbon nanotubes (FMWCNTs) nanomaterials into engine lubricants can enhance tribological performance. At a concentration of 0.1%, it can decrease the coefficient of friction (COF) and wear by 26.21% and 89.09%, respectively. The mechanism underlying the reduction of COF and wear through the integration of lubricant-reinforced ZnO/FMWCNTs nanomaterials in engine oil involves several factors: (i) the presence of nanomaterials such as ZnO and FMWCNTs can enhance the lubricating properties of the engine oil. These nanomaterials can form a stable lubricating film on the surface of the contacting components, reducing direct metal-to-metal contact and thus lowering friction. (ii) The nanostructures of ZnO and FMWCNTs possess unique surface characteristics that can help smooth out surface irregularities and asperities on the contacting surfaces. This smoother surface reduces frictional resistance and wear between the moving parts, and (iii) during the sliding motion of the contacting surfaces, the spherical shape of ZnO nanoparticles and the tubular structure of FMWCNTs combine to create tribofilms on the metal surface. These tribofilms facilitate a transition from sliding to rolling motion between the nanomaterials and the metal components, thereby reducing friction and promoting a decrease in both coefficient of friction (COF) and wear. The previous researchers confirm this mechanism, Sharif et al. [79] adopted SiO_2/Al_2O_3 nanoparticles dispersed in polyalkylene glycol (PAG) oil for application in light vehicle air conditioning compressors. Subsequently, Zawawi et al. [80] reported that using Al_2O_3/SiO_2-PAG in light vehicle air conditioning compressors can decrease the coefficient of friction (COF). The composite nanolubricants achieved the highest COF and wear rate reductions, reaching up to 4.49% and 12.99%, respectively, at a volume concentration of 0.02%.

3.8. Viscosity

Viscosity stands as a critical parameter in palm oil-based biolubricants formulation, exerting a profound influence on the end product's flow characteristics and lubricating properties [81]. While including viscosity-modifying additives is not universally obligatory, their strategic integration is often deemed indispensable for tailoring the biolubricant's viscosity to align with the specific demands of its intended application [82]. The careful viscosity adjustment ensures optimal lubrication under diverse operational conditions, promoting efficient fluid flow within the lubrication system. This customizable approach acknowledges the varied requirements across different applications. It underscores the importance of viscosity control in achieving desired performance attributes, thereby contributing to the versatility and effectiveness of palm oil-based biolubricants. The viscosity index, a key consideration in formulation, allows for nuanced control over viscosity variations with temperature changes, contributing to the adaptability and versatility of the biolubricants [83]. This customizable approach acknowledges the varied requirements across different applications, emphasizing the role of both viscosity and viscosity index in achieving the desired performance attributes and promoting the efficiency of palm oil-based biolubricants.

Fig. 10 illustrates the viscosity characteristics of various biolubricants, including those derived from sunflower, soybean, Jatropha, and waste sources. The data in the figure indicates a decrease in viscosity with increasing test temperature. The mechanism can be explained because, in general, this phenomenon occurs because higher temperatures facilitate the disruption of intermolecular forces, such as hydrogen bonds or van der Waals forces, which contribute to the viscosity of the lubricants. As these forces weaken with increasing temperature, the molecules within the lubricants can flow more freely, resulting in a decrease in viscosity. Additionally, at elevated temperatures, the viscosity of biolubricants may be further reduced due to thermal degradation or breakdown of the lubricant molecules, as reported by previous researchers [85–87]. This degradation can lead to the formation of smaller molecular fragments or the loss of functional groups, contributing to a decrease in viscosity. Overall, the observed reduction in viscosity with increasing test temperature is expected behavior in many lubricants and is influenced by factors such as molecular structure, intermolecular interactions, and thermal stability of the lubricant, and this regime is in line with the previous researchers' findings [88–90]. Biolubricants can exhibit both Newtonian and non-Newtonian behavior, depending on their composition and additives.

Dadan et al. (2019) reported that adopting a polymeric viscosity enhancer (EVA copolymer) has yielded favorable outcomes for the tribological characteristics of PKME. The ideal concentration of 4 percent EVA copolymer has been identified as it enhances friction reduction and anti-wear performance by creating a protective film between interacting surfaces [91]. Attia et al. (2020) investigated

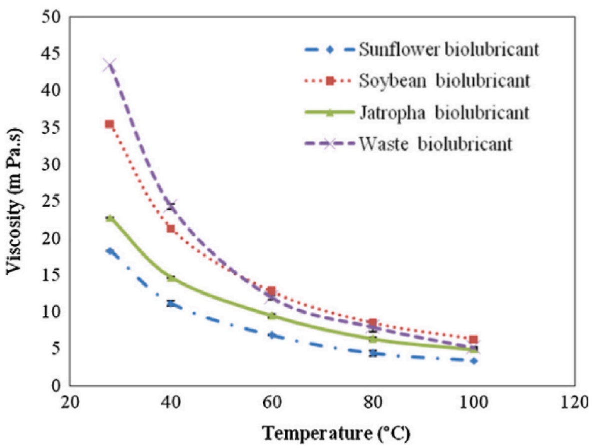

Fig. 10. Viscosity of various biolubricants in different temperatures assessment [84]. Reprinted with permission from Elsevier.

the production of biolubricants from vegetable oils, including sunflower, soybean, Jatropha, and waste oils. The production method involved obtaining fatty acid methyl esters (FAMEs) from vegetable oils through transesterification. These FAMEs were transesterified with ethylene glycol as the di-alcohol to produce ethylene glycol di-esters (EGDEs). The resulting EGDEs demonstrated superior performance, with viscosity indexes exceeding 140 for waste oil and 311 for Jatropha oil. A higher viscosity index indicates that the lubricant can maintain a more stable viscosity over various temperatures, enhancing its performance in varying thermal conditions. Notably, the EGDEs exhibited Newtonian fluid behavior, maintaining a consistent viscosity irrespective of the applied shear rate, which is crucial for their effectiveness as biolubricants., as shown in Fig. 11, indicating constant viscosity regardless of shear rate. This increase in viscosity index was achieved through the specific chemical structure of the EGDEs, optimized processing conditions, and the incorporation of ethylene glycol, which provides stability across a wide range of temperatures. A higher viscosity index indicates that the lubricant can maintain a more stable viscosity over varying thermal conditions, enhancing its performance. Notably, the EGDEs exhibited Newtonian fluid behavior, maintaining a consistent viscosity irrespective of the applied shear rate, which is crucial for their effectiveness as biolubricants. Consistent viscosity irrespective of the applied shear rate, which is crucial for their effectiveness as biolubricants [84].

For some biolubricants that behave like Newtonian fluids, it can be discussed that their viscosity remains constant irrespective of the shear rate or stress applied to them, as depicted in Fig. 11. In other words, their viscosity does not change with increasing or decreasing shear forces. Many vegetable oils, such as soybean or rapeseed oil, exhibit Newtonian behavior, as reported by Jumat and Nadia [57].

Furthermore, other biolubricants may exhibit non-Newtonian behavior, altering viscosity with shear rate or stress [92]. Common types include shear-thinning (pseudoplastic) and shear-thickening (dilatant) behaviors. Shear-thinning biolubricants flow more easily under higher shear forces, which is beneficial for narrow passages or varied-speed lubrication [93]. Conversely, shear-thickening biolubricants become more viscous with increased shear rate, sometimes enhancing film thickness and boundary lubrication [36]. The crucial viscosity index, which quantifies viscosity change with temperature, is essential for optimal biolubricants performance across different operating conditions, as listed in Table 2.

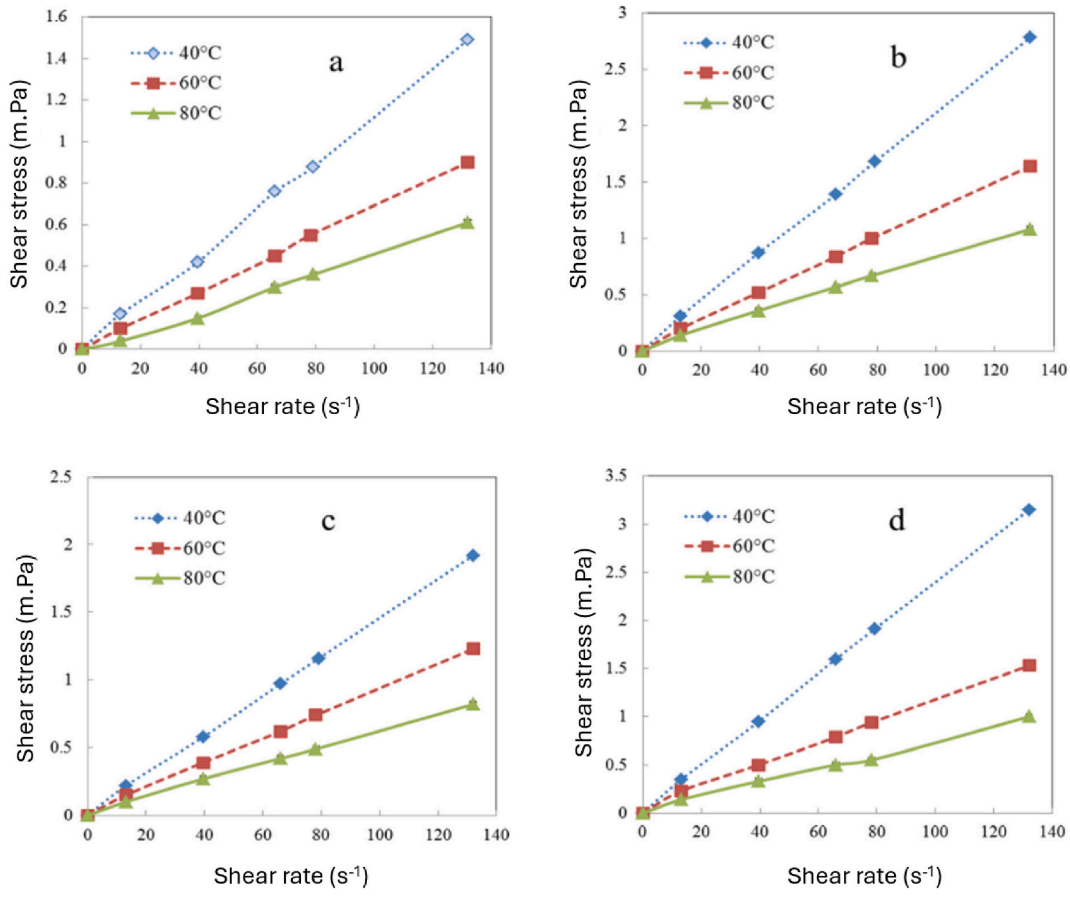

Fig. 11. Various biolubricants exhibit Newtonian behavior of (a) sunflower, (b) soybean, (c) Jatropha, and (d) waste oils [84]. Reprinted with permission from Elsevier.

3.9. Oxidation stability

Oxidation stability emerges as a pivotal aspect in formulating palm oil-based biolubricants, determining their resilience against oxidative processes that can trigger degradation over time [35]. This parameter assumes utmost significance as it directly influences the biolubricants' ability to maintain structural integrity and functionality, ensuring an extended service life. Oxidation stability in biolubricants refers to their ability to resist degradation when exposed to oxygen and elevated temperatures over time. This degradation process, known as oxidation, can lead to the formation of undesirable by-products due to double bonds present in the poly-unsaturated carbon chain, which can compromise the lubricant's performance and lead to equipment failure [95].

According to the present literature, four essential elements affect the biolubricants oxidation stability, as illustrated in Fig. 12. (i) base oil composition, the type of vegetable oil or other renewable feedstock used as the base oil significantly impacts oxidation stability. Some oils, such as canola or sunflower oil, contain higher levels of unsaturated fatty acids, making them more prone to oxidation than oils with higher levels of saturated fatty acids, such as palm oil or coconut oil [96]. (ii) Antioxidation additives: Formulating biolubricants with antioxidant additives can enhance oxidation stability by scavenging free radicals and preventing the initiation and propagation of oxidation reactions. Common antioxidants used in biolubricants include phenolic compounds, amines, and phosphates [97]. (iii) metal contamination: metals in the lubrication system, such as iron, copper, and nickel, can act as catalysts for oxidation reactions. Controlling metal contamination through proper equipment maintenance and filtration can help improve oxidation stability [98], and (iv) operating conditions: temperature, humidity, and air circulation can influence the oxidation rate. Operating equipment within recommended temperature ranges and implementing proper storage and handling procedures can help mitigate oxidation [99].

Cai et al. [50] reported that litsea cubeba (LC) kernel oil, a byproduct from essential oil processing, has been effectively repurposed as a feedstock for producing trimethylolpropane fatty acid tri-ester (TFATE), a high-quality biolubricants base oil. The resulting TFATE demonstrates excellent oxidative stability with a 35-min at 150 °C and impressive low-temperature performance with a pour point of −15 °C, making it a viable candidate for use as a biolubricants. This study underscores the potential of LC kernel oil as a valuable biolubricants feedstock and its transformation into a value-added product, contributing to the advancement of a zero-waste biorefinery model for the LC industry. It also provides new insights into optimizing oxidative stability and low-temperature performance in biolubricants, presenting LC kernel oil as an effective and sustainable feedstock for future biolubricants. Litsea cubeba (LC) kernel oil has good oxidative stability because of its high amount of medium-chain fatty acids like capric and lauric acids, which contain fewer double bonds and are less susceptible to oxidation than long-chain fatty acids. This inherent characteristic assists the oil in resisting oxidative deterioration. Furthermore, LC kernel oil may include natural antioxidants, including tocopherols and phenolic compounds, which protect against oxidative damage by scavenging free radicals. The molecular structure of TFATE increases oxidative stability, making it more resistant to disintegration at high temperatures. These characteristics combine to provide LC kernel oil-based biolubricants with enhanced oxidative stability.

Jumaah et al. [100] investigated saturated palm fatty acid distillate for biolubricants production. The finding shows that saturated palm fatty acid (SFA) – trimethylolpropane (TMP) polyol ester demonstrates the highest yield and selectivity. Conversely, SFA-di-pentaerythritol (Di)-polyol ester (PE) is produced with lower yield and hexa-ester selectivity. The research results suggest that high-grade SFA-based polyol esters can be produced through esterification methods, enabling cost-effective polyolester production from by-products of palm oil processing. The lubricating properties of the synthesized polyolester indicate their suitability for grease applications and bearing lubricants [101]. These comparative analyses validate that lubricant-based oils crafted from saturated or monounsaturated fatty acids offer a favorable blend of thermal and oxidative stability and cold flow characteristics [102].

Xiaotian et al. (2023) reported that Phenolic antioxidants, such as butylated hydroxytoluene (BHT), butylated hydroxyanisole (BHA), and hindered phenols like acetylated diphenylamine (ODPA), work by scavenging free radicals and interrupting oxidation chain reactions. These compounds effectively inhibit the formation of oxidative by-products, thereby preserving the integrity and performance of the biolubricants [103]. Amine antioxidants, including primary and secondary aromatic amines like diphenylamine (DPA) and alkylated diphenylamines, neutralize reactive oxygen species and prevent them from initiating oxidation reactions. These

Table 1
Refined palm oil specification[a] [48,49].

Properties	Value
Density (40 °C), (g/cm3)	0.897
Total glycerol (%)	1.03
Acid value (mg KOH/g oil)	0.75
Saponification value, (mg KOH/g oil)	196–205
Unsaponifiable Matter (%)	Max 1.5
Free Fatty Acid (FFA) (%)	Max 0.1 as Palmitic Acid
Moisture and Impurities (%)	Max 0.1
Color (5¼" Lovibond)	Max 3.0 Red
Melting Point (°C)	33–39
Peroxide Value (meq/kg)	Max 1
Slip Melting Point	33–39 °C
Specific Gravity (°C)	0.89–0.91 at 40°
Pour point (°C)	7
Flashpoint (°C)	240

[a] particularly for refined palm oil.

Table 2
Physicochemical properties of palm oil[a] [94].

Physicochemical properties parameter	Value
Oxidative stability (°C)	181
Kinematic viscosity at 40 °C	33–55 mm^2/s
Kinematic viscosity at 100 °C	5–12 mm^2/s
Viscosity index (VI)	150–200
ISO viscosity grade	46
Specific gravity	0.89–0.91 at 40 °C
Dynamic viscosity	30–50 mPa s at 40 °C

[a] for particular palm oil only.

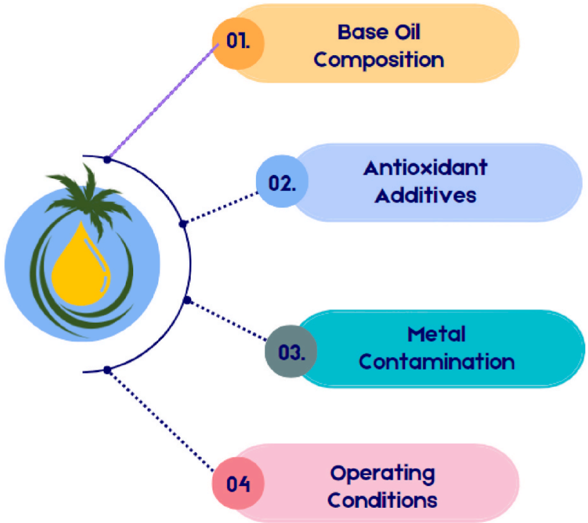

Fig. 12. Factors influencing biolubricants' oxidation stability.

antioxidants act as sacrificial agents, sacrificing themselves to protect the lubricant from oxidative degradation. Phosphite antioxidants, exemplified by compounds like tris(2,4-di-tert-butylphenyl) phosphite (PQ-3) and alkylated aryl phosphates, operate by chelating metal ions that can catalyze oxidation reactions. By sequestering these metal ions, phosphite antioxidants effectively inhibit oxidation and enhance the biolubricants' stability, as Qingkun et al. reported [104]. Thus, incorporating antioxidants into biolubricants is crucial for maintaining their stability, performance, and longevity, ultimately ensuring optimal lubrication and protection for machinery and equipment.

The mechanism of antioxidants refers to the antioxidant's function by scavenging free radicals, which are highly reactive molecules that can initiate oxidative degradation reactions in the lubricant. Free radicals can be generated during the lubricant's exposure to heat, oxygen, or other reactive species. Antioxidants neutralize these free radicals by donating electrons, stabilizing them, and preventing further chain reactions. Antioxidants interrupt the chain reaction of oxidation by breaking the propagation steps [105]. Oxidation reactions typically involve a chain reaction where one reactive molecule generates another, leading to a cascade of responses. Antioxidants disrupt this process by reacting with the reactive species and terminating the chain reaction, thus preventing the formation of harmful by-products. Some antioxidants also act as metal deactivators by chelating or sequestering metal ions in the lubricant [106].

3.10. Biodegradability

The biodegradability of biolubricants refers to their ability to be broken down by natural processes into simpler compounds by microorganisms present in the environment. This property is significant because it determines the environmental impact of biolubricants once they are released into soil, water, or air [107]. Biodegradability emerges as a cornerstone consideration in formulating palm oil-based biolubricants, reflecting their inherent capability to undergo natural decomposition and thereby curtail environmental impact [108]. This pivotal parameter underscores the lubricant's ability to break down organically, aligning with overarching sustainability objectives and mitigating ecological footprints [109,110]. The profound emphasis on biodegradability is not merely technical but a crucial determinant in assessing the product's environmental friendliness. It signifies the seamless integration of palm oil-based biolubricants into natural ecosystems, fostering a balanced coexistence with the environment by minimizing enduring ecological traces.

Shah et al. (2021) reported that biolubricants, notably saturated esters and synthetic base oils like polyalkylene glycols and bio-olefins, emerge as environmentally friendly options due to their biodegradability and renewable nature, meeting evolving societal demands and promoting innovative developments in lubricant formulations towards enhanced eco-toxicological properties and sustainability criteria [111]. Uppar et al. (2022) reported that achieving a balance between the commercial viability of biolubricants and their environmental constraints is becoming progressively intricate. If a product poses substantial risks to human health, it must be removed from lubricant applications due to concerns about toxicity and environmental repercussions. Plant-derived bio-oils are pivotal in emerging strategies, regulations, and incentives to diminish reliance on fossil fuels like mineral oil. Moreover, most biolubricants demonstrate heightened biodegradability compared to petroleum-based counterparts, which is in line with sustainable practices and efforts for environmental preservation. This attribute underscores their significance as eco-friendly alternatives across diverse industrial sectors [112].

For instance, several commercial companies have embraced biolubricants in the market by prominently displaying "eco-labels" on their products, signifying their commitment to environmental sustainability as depicted in Fig. 12. Additionally, these companies often obtain minimum 50% biodegradable raw materials certification for their biolubricants offerings, ensuring that their products meet stringent environmental standards and contribute to reducing ecological impact [113]. To acquire the European Ecolabel, lubricants must consist of at least 50% renewable raw materials, such as plant oils. These plant-based oils (e.g., palm oil) are recognized for their capacity to diminish CO_2 emissions compared to alternatives derived from fossil fuels. Furthermore, it is essential for these lubricants to demonstrate a high level of biodegradability, ensuring their rapid decomposition in the environment without inflicting any lasting damage. This certification ensures that the lubricant complies with strict environmental standards and promotes sustainability by decreasing its carbon footprint and minimizing pollution by EU rules and global sustainability goals [114]. By prioritizing high biodegradability standards, these biolubricants exemplify a commitment to ecologically responsible practices, championing the cause of sustainable lubrication solutions with utmost environmental conscientiousness.

3.11. Temperature stability

Temperature stability is crucial for palm oil-based biolubricants to maintain their properties across diverse conditions, especially at elevated temperatures, ensuring optimal performance and widespread industrial adoption. The molecular composition of the base oil significantly affects thermal stability, with saturated fatty acids offering superior resistance to oxidation compared to unsaturated ones. Higher saturation levels reduce the presence of double bonds within fatty acid chains, making fully hydrogenated vegetable oils preferable for applications requiring exceptional thermal stability. Xie et al. (2024) reported that the biolubricants derived from agro-waste resources offer a promising alternative to petroleum-based lubricants, aligning with principles of waste utilization and sustainable development. Their study synthesized high-performance biolubricants through dihydroxylation modification of extracts from abandoned aerial parts of Codonopsis pilosula. These biolubricants demonstrated remarkable thermal stability, resisting decomposition up to 298.8 °C, and exhibited excellent lubricity in the temperature range of 50–250 °C, characterized by low friction coefficients ranging from 0.108 to 0.129 and wear rates of 10^{-8} to 10^{-7} mm^3/Nm. These outstanding properties rival and surpass other biolubricants and mineral oil [115]. Fig. 13 presents a Thermogravimetric Analysis (TGA) plot illustrating the thermal decomposition profile of the dihydroxy product (HPEE-CP) under a nitrogen atmosphere.

The decomposition of HPEE-CP starts at 298.8 °C, with the initial weight loss primarily due to moisture evaporation. Beyond this temperature, the degradation of HPEE-CP begins, with 80% of the total weight loss occurring by 440 °C. The remaining residue shows stability under a nitrogen atmosphere up to 600 °C. This indicates that HPEE-CP remains thermally stable until 298.8 °C, exhibiting

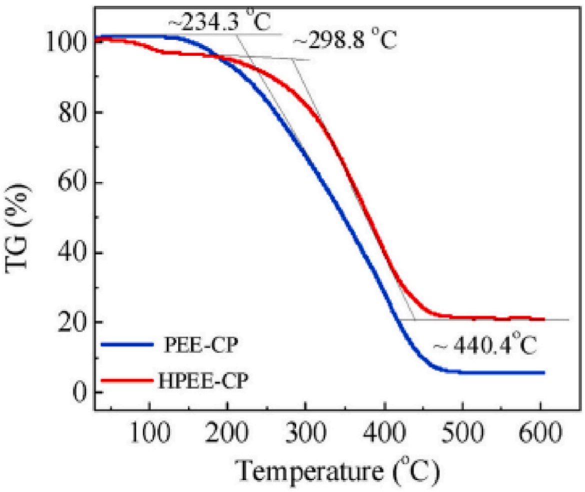

Fig. 13. Thermogravimetric Analysis (TGA) plot depicting the thermal decomposition behavior of dihydroxy product (HPEE-CP) in a nitrogen environment [115]. Reprinted with permission from Elsevier.

more excellent stability than the unprocessed petroleum ether phase, which decomposes at 234.3 °C. The increase in decomposition onset temperature is attributed to the removal of unsaturated carbon bonds, a finding consistent with related research as depicted in Fig. 13.

Furthermore, incorporating antioxidant additives is essential for enhancing the biolubricants' resistance to thermal degradation. These additives act as scavengers, intercepting free radicals and preventing the formation of oxidation by-products that could compromise the lubricant's performance [93]. Proper purification and refining techniques during processing also improve thermal stability by eliminating impurities and contaminants that may accelerate degradation. Consideration of operating conditions, such as temperature, pressure, and speed, is equally vital in selecting biolubricants tailored to withstand specific environmental stresses [116]. The physicochemical assessment of the formulated biolubricants revealed that those with a 30% concentration exhibited a higher viscosity index (VI) (Fig. 14a). Consequently, this formulation was selected as the base stock for blending with multifunctional green additives (MGA), MGA-1 and MGA-2. Both MGA-1 and MGA-2 additives demonstrated an increase in VI with rising additive concentration, acting as viscosity index improvers compared to the mineral base oil (Fig. 14b).

Furthermore, the findings show that larger quantities of waste cooking oil (WCO) and additives raise the viscosity index, which measures how a fluid's viscosity changes with temperature. Specifically, as the concentration of WCO increases from 0% to 30% (v/v), the viscosity index increases, indicating improved temperature stability. Similarly, adding additives MGA-1 and MGA-2 increases the viscosity index, with substantial benefits beginning at 0.5% (w/v) and increasing to 1% (w/v). MGA-2 surpasses MGA-1 with a slightly higher viscosity index at each concentration level. This means that both WCO and the tested additions greatly increase the fluid's viscosity behavior with temperature, with MGA-2 being slightly more effective than the other additives tested [116].

By addressing these factors cohesively, biolubricants manufacturers can ensure that their products offer reliable thermal stability, paving the way for broader adoption in automotive, industrial, and marine applications while aligning with sustainability goals. When biolubricants are subjected to high temperatures, such as those encountered in the operating conditions of electric vehicles, they undergo thermal degradation [117]. This process involves breaking chemical bonds within the lubricant molecules due to the energy supplied by heat. As a result, the molecular structure of the biolubricants may change, leading to alterations in their physical and chemical properties. Thermal degradation can have several detrimental effects on biolubricants. One of the primary consequences is viscosity changes, where the lubricant may become either too thin or too thick. This altered viscosity can weaken the lubricant's ability to form a protective film between moving parts, increasing friction and wear [118]. Unfortunately, the findings do not indicate a reduction in the viscosity index after it reaches a level of 160. Consequently, the researcher concludes that the optimal concentration of WCO is 30%, with a 1% addition of the tested additive. This concentration appears to maximize the viscosity index under the current experimental conditions. However, the study's scope is limited to these specific concentrations. Therefore, further research is necessary to determine whether the observed trend of increasing viscosity index continues if the concentration of WCO exceeds 30% and the additive concentration surpasses 1%. Such investigations would provide a more comprehensive understanding of the relationship between these variables and potentially identify even more effective concentration levels for enhancing the viscosity index. The viscosity index strongly relates to the thermal stability that maintains lubricants' performance during the EV operation, which requires higher thermal stability as reported by Rio et al. [119].

3.12. Life Cycle Assessment for sustainable development goals

Integrating Life Cycle Assessment (LCA) into palm oil-based biolubricants production is instrumental in comprehensively evaluating its environmental footprint. This comprehensive process involves thoroughly examining the entire life cycle, from the extraction of raw materials to the ultimate disposal phase [120]. The significance of LCA lies in its ability to provide a holistic perspective on the environmental impact, accounting for various stages such as production, distribution, utilization, and eventual disposal. By scrutinizing factors throughout the life cycle, LCA enables a nuanced understanding of the environmental implications of bio lubricants, fostering informed decision-making for sustainable and eco-friendly practices [121]. Maheshwari et al. (2023) reported that the selected LCA model allows industries to devise sustainable manufacturing methods by assessing the potential impacts of environmental factors on human health, ecosystems, and resource availability [122]. This commitment to LCA underscores dedication to transparency

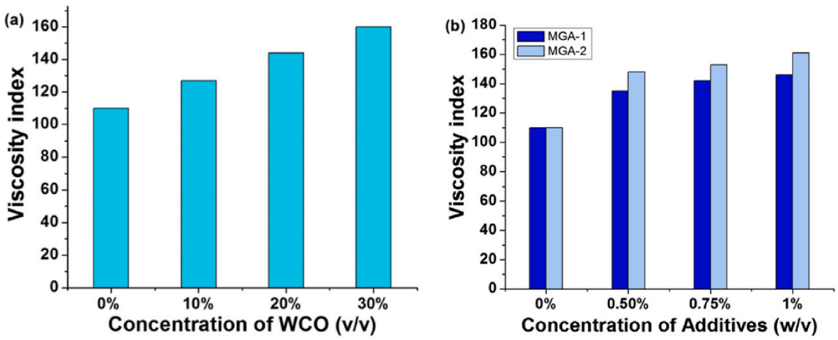

Fig. 14. Physicochemical assessment: (a) Relationship between viscosity index and concentration of waste cooking oil (WCO), and (b) Relationship between viscosity index and concentration of additives [116]. Reprinted with permission from Elsevier.

and environmental responsibility, ensuring that palm oil-based biolubricants align with stringent environmental standards and contribute positively to the broader sustainability landscape.

Thus, according to the LCA concept and previous literature, commencing a Life Cycle Assessment (LCA) for biolubricants used in electric vehicles involves several vital steps: (i) *Goal Definition and Scope*, clearly define the goal of the LCA study, including the specific objectives, boundaries, and scope. Determine the functional unit, which represents the functional performance of the biolubricants (e.g., lubricating capacity for a certain distance or period); (ii) *Inventory Analysis*, identify and quantify all inputs (e.g., raw materials, energy, water) and outputs (e.g., emissions, waste) associated with the life cycle of the biolubricants, from raw material extraction to disposal. This includes gathering data on the production process, transportation, use phase (e.g., lubrication in electric vehicles), and end-of-life treatment; (iii) *Impact Assessment*, assess the potential environmental impacts of the biolubricants throughout their life cycle. This involves evaluating factors such as greenhouse gas emissions, energy consumption, water use, land use, and toxicity. Use appropriate impact assessment methods and indicators to quantify and compare the environmental burdens associated with different life cycle stages; (iv) *Interpret the LCA results* to identify hotspots and areas for improvement in the environmental performance of the biolubricants. Consider the trade-offs between different environmental impact categories and explore opportunities for reducing overall ecological impacts; (v) *Improvement Analysis*, develop and evaluate alternative scenarios or strategies to improve the environmental performance of the biolubricants. This may involve optimizing the production process, sourcing sustainable raw materials, reducing energy consumption, minimizing emissions, and enhancing end-of-life management practices; and (vi) *Reporting and Verification*, preparing a comprehensive report summarizing the methodology, findings, and conclusions of the LCA study. Communicate the results effectively to stakeholders, including policymakers, industry representatives, researchers, and consumers, to inform decision-making and promote transparency. This step includes reviewing the LCA study to ensure its accuracy, reliability, and compliance with relevant standards and guidelines. Consider seeking independent verification or certification from recognized authorities to enhance the credibility of the results. The described steps are illustrated in Fig. 15.

The intersection between Life Cycle Assessment (LCA) and the Sustainable Development Goals (SDGs) in the context of biolubricants development and application in the engineering field can be seen in several ways, including (i) Goal 9: *Industry, Innovation, and Infrastructure,* LCA can be used to assess the environmental impacts of producing and using biolubricants compared to conventional petroleum-based lubricants. By identifying areas for improvement in production processes and infrastructure development, engineers can contribute to achieving more sustainable industrial practices (SDG 9); (ii) Goal 12: *Responsible Consumption and Production,* LCA helps evaluate the life cycle environmental impacts of biolubricants, promoting responsible consumption and production patterns. Engineers can use LCA results to optimize biolubricants formulations, reduce resource consumption, and minimize waste generation throughout the product life cycle, aligning with SDG 12; (iii) Goal 13: *Climate Action*, biolubricants often have lower carbon footprints and contribute to mitigating climate change compared to conventional lubricants. LCA provides insights into the greenhouse gas emissions associated with biolubricants, supporting efforts to reduce carbon emissions and achieve climate action goals (SDG 13); (iv) Goal 14: *Life Below Water* and (v) Goal 15: *Life on Land,* by assessing the environmental impacts of biolubricants throughout their life cycle, including potential effects on ecosystems and biodiversity, LCA contributes to sustainable management of terrestrial and aquatic resources, promoting goals related to life below water and life on land (SDGs 14 and 15), and (vi) Goal 17: *Partnerships for the Goals,* Collaboration between stakeholders, including engineers, policymakers, industry representatives, and researchers, is essential for

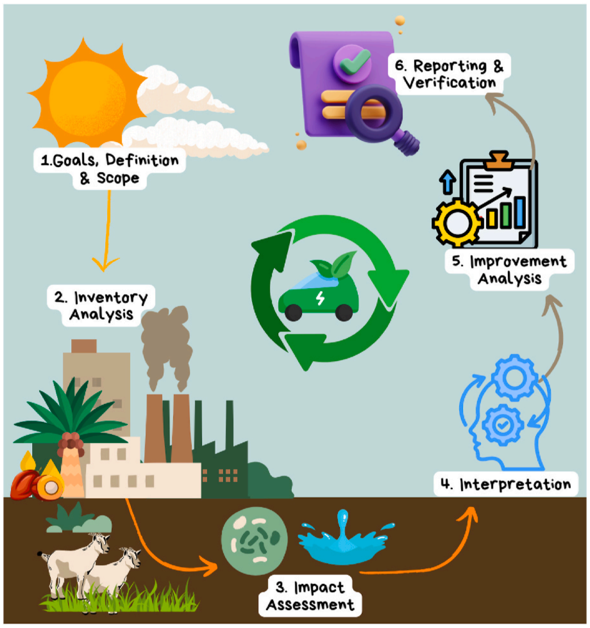

Fig. 15. Life Cycle Assessment cycle.

advancing sustainable biolubricants development and application. LCA is a standard methodology for evaluating and comparing different biolubricants options, facilitating partnerships and knowledge sharing to achieve the SDGs (SDG 17) [123–125].

By integrating LCA into the development and application of biolubricants in EV applications, stakeholders can make informed decisions that support multiple SDGs, contributing to sustainable development and a more environmentally friendly approach to lubrication in various EV industries.

4. Results and discussion

4.1. Nanoparticles in biolubricants

Nanoparticles in biolubricants considerably improve their performance and stability. When these microscopic particles are introduced to biolubricants, they increase lubricity, thermal stability, and wear resistance. The use of nanoparticles lowers friction and wear between mechanical components, hence increasing their lifespan and efficiency. Furthermore, nanoparticles can improve the oxidative stability of biolubricants, making them more resistant to deterioration under high temperatures and long-term use. This innovation increases biolubricants performance and allows them to be used in a broader range of industrial applications, encouraging sustainability and decreasing environmental impacts.

Recent discoveries by Silva-Alvares et al. [29] reported that incorporating nanotechnology, specifically nanoparticles include graphene oxide, copper oxide (CuO), titanium dioxide (TiO_2), zinc oxide (ZnO), magnesium oxide (MgO), aluminum oxide (Al_2O_3), and silicon dioxide (SiO_2), has emerged as a promising avenue for overcoming these challenges. Adding nanoparticles into biolubricants significantly enhances their performance under extreme conditions such as high temperature and high pressure. The following mechanisms explain how nanoparticles contribute to this improvement. (1) High thermal conductivity; nanoparticles like diamond, metal oxides, and carbon-based materials have high thermal conductivity. When dispersed in biolubricants, they help dissipate the heat generated at the contact interfaces more efficiently. This prevents localized overheating, maintaining the lubricant's viscosity and performance even at elevated temperatures; (2) Generally, nanoparticles are thermally stable and do not degrade at high temperatures. Their presence in the lubricant helps maintain its structural integrity and performance; (3) Under high-pressure conditions, nanoparticles can promote the formation of protective tribofilms on the contact surfaces. These films act as a barrier, protecting the underlying material from direct contact and reducing wear through protective tribofilms formation; and (4) Some nanoparticles can modify the contact surfaces at the molecular level, reducing the adhesive forces and enhancing lubricity. This is especially beneficial under extreme conditions where the lubricant film might otherwise break down [38,126,127]. This integration of nanotechnology showcases the dynamic nature of recent progress in biolubricants research. It underlines the potential for these sustainable lubricants to meet the stringent demands of diverse industrial applications. This rising need for eco-friendly lubrication solutions positions biolubricants as a pivotal player in meeting the evolving demands of a conscientious and environmentally responsible industrial landscape. Table 3 provides a comparative analysis of biolubricants enhanced with various nanoparticle additives.

Based on Table 1, Afifah et al. [132] reported that a thick lubrication film becomes thinner over time, reducing its strength and ability to separate metal surfaces, which leads to high coefficient of friction (COF) values, as observed in the PSME results. The effect of epoxidation, particularly the broken oxygen oxirane ring in EPSME, does not significantly impact the length of the hydrocarbon chain or the properties of the lubrication film. Modifying the unsaturated fatty acids in vegetable oil allows a thick lubrication film to be preserved longer before degradation occurs. The optimal epoxidation conditions—a reaction temperature of 52 °C, a catalyst concentration of 6.416 wt%, and 0.163 mol of acetic acid—resulted in a maximum relative conversion of 98.9 ± 0.6% of palm stearin methyl ester oil. Utilizing the four-ball tribological test, each experiment demonstrated a reduction in friction and wear properties following the modification, highlighting the effectiveness of the process in enhancing the tribological performance of the biolubricants.

Table 3
Comparison of biolubricants with nanoparticle additives.

Base Oil	Nanomaterials	Fraction	Diameter size of nanomaterials	Coefficient of Friction (COF)	Wear Scar Diameter (WSD)	Reference
Karanja oil	TiO_2	0.50	10 and 80 nm	0.042	131.3 μm	Wagh et al. [128]
Orange peel oil	–	–			0.66 μm	Pathak et al. [129]
Soyabean oil Sunflower oil Rapeseed oil	CuO and ZnO	0.50	4.35 and 11.71 nm	0.051	187 μm	Alves et al. [130]
Rapeseed oil	CuO	0.5	40–70 nm	0.075	0.60 mm	Arumugam et al. [131]
Palm Oil	–	–	–	0.05	0.7 mm	Afifah et al. [132]
Biomass	–	–	–	0.057	0.95 mm	Lu et al. [133]
Coconut oil	–	–	–	0.070	0.48 mm	Jayadas et al. [134]
Jatropha oil 6%	–	–	–		361 μm	Masjuki et al. [135]
Rice barn oil Pongamia oil 20%	–	–	–	0.09	0.485 mm	Rani et al. [136]
Moringa oil	–	–	–	0.045	–	Singh et al. [137]
Neem seed oil	–	–	–	0.06	57.014 μm	Menon et al. [138]

Table 4
Summary of nanoparticle properties and their effects in enhancing biolubricants performance.

Nanoparticle properties	Description	Reference
Lubricity Enhancement	Nanoparticles, including graphene, metal oxides (e.g., CuO, ZnO), and carbon nanotubes, facilitate the formation of a protective coating on metallic surfaces. The nanoparticles function by altering the surface interactions between lubricated components, resulting in enhanced operational smoothness and reduced energy loss from friction.	[29,140]
Thermal Stability	Nanoparticles enhance thermal stability, preserving lubricant efficacy at elevated temperatures.	[29,115]
Wear Resistance	They provide protective layers that inhibit metal-to-metal contact, hence improving wear resistance.	[141, 142]
Thermal Conductivity	Nanoparticles enhance thermal conductivity, facilitating superior heat dissipation in electric vehicle applications.	[143, 144]
Tribofilm Formation	Under elevated pressure conditions, nanoparticles facilitate the development of tribofilms—thin layers that serve as a barrier between interacting surfaces. These films markedly diminish wear and improve overall mechanical performance by maintaining the lubricant's integrity under severe stress.	[145, 146]
Rolling Effect	Diamond nanoparticles, due to their spherical morphology, function as nano-rollers between contact surfaces, diminishing friction via a rolling mechanism.	[147, 148]
High Pressure Stability	Nanoparticles maintain stability under elevated pressure and temperature, guaranteeing that lubricant efficacy does not diminish in harsh conditions.	[144]
Additive Concentration	Different concentrations of nanoparticles (e.g., diamond nanoparticles) yield varied effects on friction and wear reduction. For example, a 0.1% concentration may reduce wear by 4%, whereas a 0.5% concentration can reduce it by 30%. The appropriate concentration of nanoparticles is essential to achieving optimal tribological performance.	[26,149]

The coefficient of performance was 0.05 mm, which aligns with the recent assessment reported by Mujtaba et al. [139].

Table 4 presents a comparative analysis of nanoparticle properties and elucidates how dispersed nanoparticles substantially improve biolubricants by enhancing critical attributes such as lubricity, thermal stability, wear resistance, and thermal conductivity. They create protective layers on metal surfaces, minimizing friction and wear, while enhancing thermal stability to prevent degradation at elevated temperatures.

4.2. *Dispersing nanomaterials in biolubricants*

The formulation employs a meticulous two-step method to integrate cutting-edge nanotechnology with eco-friendly materials, resulting in high-performance lubricants with minimal environmental impact [147]. Utilizing nanoparticle compounds as additives presents a sustainable strategy to enhance the efficacy of biolubricants. Their effectiveness in lubricating tribo systems hinges on their morphology, dimensions, chemical properties, and concentration. These attributes determine their effectiveness as active components, primarily aimed at diminishing the coefficient of friction (COF) [29]. Vinay et al. (2020) reported that Polytetrafluoroethylene (PTFE) nanoparticles (NPs) are combined with sulfur present in the base oil to interact with the base metal surface. This interaction forms a stable and durable tribo-film, serving as an extreme-pressure additive (EPA) within the oil. The notable enhancement in EP performance was linked to the chemical interaction between PTFE particles and ball surfaces, resulting in the formation of FeF2 and FeS, as confirmed by XPS analysis. The superior performance observed in the nano-oil derived from API Group I oil was attributed to the synergistic mechanism of film formation facilitated by PTFE and sulfur, both recognized for their effectiveness as extreme-pressure additives [150]. Ong et al. (2022) recently reported that sulfur-based EP additives are more environmentally friendly and biodegradable [151].

Step 1. Dispersing nanoparticles into biolubricants

The initial step involves the precise dispersion of specialized nanoparticles, such as graphene, carbon nanotubes, or functionalized Al_2O_3 nanoparticles, into carefully selected biolubricants. This integration harnesses the inherent friction-reducing properties of nanomaterials while ensuring compatibility with our chosen biodegradable base oil.

Essential actions in step 1.

- Nanoparticle dispersal aims to achieve uniform dispersion of nanoparticles in the biolubricants.
- Compatibility enhancement ensures optimal compatibility between nanoparticles and the biodegradable base oil.

Step 2. Ultrasonication for enhanced stability

Following nanoparticle dispersion, the second step employs ultrasonication to the formed bio-nanolubricant. This technique acts as a precision tool to prevent any agglomeration of nanoparticles, enhancing stability and homogeneity within the lubricant. Ultrasonication is a crucial step to maintain the integrity of the bio-nano lubricant and ensure consistent performance, as suggested by Nugroho et al. [148]. This method has also become familiar and has been adopted by previous researchers, thus establishing it as a

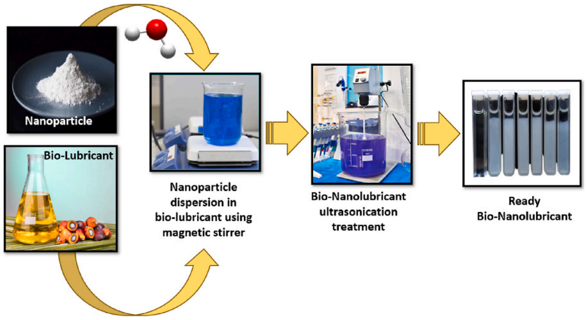

Fig. 16. Two-step method schematic diagram.

common practice for formulating biolubricants reinforced with nanomaterial [152–155]. Fig. 16 displays a schematic diagram illustrating the two-step method.

Essential actions in step 2.

- Ultrasonication homogenizer adoption is subject to preventing agglomeration and improving the stability of the biolubricants nanosuspension.
- Homogeneity assurance is a step to enhance the uniformity of the bio-nanolubricant for optimal performance.
- By combining nanoparticle dispersion with ultrasonication, the two-step formulation method not only maximizes the lubrication potential of nanomaterials but also prioritizes stability and eco-friendliness. This approach results in a bio-nanolubricant that excels in both performance and sustainability, meeting the demands of modern lubrication standards.

4.3. Tribological performance

From a tribology performance perspective, biolubricants and bio-nanolubricants offer promising alternatives to traditional lubricants derived from fossil fuels [156]. Biolubricants, typically sourced from renewable feedstocks such as vegetable oils, demonstrate favorable attributes such as biodegradability, low toxicity, and reduced environmental impact [157]. These lubricants exhibit satisfactory friction reduction and wear protection properties, making them suitable for various industrial applications. On the other hand, bio-nanolubricants, formulated by incorporating nanoparticles into biolubricants matrices, further enhance tribological performance. Nanoparticles such as graphene, carbon nanotubes, and several types of metal oxides improve lubricant film strength, reduce friction coefficients, and enhance load-bearing capacity [158]. This synergistic combination of biolubricants and nanotechnology holds great potential for achieving superior lubrication efficiency, prolonging machinery lifespan, and advancing sustainable tribological solutions in diverse engineering fields.

Rio et al. (2021) demonstrated the efficacy of incorporating two functionalized graphene oxides, namely reduced graphene oxide (rGO) and reduced graphene oxide modified with octadecyl amine (rGO@ODA), along with a phosphonium ionic liquid (IL), as additives into a biodegradable ester base oil (BIOE). Their investigation revealed that the formulation containing one wt% IL and 0.05 wt % rGO achieved the most substantial reduction in friction, amounting to 34%. Utilizing the prepared bio-nanolubricants resulted in

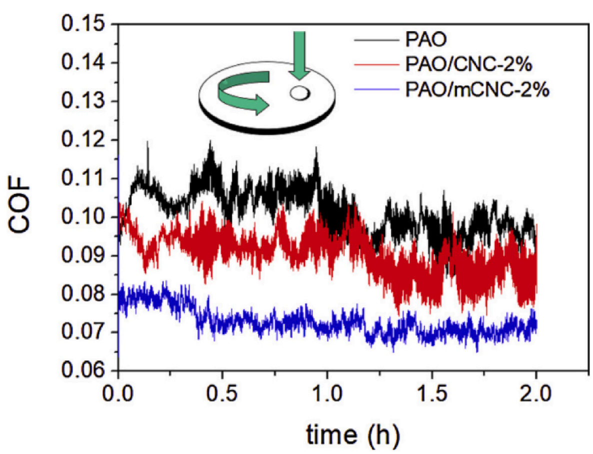

Fig. 17. Results of coefficient of friction evaluation for pure PAO and PAO-CNCs-based lubricants over different time intervals [159]. Reprinted with permission from Elsevier.

decreased wear on discs compared to those lubricated solely with pure BIOE, with the one wt% IL and 0.05 wt% rGO formulation exhibiting the highest reduction (34%) in wear track width [159]. Li et al. (2019) reported that with the increasing environmental protection requirement, the development of lubricating materials with non-toxicity and good biodegradability becomes increasingly significant. Thus, they dispersed cellulose nanocrystals (CNCs) into polyalphaolefin (PAO) base oil as the lubricant additive for tribology performance improvement indicated by the COF reduction. The finding shows that As the PAO/mCNC-2% sample shows the best dispersive stability, it was selected as the lubricant in the following tribological measurement. PAO/CNC-2% and pure PAO were also tested for reference purposes. Fig. 17 depicts the rotary friction test of three oils on steel surfaces. PAO's coefficient of friction (COF) slightly decreased from 0.11 to 0.10 during the testing time (2 h). PAO/CNC-2% showed a smaller COF than pure PAO, which was about 0.09 at the test's end. When PAO/mCNC-2% was applied, the friction was much smaller than the other two samples (COF ≈ 0.07), and the friction curve was much smoother, indicating a weaker stick-slip effect [160].

Additionally, Chen et al. (2022) dispersed a hybrid of protic ionic liquid-modified nanosilica (SiO2-PIL) and triphenyl phosphate (TCP) into pentaerythritol ester vegetable oil. The stability and performance of the resulting lubricant were evaluated in terms of antiwear properties and friction reduction. The results indicate that all additives outperformed the pure oil. However, the formulation containing 0.5% SiO_2-PIL exhibited the highest performance compared to pure oil and other prepared samples. This suggests that an increased fraction of additives does not necessarily guarantee superior performance [161]. Fig. 18 depicts the periodical fluctuation of the coefficient of friction (COF) for various lubricants. The picture directly compares the coefficient of friction (COF) of a base oil (PE base oil) with different quantities of SiO_2-PIL (Silica-Polyionic Liquid) additions, as well as with a conventional anti-wear ingredient, TCP (Tricresyl Phosphate). SiO_2-PIL additions provide superior performance in friction reduction compared to the conventional TCP additive.

This demonstrates the potential of SiO_2-PIL as a highly efficient friction-reducing ingredient in lubricants. Every lubricant exhibits an early decrease in coefficient of friction (COF), which can be ascribed to the creation of a lubricating film or the initial adjustment of the surface to the lubricant. The stabilization of the coefficient of friction (COF) at various levels indicates the consistent and ongoing performance of the lubricant in maintaining a steady condition. The addition of SiO_2-PIL to the base oil greatly enhances its lubricating qualities. The optimum concentration of SiO_2-PIL is approximately 0.7%, which results in the lowest coefficient of friction (COF). Therefore, it can be inferred that SiO_2-PIL is an effective additive for lubrication. Nevertheless, surpassing a SiO_2-PIL concentration of 0.7% does not result in a substantial additional decrease in COF and may even cause a little rise, suggesting that there is a limit to the advantageous effects of the additive. The SiO_2-PIL additive demonstrates superior performance compared to the standard TCP addition in friction reduction, indicating its potential for wider application in lubricants to boost performance. The study substantiates the advancement of SiO_2-PIL for the creation of lubricants that are both more efficient and perhaps more sustainable. This technology aims to decrease energy loss caused by friction and wear.

In 2022, Pratiba et al. [162] integrated TiO_2 into hydroxyl ether-based biolubricants and evaluated their performance using a pin-on-disc tribometer according to ASTM G99 standards. They found that adding 0.05% TiO_2 reduced COF effectively, from 0.06 to 0.04, with similar improvements observed in biolubricants based solely on hydroxyl ether. However, a further increase in TiO_2 concentration to 0.1% led to an elevated COF of approximately 0.25. This trend persisted across different sliding speeds. The reduction in friction attributed to 0.05% TiO_2 was likely due to nanoparticle adsorption on the metal surface. The fatty acid composition of biolubricants is essential in reducing surface wear by creating a protective barrier that prevents direct contact between metal surfaces. This layer functions as a tangible obstacle, effectively diminishing friction and augmenting the total lubricating efficacy. Nevertheless, the absence of further reduction in friction beyond a concentration of 0.05% additive indicates that the protective layer achieves its maximum thickness at this particular point. Once a certain point is reached, additional additives may not enhance the creation of more layers and could potentially compromise the integrity of the existing layer. The finding is in-line with the Cao et al. [163] discovery

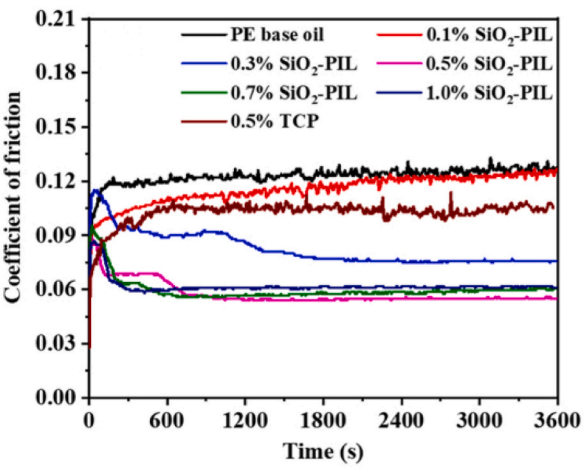

Fig. 18. Time-dependent coefficient of friction curves observed during the lubrication of pentaerythritol ester (PE) with 0.5% TCP or varying concentrations of SiO_2-PIL [161]. Reprinted with permission from Elsevier.

which states that lubricants reduce friction and heat in mechanical systems. The plateau effect emphasizes the need of attaining the optimal equilibrium between additive content and lubricating efficiency, emphasizing the requirement for meticulous formulation in the creation of biolubricants. Gaining a comprehensive understanding of these systems provides useful insights into why surpassing a specific threshold of additive concentrations may not lead to enhanced outcomes. as illustrated in Fig. 19.

Ruliandini et al. [164] investigated the behavior of MXene nanoparticles within a palm oil methyl ester (POME)-based bio-lubricant. They reported by incorporation of MXene nanoparticles into bio-lubricants, specifically within a palm oil methyl ester (POME)-based lubricant, has a notable impact on enhancing tribological performance, which refers to the friction, wear, and lubrication characteristics of interacting surfaces. The research reveals that MXene contributes to improved thermal properties, which is crucial for maintaining lubricant performance under varying temperatures and reducing wear on mechanical components. However, the study also highlights a challenge: while MXene enhances these properties, it can introduce instability in the nanolubricants, potentially increasing friction due to nanoparticle aggregation. Despite this, the molecular dynamic simulations provide valuable insights into how MXene layers interact within the bio-lubricant. The findings show that MXene layers, particularly those with three layers (POMEX3), exhibit the highest self-diffusion coefficient, indicating better dispersion and less aggregation within the lubricant. This improved dispersion is critical as it reduces the likelihood of nanoparticle clustering, which is a major factor in increased friction and wear. The strong interlayer coupling observed in MXene layers, especially in odd-numbered configurations, leads to more stable and resilient lubricants, which can sustain better tribological performance over time. MXene's ability to enhance thermal properties, coupled with its stable behavior in specific configurations, can significantly improve the overall tribological performance of bio-lubricants. This can lead to reduced friction, lower wear rates, and extended lifespan of mechanical components, making MXene an attractive additive for the development of high-performance, environmentally friendly lubricants.

Ahmad et al. [33] successfully produced a high-yield biolubricant (94%) from castor oil using Fe_3O_4 nanoparticles and ethylene glycol in a transesterification process, optimized at 160 °C with a FAME/alcohol ratio of 2:1 and 1% w/v catalyst concentration. The addition of these nanoparticles significantly improved the biolubricant's physiochemical properties, with the formulation of MCSO, ethylene glycol, and 0.5% Fe_3O_4 nanoparticles demonstrating the lowest coefficient of friction (nearly 50% reduction) and a 40% decrease in wear compared to raw castor oil and other samples. The biolubricant yield was accurately predicted using an artificial neural network (ANN) model, which showed a strong linear correlation between output and target values across various conditions, including temperature, catalyst loading, and alcohol/FAME ratios. The ANN models proved effective in predicting biolubricant yield, with the sensitivity analysis indicating that catalyst loading, and alcohol/FAME ratios had a greater impact on yield than temperature. The introduction of Fe_3O_4 nanoparticles and ethylene glycol into castor oil-based biolubricant formulations provides significant tribological benefits, particularly in terms of friction and wear reduction. According to the study, the improved biolubricant formulation (MCSO, ethylene glycol, and 0.5% Fe_3O_4 nanoparticles) reduced the coefficient of friction by approximately 50% when compared to raw castor oil and other evaluated biolubricants. This significant decrease in friction means that mechanical components using this biolubricant will encounter less resistance during movement, resulting in more efficient operation and lower energy usage.

Furthermore, the biolubricant reduced wear by 40%, which is crucial for extending the life of machines and lowering maintenance expenses. The improved wear resistance suggests that the biolubricant creates a more effective protective layer between moving elements, reducing direct contact and surface degradation over time. These improvements in tribological performance, owing to the enhanced formulation and inclusion of nanoparticles, make the biolubricant ideal for applications requiring low friction and wear, resulting in more reliable and lasting mechanical systems.

Agarwal et al. [165] investigated the synthesis and characterization of a nanoadditive formed by functionalizing graphene oxide (GO) with hexadecanol (HD) and evaluates its effectiveness in enhancing the performance of mineral base oil. The GO-HD nanoadditive was found to improve the lubricant's viscosity index and pour point while exhibiting significant tribological benefits, including a 9.5% reduction in wear scar diameter (WSD) and an 11.8% decrease in the coefficient of friction (COF). The study confirms the thermal stability and good dispersion of the nanoadditive in the base oil, attributing the performance improvements to the weak van der Waals interactions between the lamellas of GO-HD, which effectively reduce friction and wear. The enhanced tribological

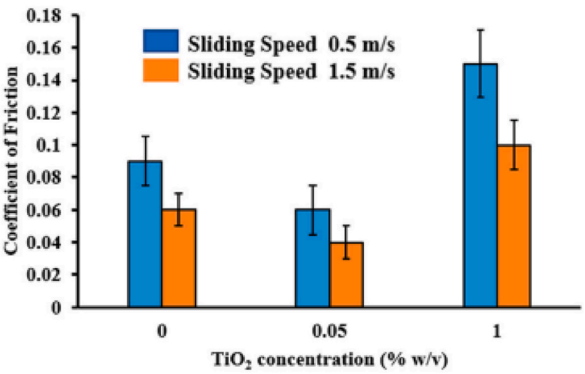

Fig. 19. Effect of additive TiO_2 and Sliding speed on the Coefficient of friction of the bio-nanolubricants [162]. Reprinted with permission from Elsevier.

performance of the GO-HD nanoadditive in the lubricant can be explained by the following mechanisms. Adding graphene oxide (GO) functionalized with hexadecanol (HD) enhances the lubricant's physicochemical qualities. The enhanced viscosity index allows the lubricant to retain a consistent viscosity across a wide temperature range, whereas the reduced pour point keeps the oil fluid at lower temperatures, improving its performance under various operating conditions. The GO-HD nanoadditive modifies the lubricant's rheological properties, resulting in non-Newtonian behavior. This change helps to generate a more stable and effective lubricating coating between the contacting surfaces. The weak van der Waals interactions between the GO-HD layers reduce shear resistance in the lubricant, lowering the coefficient of friction (COF). Besides, the nano-additive's ability to reduce friction also contributes to decreased wear. The GO-HD layers act as a protective barrier, reducing direct metal-to-metal contact between the surfaces. This protective layer minimizes surface damage and wear, resulting in a lower wear scar diameter (WSD).

Singh et al. [166] investigated the effects of copper nanoparticles as additives in biolubricants, finding that up to 0.9% concentration significantly improves tribological properties by forming an effective boundary lubricant film and enhancing physicochemical characteristics. However, higher concentrations beyond 0.9% decrease performance, highlighting the optimal nanoparticle concentration for maximizing lubricant efficacy. The addition of up to 0.9% copper nanoparticles greatly improves the tribological properties of the biolubricant. This concentration creates an efficient boundary lubricant coating that can tolerate applied loads, enhancing tribological performance over mineral oil. However, performance peaks at 0.9% copper, with the maximum coefficient of friction (COF), wear, and wear scar diameter measured at 1.25 m/s sliding speed and 95 N maximum load. The mechanism of copper into lubricant can increase the tribological performance can be discussed as follows: copper nanoparticles contribute to the formation of a boundary lubricant film between the contacting surfaces. This film is a protective layer that reduces direct metal-to-metal contact, minimizing friction and wear. The nanoparticles help in stabilizing this film, making it effective under varying loads and speeds. Copper nanoparticles, at suitable quantities, boost the biolubricant's viscosity index. Higher viscosity aids in maintaining a uniform lubricant layer thickness under various operating situations, enhancing the lubricant's capacity to carry loads and protect surfaces. Copper nanoparticles, at suitable quantities, boost the biolubricant's viscosity index. Higher viscosity aids in maintaining a uniform lubricant layer thickness under various operating situations, enhancing the lubricant's capacity to carry loads and protect surfaces. The nanoparticles interact with the surfaces in contact, potentially filling in micro-asperities and reducing surface roughness. This interaction further contributes to lower friction and reduced wear, as the nanoparticles help in smoothing out irregularities on the surfaces. However, the addition of 0.9% nanoparticles into biolubricant leads to the decrease of tribological performance, which can be explained as follows. At concentrations above the optimal 0.9%, copper nanoparticles may begin to agglomerate or cluster. This agglomeration can disrupt the uniform distribution of nanoparticles in the lubricant, leading to inconsistent lubrication and decreased effectiveness in forming a protective film. Increased Viscosity and Flow Issues: Excessive nanoparticle concentration can lead to an overly high viscosity, which may hinder the lubricant's flow properties. This can increase resistance to movement and poor film formation, potentially causing higher friction and wear instead of reducing them.

Later, Singh et al. [167] examined the application of alumina (Al_2O_3) nanoparticles in polanga oil (*Calophyllum inophyllum*) to enhance its lubricating characteristics. The results indicated that a nanoparticle concentration of 0.075% was the most effective, resulting in the lowest coefficient of friction (COF) and wear rates and a smoother pin surface compared to using only polanga oil. At this specific concentration, nanoparticles functioned efficiently as spacers resembling ball bearings, resulting in a decrease in both friction and wear. However, when the nanoparticle concentration was increased to 0.1%, it led to higher levels of friction and wear. This was caused by the probable clumping together of the nanoparticles and their inadequate dispersion. Scanning Electron Microscopy (SEM) confirmed that the pin's surface quality was optimal when the concentration was at 0.075%. In addition, when the rotational speed was changed from 200 to 800 revolutions per minute (rpm), it was noticed that the coefficient of friction (COF) reduced as the speed increased. The lowest COF was recorded at 800 rpm, while the maximum COF was observed at 200 rpm. The decrease in contact duration between sliding surfaces at greater speeds is the reason for this reduction. The addition of nanoparticles to polanga oil, which already possesses unsaturated fatty acids that aid in forming a protective layer, resulted in an enhanced lubricating effect by increasing the longevity of this layer. Once the concentration of nanoparticles exceeded 0.075%, their clumping caused a rise in the COF, which in turn hindered their dispersion. These findings are consistent with prior research, emphasizing the importance of achieving the ideal concentration of nanoparticles to improve the effectiveness of lubricants. Subsequent investigations should examine the impacts of diverse nanoparticles and concentrations in different non-edible oils to enhance lubrication efficiency.

Gulzar et al. [168] explored the improvement of the anti-wear (AW) and extreme pressure (EP) characteristics of chemically modified palm oil (CMPO) by adding nanoparticles, specifically copper(II) oxide (CuO) and molybdenum disulfide (MoS_2). The findings indicated that both categories of nanoparticles enhanced the AW/EP characteristics by 1.5 times, with MoS_2 exhibiting greater efficacy than CuO. The tribological experiments, including four-ball and piston ring on cylinder liner evaluations, indicated that nanolubricants supplemented with MoS_2 exhibited improved lubrication characteristics and a more uniform dispersion. The wear protection methods differed based on the contact geometry and testing conditions, with tribosintering in non-conformal geometries and creating tribofilms in conformal tests. In addition, including 1 wt% oleic acid as a surfactant enhanced the dispersion of nanoparticles by decreasing the formation of agglomerates, resulting in less wear. In general, MoS_2 nanoparticles exhibited superior efficacy in improving the lubricating properties of CMPO, with the addition of oleic acid further enhancing its performance.

The mechanism of wear reduction due to the addition of nanoparticles (CuO and MoS_2) to chemically modified palm oil (CMPO) can be explained as follows Nanoparticles serve as solid lubricants within the CMPO. Upon dispersion in the oil, these substances create a thin and defensive layer on the metal surfaces. This film is a protective layer, diminishing direct contact between metal surfaces, lowering friction, and minimizing wear. The Ball-Bearing Effect refers to the behavior of nanoparticles, particularly MoS_2, which act as little ball bearings when present in lubricants. They aid in separating the surfaces that come into contact, lowering friction by limiting the contact between them. This segregation also reduces the probability of surface erosion. The production of protective tribofilms is facilitated by CuO and MoS_2 nanoparticles on the contact surfaces. Tribofilms are thin layers that develop due to the interaction between nanoparticles and surfaces. These coatings offer further protection by providing a cushioning effect on surfaces and minimizing wear and tear. MoS_2 exhibits exceptional efficacy in producing durable and consistent tribofilms, augmenting the safeguard against wear. This phenomenon occurs and is in line with the previous researcher's findings [169–171].

The mechanism behind incorporating nanomaterials into biolubricants to enhance their tribological performance, particularly in terms of anti-wear and friction reduction, involves several key factors: (i) *surface smoothing and protection,* nanoparticles dispersed within the biolubricants can adhere to the surface of the contacting materials, smoothing out roughness and irregularities. This layer acts as a protective barrier, reducing direct contact between mating surfaces and thereby minimizing wear; the regime allows the changing of sliding into rolling movement; (ii) *load-bearing capacity,* nanomaterials possess unique mechanical properties, such as high strength and hardness. When dispersed in the biolubricants, they can enhance the load-bearing capacity of the lubricant film, preventing metal-to-metal contact under high-pressure conditions and reducing wear in dynamic motion [172]; (iii) boundary lubrication enhancement, nanoparticles can migrate to the surface of the contacting materials, forming a boundary layer that reduces friction by providing additional lubrication at the interface. This boundary lubrication helps to maintain a separation between the surfaces, thereby decreasing frictional forces; (iv) *chemical interaction,* some nanomaterials exhibit chemical reactivity with the surfaces of the contacting materials. This interaction can lead to the formation of protective surface films or tribo-chemical reactions that further reduce wear and friction; (v) *temperature and oxidation stability,* specific nanomaterials possess thermal and oxidative stability properties, which can enhance the performance of biolubricants at elevated temperatures and in oxidative environments. This stability helps to maintain the lubricant's effectiveness over extended periods, contributing to improved tribological performance, as reported by the previous researchers [16,173,174].

Fig. 20 illustrates that both metal surfaces appear smooth and flat to the naked eye but are not entirely smooth and flat on a microscale. The surfaces exhibit topographical features consisting of various peaks and valleys along their surfaces. Schematic lubrication using pure biolubricants allows these surfaces to experience direct friction, particularly when the metal surfaces are subjected to pressure during specific rotational directions while in operation. The friction between each peak and valley promotes surface wear on specific components. Under high-temperature operating conditions, the viscosity of the biolubricants decreases drastically, leading to a sliding friction scheme between the two metal surfaces that promotes wear up to severe damage. Severe damage will not occur on mechanical components adopting nano-lubricants. Despite the pressure exerted on the metal surfaces and the operation at high temperatures, nanomaterials that have been perfectly dispersed within the biolubricants can transform the sliding effect into rolling, thus reducing the coefficient of friction. Additionally, nanomaterials fill the gaps in the peaks and valleys along the metal surfaces, as observed in Fig. 21. This prevents direct friction between the surface material peaks, mitigating wear on the metal surfaces.

Understanding that biolubricants is derived from renewable biological sources such as plant oils, are increasingly recognized for their environmentally friendly attributes. Unlike traditional petroleum-based lubricants, biolubricants are biodegradable and non-toxic, significantly reducing the risk of environmental contamination, particularly in sensitive ecosystems [175]. Their production and use contribute to lower carbon emissions, as they are derived from renewable resources that can be sustainably managed. Additionally, biolubricants often have a higher flash point and better lubricity, leading to reduced energy consumption and extended equipment life, further enhancing their environmental benefits [158]. By integrating biolubricants into industrial and automotive applications, we can reduce our dependence on fossil fuels and promote a more sustainable approach to lubrication that aligns with global efforts to mitigate climate change and protect natural resources.

Employing palm oil as a biolubricants also has important societal ramifications, especially in areas where palm oil output is a main economic driver. For millions of smallholder farmers and workers in rural areas, the growing palm oil sustains livelihoods in many developing nations by offering income and jobs [176]. Still, it's important to take care of the social obligations connected to the production of palm oil, like guaranteeing fair labor standards, advancing equal land use, and endorsing sustainable farming practices. Adopting ethical sourcing and sustainability criteria helps to minimize negative effects on local ecosystems and communities while nevertheless enabling the use of palm oil as a biolubricant to help social development [158].

5. Statistical analysis: multiple regression analysis

Table 5 reflects the strong explanatory and predictive power of the regression models, showing the significant impact of

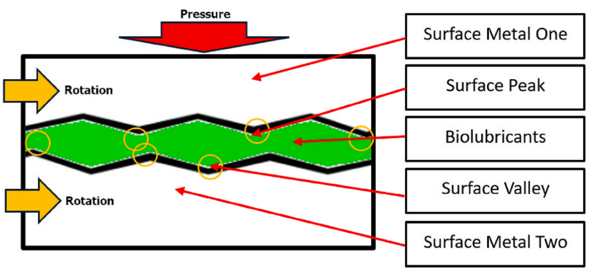

Fig. 20. Lubrication schematic using biolubricants.

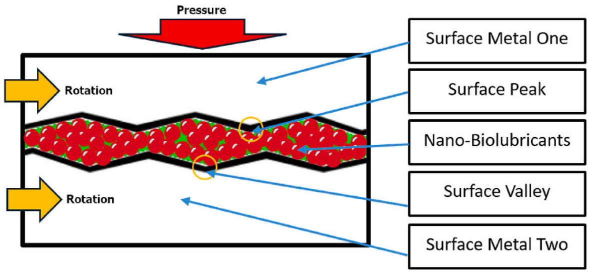

Fig. 21. Lubrication schematic using nano-biolubricants.

Table 5
Multiple regression analysis output.

Dependent Variable	Independent Variable	Coefficient	Standard Error	t-Statistic	p-Value	R^2	Adjusted R^2	Predicted R^2	Significance
COF	Constant	0.0007	0.000	4.730	0.005	0.998	0.997	0.998	Significant
	Nanoparticle Concentration	−0.0218	0.001	−15.588	<0.001	0.998	0.997	0.998	Highly Significant
	Temperature	0.0005	2e-05	25.202	<0.001	0.998	0.997	0.998	Highly Significant
	Base Lubricant Type (PSME/Palm Oil)	0.0032	0.001	3.899	0.011	0.998	0.997	0.998	Significant
	Catalyst Concentration	0.0025	0.000	16.207	<0.001	0.998	0.997	0.998	Highly Significant
	Reaction Time	0.0026	0.000	18.103	<0.001	0.998	0.997	0.998	Highly Significant
WSD	Nanoparticle Concentration	−0.0218	0.001	−15.588	<0.001	0.998	0.997	0.998	Highly Significant
	Temperature	0.0005	2e-05	25.202	<0.001	0.998	0.997	0.998	Highly Significant
	Base Lubricant Type (PSME/Palm Oil)	0.0111	0.001	13.478	<0.001	0.998	0.997	0.998	Highly Significant
	Catalyst Concentration	0.0062	0.000	24.946	<0.001	0.998	0.997	0.998	Highly Significant
	Reaction Time	0.0026	0.000	18.103	<0.001	0.998	0.997	0.998	Highly Significant

nanoparticle concentration, temperature, and other factors on COF and WSD.

The results of the multiple regression analysis indicate that all independent variables—nanoparticle concentration, temperature, base lubricant type (PSME/Palm Oil), catalyst concentration, and reaction time—highly significant effects on both the coefficient of friction (COF) and wear scar diameter (WSD). The negative coefficient of nanoparticle concentration signifies a decrease in both COF and WSD, implying that increased nanoparticle concentrations enhance tribological performance. The coefficients for temperature, catalyst concentration, and reaction time are all positive, indicating that increases in these variables result in elevated COF and WSD values. The type of base lubricant influences performance, however this effect varies according to the individual tribological parameter, such as coefficient of friction (COF) or wear scar diameter (WSD).

There are five independent variables analyzed in this section, they are nanoparticle concentration, temperature, base lubricant type (PSME/Palm Oil), catalyst concentration, and reaction time. In terms of nanoparticles concentration, for both COF and WSD, the negative coefficient (−0.0218) signifies that an increase in nanoparticle concentration results in a substantial reduction in both friction and wear. This indicates that nanoparticles are essential in diminishing friction and wear, hence improving the lubricant's overall efficacy. The link is significant (p-value <0.001), indicating that the influence of nanoparticle concentration on COF and WSD is statistically robust. Regarding the temperature, a modest yet positive coefficient (0.0005) for both COF and WSD indicates that when temperature rises, there is a little escalation in friction and wear. Although the effect size is modest, it is statistically significant (p-value <0.001), suggesting that temperature affects tribological performance, albeit to a smaller degree than certain other variables [177]. This is significant as it indicates that elevated operating temperatures may result in heightened wear and friction, however the impact is effectively controlled. Base Lubricant Type (PSME/Palm Oil): The coefficient for base lubricant type is positive (0.0032 for COF and 0.0111 for WSD), suggesting that the choice of base oil also impacts friction and wear. For WSD, the effect is more pronounced compared to COF, indicating that the type of base oil has a greater impact on wear reduction than on friction. This finding is statistically significant (p-value <0.05 for COF and <0.001 for WSD), implying that selecting the right base oil is critical in optimizing lubricant performance. The positive coefficient (0.0025 for COF and 0.0062 for WSD) shows that increasing catalyst concentration leads to higher friction and wear [178]. This might suggest that while catalysts can enhance the chemical reactivity in the lubricant formulation, they can also lead to increased wear, possibly due to interactions with the metal surfaces. The effect is highly significant (p-value <0.001), indicating that careful control of catalyst concentration is important to avoid diminishing the lubricant's effectiveness. Lastly, when it comes to reaction time, it also has a positive coefficient (0.0026 for both COF and WSD), meaning that longer reaction times lead to higher friction and wear. This could be related to extended exposure of the lubricant to operating conditions, which may cause deterioration in its tribological properties. Like the other variables, this effect is highly significant (p-value <0.001), underscoring the need to optimize reaction time in lubricant formulations.

Overall, the model is reliable, with R^2 values of 0.998 for both COF and WSD, meaning that 99.8% of the variability in friction and wear can be explained by the included variables. The adjusted R^2 and predicted R^2 values confirm the model's robustness. All the independent variables show statistically significant impacts on tribological performance, with nanoparticle concentration being the most impactful in reducing friction and wear, while temperature, catalyst concentration, and reaction time increase them as reported by previous researchers [178–180]. Base lubricant choice also affects performance, especially wear. The results highlight the necessity of optimizing nanoparticle concentration and precisely regulating temperature, catalyst concentration, and reaction duration to improve the efficacy of biolubricants in minimizing friction and wear across diverse applications.

6. Biolubricants drawbacks

Oxidative stability is a fundamental characteristic of biolubricants that can present a notable disadvantage. Oxidative stability is the term used to describe a lubricant's capacity to withstand deterioration when exposed to oxygen, heat, and other oxidative conditions. Several factors can limit the oxidative stability of biolubricants. Biolubricants, commonly obtained from natural oils like vegetable or animal fats, contain unsaturated fatty acids and other reactive chemicals susceptible to oxidation. Unsaturated fats possess double bonds that have the ability to undergo a chemical reaction with oxygen, resulting in the creation of peroxides and other products of oxidation. Biolubricants are more prone to oxidative deterioration than synthetic lubricants. Oxidative degradation causes the lubricant's chemical structure to break down, resulting in higher viscosity, the creation of sludge and varnish, and a reduction in lubricating abilities. This diminishes the longevity of the lubricant and requires more frequent changes, which might incur significant expenses and cause inconvenience. When biolubricants undergo oxidation, their performance qualities decrease, including lubricating ability, anti-wear properties, and corrosion resistance. These lubricants can harm the efficiency and lifespan of machinery and engines that depend on them. To overcome these limitations, creating biolubricants with enhanced oxidation resistance is necessary. This can be achieved by using more stable raw materials, incorporating sophisticated additives, and optimizing manufacturing techniques. Technological advancements and improvements in the formulation can effectively address these problems and significantly improve the performance and dependability of biolubricants.

7. Limitation of study

The limitations of this study primarily stem from the variability of biolubricant formulations, especially in terms of their thermal stability and long-term performance in electric vehicle applications. Despite significant enhancements observed with the use of nanoparticle additives, there remain challenges in ensuring consistent dispersion and preventing nanoparticle aggregation over extended periods of operation. This phenomenon may reduce the efficacy of the nanolubricants, particularly under extreme temperature fluctuations experienced in electric drivetrains.

Furthermore, the study's scope was limited to specific concentrations of nanoparticle additives and particular operating conditions. Extensive evaluation in real engines is essential to determine the actual performance and efficacy of these nanoparticle-enriched biolubricants under real-world operational conditions. Additionally, further analysis of vibration effects is necessary to ensure that the biolubricants can maintain their performance and stability during long-term use. This evaluation is crucial to confirm the suitability of these formulations for widespread adoption in electric vehicles, especially under prolonged mechanical stress and variable operational environments.

8. Future trends and research directions

Future trends and research directions for biolubricants focus on several key areas to enhance their performance, sustainability, and applicability. Some of these trends and directions include.

8.1 Future research should prioritize the optimization of nanoparticle formulations, specifically graphene and metal oxides, by fine-tuning their kinds and concentrations. This will lead to significant improvements in the tribological properties of biolubricants derived from palm oil. This involves examining the combined impacts of various nanoparticle combinations in order to attain the most minimal coefficients of friction and rates of wear.

8.2 Enhancement of oxidative stability; further investigation is needed to develop enhanced techniques for improving the oxidative stability of biolubricants derived from palm oil. This could involve including innovative antioxidants or stabilizing agents. By subjecting these biolubricants to different operating circumstances, especially in high-temperature situations commonly found in electric vehicles, their long-term durability will be guaranteed.

8.3 Additional research is required to improve the capacity of nanoparticle-enriched palm oil-based biolubricants to break down naturally, while yet maintaining their effectiveness. This may entail the creation of novel biodegradable additives or the utilization of altered palm oil derivatives that decompose more easily in the environment.

8.4 A comprehensive evaluation should be conducted to determine the compatibility of these biolubricants with different electric vehicle components, such as seals, bearings, and gears. It is essential to ensure that the lubricants do not cause any material deterioration or negative reactions with other automotive fluids to promote their wider use.
8.5 Expanding the scope of Life Cycle Analysis (LCA) to encompass a wider array of environmental consequences, including water usage, land use, and end-of-life disposal, will yield a more comprehensive assessment of the sustainability of these biolubricants. It is necessary to undertake comparative studies with various biolubricants and conventional lubricants.

These future research directions aim to guide the development of more effective, sustainable, and widely adopted palm oil-based biolubricants, ultimately contributing to the advancement of green automotive technologies.

9. Conclusions

This study demonstrates that nanoparticle-enriched palm oil-based biolubricants significantly improve the tribological performance required for electric vehicle (EV) applications, offering enhanced thermal stability, friction reduction, and wear resistance. These improvements are crucial for the long-term efficiency and reliability of EV components, especially under the high-temperature and high-pressure conditions typical of EV drivetrains and bearings.

The practical implications of these findings are far-reaching. By integrating sustainable, plant-derived oils with advanced nanomaterials, the study provides a viable alternative to conventional, fossil fuel-based lubricants. Palm oil-based biolubricants, enriched with nanoparticles such as TiO_2 and ZnO, not only reduce wear and extend maintenance intervals but also contribute to the overall energy efficiency of EVs. The use of these lubricants can lower energy losses due to friction, improve heat dissipation, and enhance the lifespan of critical components, ultimately reducing the environmental impact and operational costs of EVs.

These results represent a significant step forward in advancing sustainable practices in the automotive industry. The adoption of eco-friendly nanolubricants aligns with global efforts to reduce dependency on non-renewable resources, lower greenhouse gas emissions, and promote the use of biodegradable materials. Thus, nanoparticle-enriched palm oil-based biolubricants hold great promise for the future of sustainable lubrication in electric vehicles and contribute directly to the broader goals of green automotive technology.

CRediT authorship contribution statement

Agus Nugroho: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft. **Muhammad Kozin:** Conceptualization, Methodology, Resources, Supervision. **Rizalman Mamat:** Methodology, Validation, Writing – review & editing. **Zhang Bo:** Formal analysis, Funding acquisition, Supervision. **Mohd Fairusham Ghazali:** Validation, Writing – review & editing. **Muhammad Prisla Kamil:** Data curation, Methodology, Writing – review & editing. **Prabowo Puranto:** Methodology, Resources, Writing – review & editing. **Diah Ayu Fitriani:** Data curation, Software, Visualization. **Siti Amalina Azahra:** Data curation, Visualization. **Kusuma Putri Suwondo:** Formal analysis, Investigation. **Putri Sayyida Ashfiya:** Data curation, Software. **Sarbani Daud:** Formal analysis, Investigation, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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