Type of contribution:
Editorial
Research Paper
Case Study
▶ Review Paper
Scientific Data
Report of Tech. Application

mesi
e-issn. 2798-5245
Mechanical Engineering for Society and Industry
Vol. 4, No. 3 (2024) pp 535-555
Special Issue on Technology Update 2024
https://doi.org/10.31603/mesi.12549

Mapping the landscape of WCO biolubricant studies: A Comprehensive bibliometric review with vosviewer

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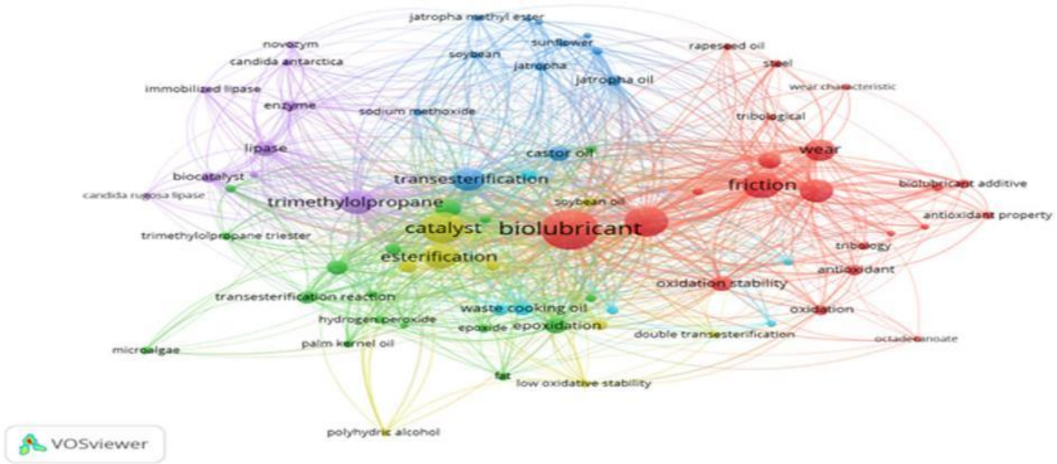
This article contributes to:

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

SUSTAINABLE DEVELOPMENT GOALS



Highlights:
- Focus on biolubricants from Waste Cooking Oil O (WCO).
- Significant increase in research from 2018 to 2022.
- Malaysia and India are top contributors to the field.
- Key trends: transesterification, oxidation stability, catalysis.
- WCO biolubricants offer eco-friendly alternatives to petroleum lubricants.

Article info

Submitted:
2024-10-26

Revised:
2024-12-29

Accepted:
2024-12-30

Publisher
Universitas Muhammadiyah Magelang

Abstract

This study explores the growing field of biolubricants as sustainable alternatives to petroleum-based lubricants. This paper highlights the gap in the current literature regarding biolubricants from Waste Cooking Oil (WCO) using a mixed-methods approach of bibliometric analysis and systematic literature review (SLR). A bibliometric analysis was conducted using data from the Scopus database, covering 650 publications from 2000 to 2024. Furthermore, a systematic literature review provides a comprehensive analysis of the methods used for synthesizing biolubricants from WCO, particularly evaluating the types of catalysts and methods employed that influence the physicochemical properties. The findings show a significant increase in research activity from 2018 to 2022, with Malaysia and India leading in this area. Key research trends identified include catalysts, oxidation stability, and transesterification processes. Optimal conditions for biolubricant production from WCO were achieved using an Amberlyst catalyst at 81°C, yielding a 99% conversion rate. These results highlight the potential of WCO-derived biolubricants to support more sustainable industrial applications. This study is the first to combine bibliometric analysis and systematic literature review methods to provide a comprehensive overview of research on WCO-based biolubricant production. Through a systematic review of existing studies, this research provides a useful resource for industry professionals and renewable energy policymakers in their efforts.

Keywords: Biolubricant; Bibliometric analysis; Catalyst; SLR; WCO

1. Introduction

Lubricants largely determine engine performance because they play an essential role in minimizing surface friction [1]. Lubricants reduce friction and wear between contacting surfaces [2]. Additionally, they aid in dissipating heat and removing foreign particles that accumulate in the operational area [3]. In addition to reducing wear, the main functions of lubricants are to maintain stability during operation, extend component lifespan, and improve engine efficiency [4]. Lubricants are composed of 70–99% base stock, with the remaining 1–30% being performance-enhancing additives [1]. Oxidative stability, lubricity, and low-temperature flow are the essential characteristics of lubricants. Lubricants can generally be categorized as either mineral-based or biolubricants, depending on the type of base oil used [5]. Traditional lubricants are primarily derived from petroleum and are extensively used globally [6]. The heavy reliance of the industrial and automotive sectors on these environmentally unfriendly lubricants, along with the fast depletion of petroleum reserves, has created an urgent need for sustainable alternatives to promote economic development and environmental sustainability [7].

Global lubricant demand has averaged 40 million metric tons in the last decade. Almost more than 95% of global demand is dominated by petroleum-based lubricants. The composition of oil from petroleum base ingredients consists of alkanes (waxes), paraffins, aromatics, olefin chains, alicyclics (naphthenates), and a high concentration of heteroatoms, especially sulfur, which makes them environmentally unfriendly [8]. Mineral oil has a high viscosity; unfortunately, low molecular weight components often evaporate, so this lubricating oil thickens over time. With the same viscosity, natural oil has a higher flash point than mineral oil due to these high molecular weight compounds [8]. The cost of petroleum products rises annually because of the quick depletion of oil reserves. Moreover, various environmental and health problems are caused by petroleum-based lubricants, such as water contamination that is toxic and non-biodegradable, as well as soil pollution [9].

Bio-lubricants serve as effective alternatives to petroleum-based lubricants due to their desirable properties. These renewable oils contain aromatics, minimal sulfur, high flash point, low volatility, high lubricity, and a high viscosity index [10]. They are biodegradable and non-toxic to the ecosystem [11]. Bio-based lubricants present a viable alternative to petroleum-based lubricants, providing similar technical properties while being environmentally friendly [11]. The heavy dependence of the industrial and automotive sectors on petroleum-based lubricants, which have ecologically harmful raw materials, has highlighted the necessity for sustainable alternatives to promote economic growth and environmental sustainability [1]. Using biodegradable lubricants lessens environmental harm when disposing of used lubricants or dealing with accidental spills [11].

Vegetable oils mainly contain triglycerides, including free fatty acids, tocopherol, and diglycerol, chains of fatty acids, and their derivatives. When applied to protect interfaces, the triglyceride structure is especially suitable for boundary lubrication, while fatty acid chains are especially suitable for increasing the strength of the surface layer [8]. Polyol esters, essential components of biolubricants, can be synthesized from rapeseed oil, [12], Karanja oil [13], Calophyllum inophyllum L oil [14], [15], canola oil [16], Palm oil [11], soybean oil [17], coconut oil [18], jatropha seed oil and castor oil [19],[20], sunflower oil [21], rice bran and karanja oil [3], mustard seed oil [22], safflower oil [23], cottonseed oil [24], Tilapia fish fat [25] beef tallow [26], WCO- Callophyllum inophyllum [27], and WCO [28].

Handling waste from Waste Cooking Oil (WCO) frequently poses considerable challenges. Incorrect disposal of WCO can result in environmental harm and financial setbacks [29]. Although it has drawbacks, including elevated water content and free fatty acid (FFA) levels, WCO holds great potential as a raw material for bio-oil [30]. Utilizing WCO as an affordable raw material for animal feed production, eco-friendly solvents, fermentation products, biolubricants [31], and biodiesel [32]. Recently, several technologies have been developed to reuse WCO as a raw material for biofuels and biolubricants. Several techniques used for synthesizing used cooking oil into biolubricants include the double transesterification method [28], hydrolysis [33], and epoxidation [34].

Literature on biolubricant production is relatively abundant, but it involves various feedstocks and synthetic methods for biolubricants. Although there has been progress in research outcomes, no bibliometric analysis has focused explicitly on biolubricants from WCO. This study aims to fill the gap in the literature, specifically focusing on WCO biolubricants. Furthermore, this study provides insights into the potential and challenges of WCO as a biolubricant through bibliometric analysis and a systematic literature review (SLR). The primary objective of this study is to analyze research trends in the Scopus database from 2000 to 2024, encompassing 650 papers using VOSviewer and visualizing the findings. This study maps the collaborative network and identifies influential institutions, the most cited researchers, and the countries that publish the most on biolubricants. This paper is structured in the following order: Section 2 describes the research methodology. Section 3 covers the findings from the bibliometric analysis. while Section 4 outlines the Results of the systematic literature review. Section 5 offers the research conclusions.

2. Methods

2.1. Scientific Literature Search

This research performed a comprehensive bibliometric analysis to evaluate the existing studies on the possible use of WCO for biolubricant production. In June 2024, the Scopus Core Collection (www.scopus.com) was searched to evaluate the worldwide scientific output on WCO lubricants. The initial collection of relevant data was carried out for the bibliometric evaluation. The literature review for biolubricants was performed using a single database: Scopus. The reasons for selecting this database are as follows. First, Scopus offers a broad range of coverage, including numerous publishers, and is a significant platform for indexing scientific articles and various papers worldwide. Additionally, Scopus allows searches across multiple disciplines, either broadly or by narrowing the search to specific fields like title, abstract, and keywords, using predefined keywords. Additionally, the most significant citation and abstract database for peer-reviewed literature can be found on Scopus, which provides detailed information for each reference.

After choosing the database, relevant keywords were identified to select representative articles, with "biolubricant" being the primary keyword for this study. Initially, keyword selection was based on a preliminary review of existing biolubricant literature. Additional inclusion criteria were applied along with keyword searches to refine the paper selection process. Refined keywords were used to select subject areas and research fields in Scopus to find more pertinent documents. Only papers written in English were chosen due to their prevalence in bibliometric analysis. The search focused on articles, reviews, and early access materials published from 2000 to June 2024. Using the "ABS, TITLE, OR KEYWORDS" fields in Scopus, the search yielded 650 documents for all types of feedstocks biolubricant and 22 documents for WCO biolubricant. However, this study excluded non-article and non-review documents and regionally based scientific papers. The retrieved papers were imported and converted to RIS format for bibliometric analysis using VOSviewer. The search criteria in the review paper are shown in Figure 1.

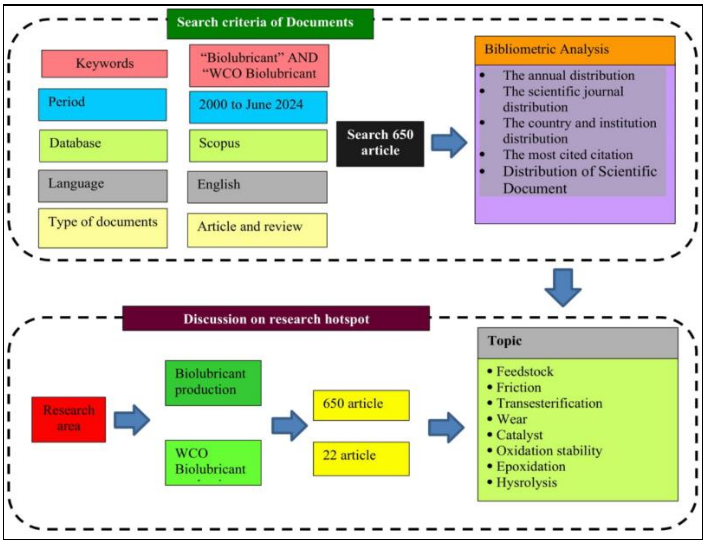


Figure 1. Document selection on bibliometric analysis

The systematic literature review discusses the characteristics of WCO biolubricants, the disadvantages of biolubricants, the evaluation of methods and types of catalysts in WCO biolubricant production, various synthesis techniques for WCO biolubricants such as double transesterification and epoxidation, as well as the physicochemical properties of WCO biolubricants.

2.2. Data Analysis of Scientific Literature

Details on the publication year and research fields of the selected papers were gathered from the Scopus database using the 'analyze results' feature. The data was subsequently imported into a Microsoft Excel spreadsheet and analyzed using OriginPro version 8.0 (Northampton, USA). Next, VOSviewer version 1.6.15 (www.vosviewer.com) was used to analyze the data compiled from all selected papers to determine the most productive institutions and countries, as well as the most frequently cited journals, authors, and publications. Additionally, research trends were identified through keyword analysis.

3. Bibliometric Results

3.1. Visualization of Research Trends and Interrelations in Biolubricant Studies

Figure 2 shows a visualization map of the relationships between research topics related to biolubricants from WCO generated using VOSviewer. This map groups various topics into clusters identified by different colors, showing the proximity and interconnections between issues based on their co-occurrence frequency in scientific literature. Key topics such as "biolubricant," "catalyst," "transesterification," and "oxidation stability" appear as large nodes, indicating they are central to much research and have many interconnections with other topics. Each color cluster represents a specific research area with a different focus. For instance, the green cluster focuses on the "transesterification" method and catalysts like "trimethylolpropane." The purple cluster groups research on enzymes and biocatalysts, while the red cluster highlights subjects about tribological properties, including "friction" and "wear." The blue cluster connects various vegetable oils used in biolubricant production, such as "jatropha " and "soybean oil." This visualization helps understand how these topics are interconnected and provides insights into which areas are most researched and the relationships between various aspects in developing biolubricants from WCO.

The visualization reveals active research areas, such as feedstock optimization and tribological properties by identifying densely connected terms. It also highlights potential gaps where less attention may have been given, such as the scalability of enzymatic processes or the economic feasibility of specific feedstocks. By leveraging this bibliometric data, primary research can align with prominent trends or address less-explored areas. For example, if "oxidation stability" or "biolubricant additive" appears as a recurring challenge, the study can focus on novel solutions in these areas.

The updated visualization map of research topics related to biolubricants from WCO uses color gradients to represent the publication years of the research (Figure 3). The color spectrum ranges from blue (older publications, around 2016) to yellow (more recent publications, around 2021). This time-based gradient provides insights into how research interests and focuses have evolved. For example, more recent topics such as "wear" and "friction" in yellow indicate growing interest and advancements in these areas in recent years, while foundational topics like "transesterification" and "catalyst" in green show ongoing but established research.

The map also highlights the interconnected nature of various research topics within the domain of WCO biolubricants. Central nodes such as "biolubricant," "catalyst," and "transesterification"

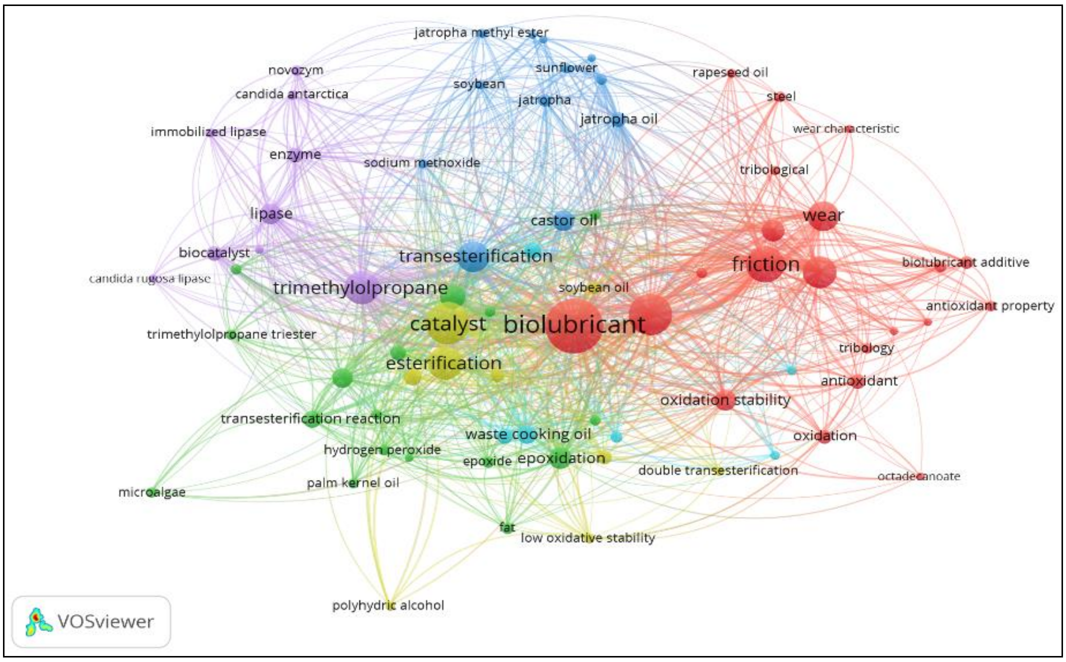


Figure 2. Mapping research trends in WCO-based biolubricants

have numerous connections, signifying their fundamental role in this field. The presence of interconnected terms like "oxidation stability," "esterification," and "WCO" demonstrates the complexity and multidisciplinary approach required in biolubricant research. This visualization is instrumental in identifying key research areas, emerging trends, and the chronological progression of scientific inquiry in developing biolubricants from WCO (**Figure 3**).

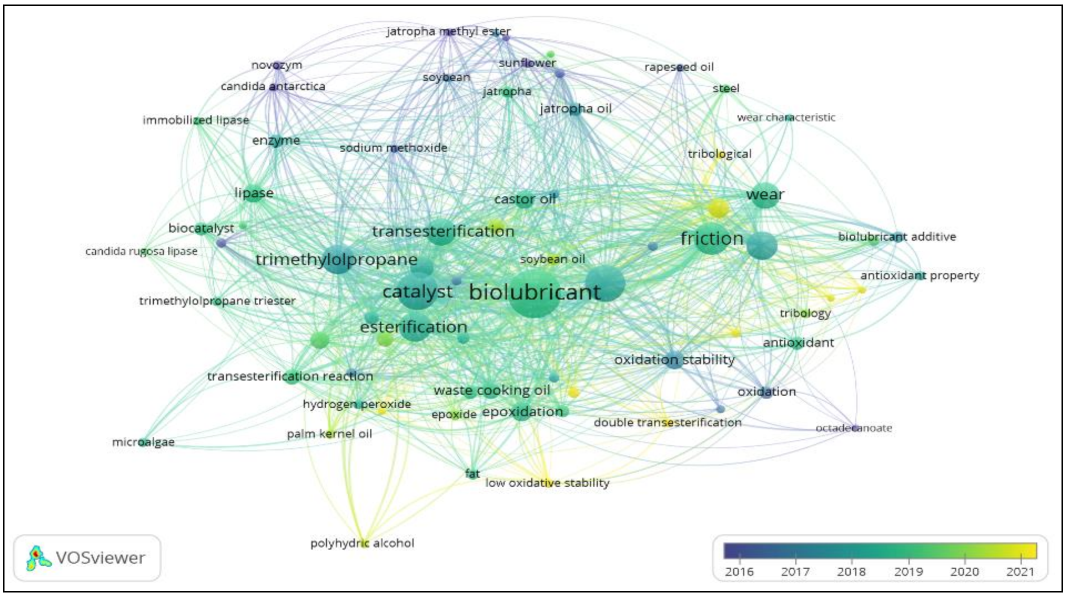


Figure 3. Trends and interconnections in biolubricant studies using WCO

3.2. Trends in Lubricant Research Publications: A Rapid Growth from 2000 to 2024

Figure 4a illustrates the number of documents published each year related to lubricants from 2000 to 2024. It shows a gradual publication growth from 2000 to approximately 2015, with occasional fluctuations. After 2015, there was a significant and rapid rise in publications, peaking around 2020 with over 80 documents. Post-2020, there is a noticeable decline, though the number of publications remains higher than in the earlier years. This trend suggests a growing interest and research activity in lubricants, reaching its highest intensity around 2020, possibly due to technological advancements or heightened environmental concerns driving innovation and study in lubricant materials.

The number of documents published each year related to WCO lubricants from 2012 to 2024 (**Figure 4b**). Initially, there was a steady increase from 2012 to 2014, peaking at around three documents. This was followed by a sharp decline to nearly zero in 2016 before another rise, reaching similar peak levels in 2017. The trend then shows fluctuations, with a notable dip in 2018, followed by a recovery and stabilization between 2 and 3 documents from 2019 onwards. The overall pattern indicates intermittent research interest and publication activity in WCO lubricants, with both high and low activity periods, suggesting evolving interest and potential challenges in this research field over the observed years.

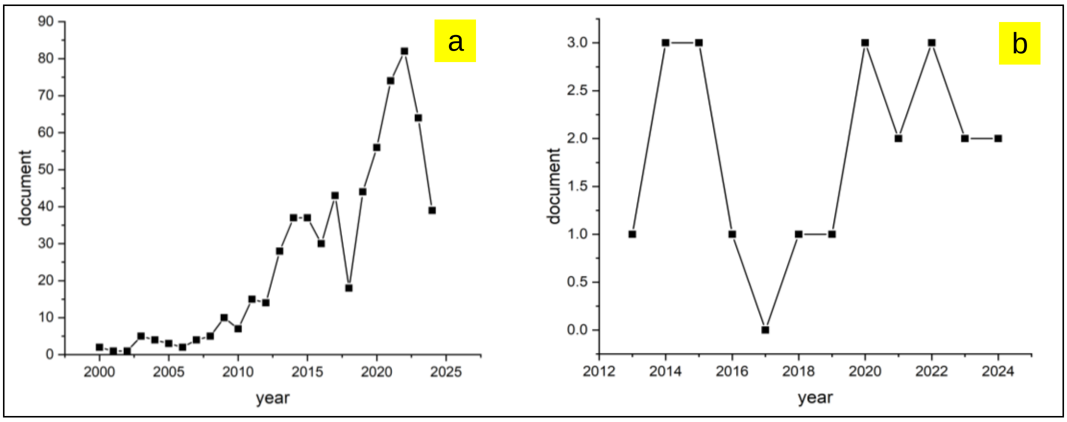


Figure 4. Trend Analysis of Lubricant Research Publications (2000-2024): a) lubricant of all feedstock and b) WCO lubricant

3.3. The Landscape of Biolubricant Research: Key Author Contributions Based on Scopus Data

Figure 5a shows that the bar chart presents the number of documents published by various authors in the field of lubricants. The chart reveals that Salimont, J. is the most prolific author, with over 60 publications, followed by Salih, N., who has around 40 documents. Other notable contributors include Yunus, R., with approximately 30 publications, and Yousif, E., with about 25 documents. Authors such as Kalam, M.A., Masjuki, H.H., Derawi, D., and Nogales-Delgado, S. have moderate contributions ranging between 15 to 20 documents. Meanwhile, Abdullah, B.M. and Freire, D.M.G. have the least publications, each under 15 documents. This distribution indicates a significant variance in publication output among these researchers, highlighting the leading influence of Salimont, J. in lubricant research. The image displays a bar chart from Scopus, comparing the document counts of up to 15 authors in the context of biolubricant research or a related topic. The chart highlights the number of documents published by each author, allowing for a quick comparison of their contributions to the field. Notably, Chowdhury, A. leads with the highest document count, significantly contributing to the field. Mitra, D. closely follows with many publications, while Biswas, D. ranks third with a notable presence in the research area. Mid-level contributors like Abdullah, R. and Agarwal, P. also play essential roles with document counts slightly lower than Biswas. Other contributors such as Chen, L., Porwal, S.K., Shamsuddin, N.H.A., Singh, N., and Xiang, S. have each contributed two documents, indicating consistent but less prolific involvement than the top contributors.

Contributors in biolubricant research of WCO biolubricant illustrated in Figure 5b. Authors with higher document counts, such as Chowdhury and Mitra, likely substantially impact the development and advancements in this field. Identifying these leading authors can help find potential collaborators for future research projects. The chart also indicates that multiple researchers are actively contributing to this area, suggesting a growing interest and expanding body of literature on biolubricants. This offers a clear graphical depiction of the leading authors, highlighting their contributions and offering insights into the ongoing research and potential collaborative opportunities in the field.

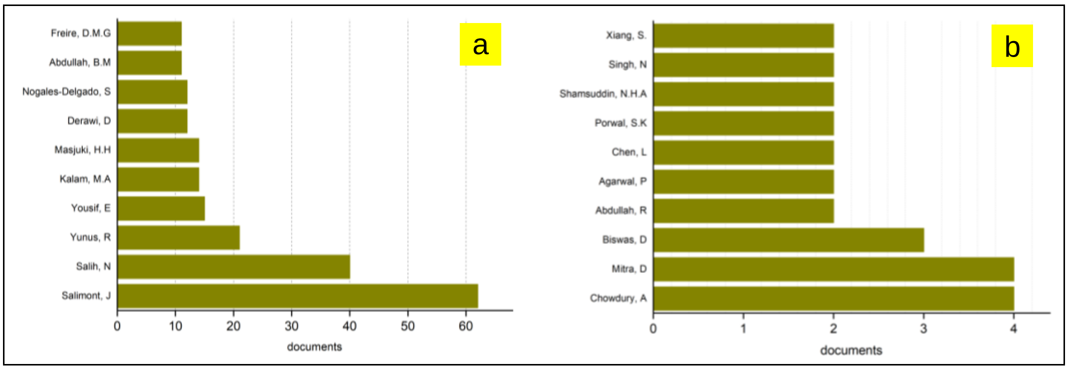


Figure 5. Document counts by author: a) biolubricants from various types of feedstock and b) WCO biolubricant

3.4. Research Output on Lubricants and WCO: Country-wise Publication Analysis

Figure 6a shows a bar chart of the number of documents published by various countries related to general lubricant research. Malaysia has the highest number of publications, exceeding 150 papers, followed by India and China, with substantial contributions. Countries like Brazil, Spain, and the United States also show significant research activity. France, Indonesia, and Iraq have the least publications, suggesting less focus on lubricant research in these countries. The comparison between the two charts indicates that while some countries like India and China are active in WCO and general lubricant research, others show a more specialized focus in one area. The number of documents published by various countries related to WCO research is illustrated in Figure 6b. India ranks first in the number of publications, followed by China and Malaysia, each with significant contributions. Other countries like Italy, Saudi Arabia, Spain, and Brazil have moderate contributions ranging from 3 to 5 documents. Egypt and South Africa have the least publications, indicating relatively lower research activity in this field within these regions.

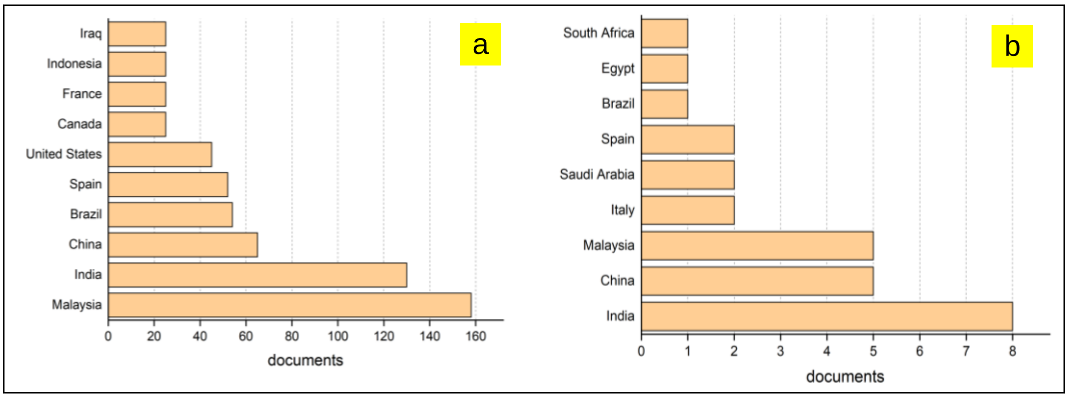


Figure 6. Number of lubricant research publication documents by country: a) biolubricants from various types of feedstocks and b) WCO bio lubricant

3.5. Distribution of Research Output in the Field of Lubricants by International Research Institutions

The first image presents a bar chart depicting the number of documents produced by various institutions related to a specific topic (**Figure 7**). The institutions listed include Universiti Teknologi MARA, Faculty of Engineering, Ministry of Education of the People's Republic of China, University of Johannesburg, DIT University, Universiti Malaysia Perlis, Logistical Engineering University of China, King Abdulaziz University, Oil Technical Supervision Office, and University of Calcutta. Among these, the University of Calcutta is the highest contributor with four documents, while the rest have a single document each. This suggests a concentrated research output in the University of Calcutta, highlighting its significant focus or expertise in the subject matter compared to other institutions. Furthermore, **Figure 8** shows the number of documents produced by different universities and research institutions on a similar or related topic. This chart includes Instituto de Catalysis y Petroleoquimica, University of Saskatchewan, Universiti Teknologi Malaysia, Universidad de Extremadura, Universiti Teknologi MARA, Al-Nahrain University, Universidade Federal do Ceara, Universiti Malaya, Universiti Putra Malaysia, and Universiti Kebangsaan Malaysia. Universiti Kebangsaan Malaysia emerges as the leading contributor with around 65 documents, followed by Universiti Putra Malaysia and Universiti Malaya with approximately 30 and 25 papers, respectively. This data indicates a substantial concentration of research activities in these Malaysian institutions, reflecting their strong emphasis and expertise in the field under study.

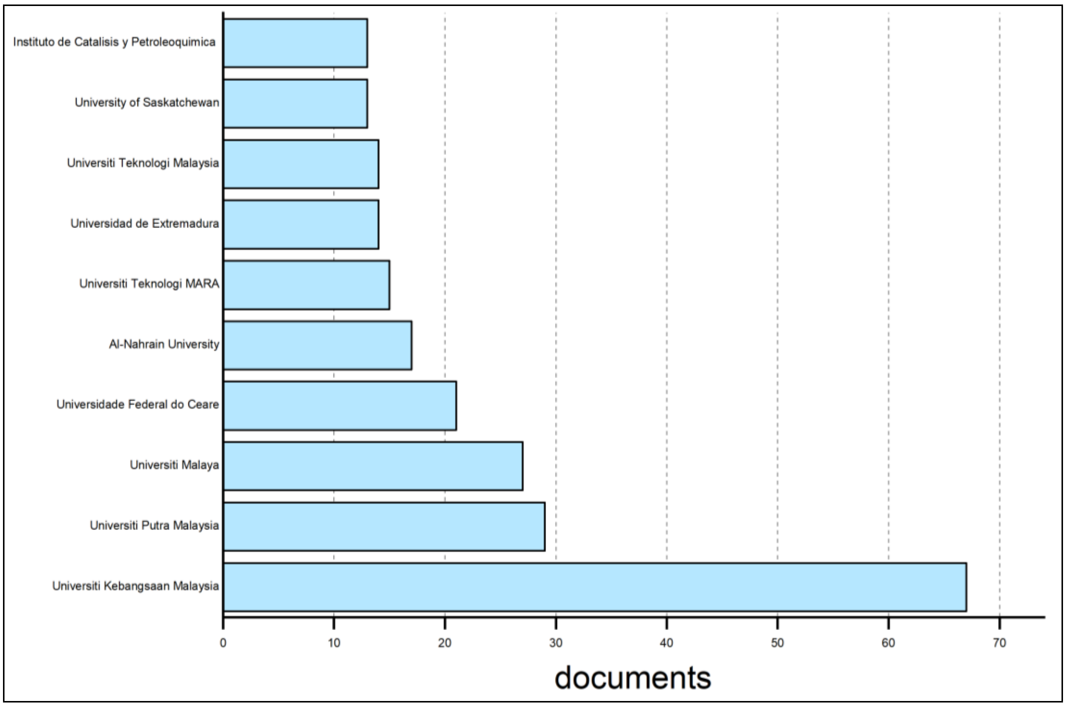


Figure 7. Distribution of documents by international research institutions country on biolubricants from various types of feedstocks

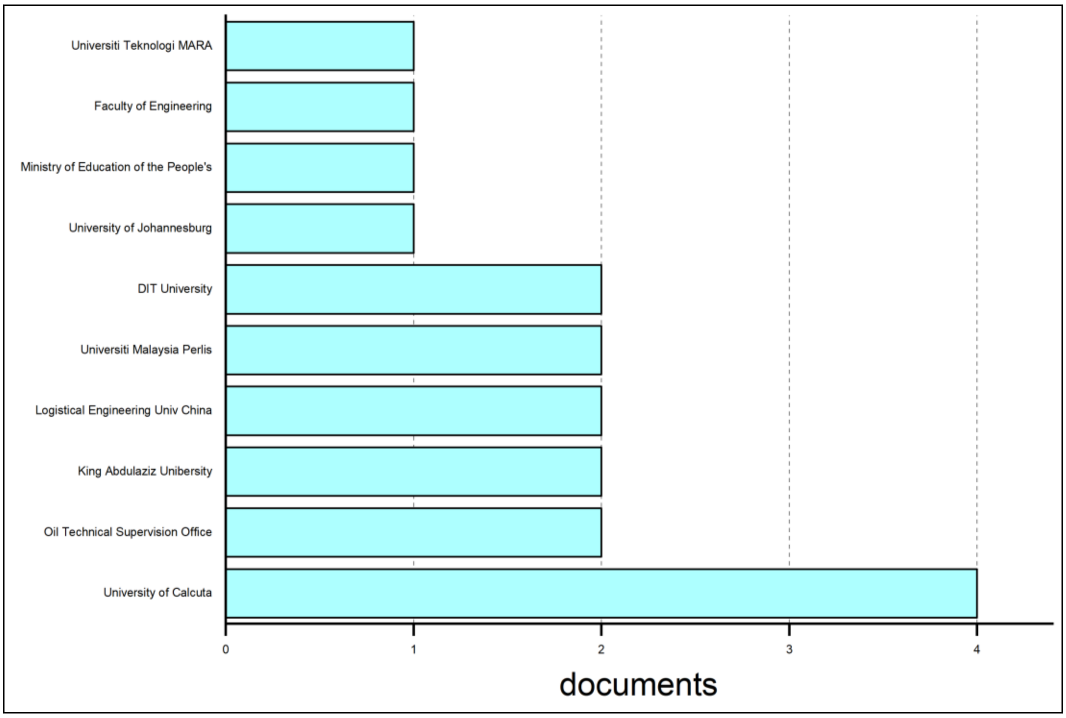


Figure 8. Distribution of documents by international research institutions country on WCO bio lubricant

Figure 9a shows a pie chart illustrating various types of scientific documents and their respective percentages. The most produced document type is articles, accounting for 77.5% of the total publications. Other document types include reviews (10.3%), conference papers (7.8%), book chapters (2.5%), conference reviews (0.6%), errata (0.5%), and other documents, each comprising less than 1% of the total publications. This indicates the dominance of articles as the primary form of scientific publications in this dataset, with other documents contributing much less. Next is the distribution of scientific document types with slight category variations (**Figure 9b**). Articles remain the most produced document type, accounting for 77.3%. The other document types in this image are reviews (13.6%) and conference papers (9.1%). The comparison of the two images demonstrates that articles continue to be the dominant form of publication, while the proportion of other documents fluctuates based on the classification and context of the publications.

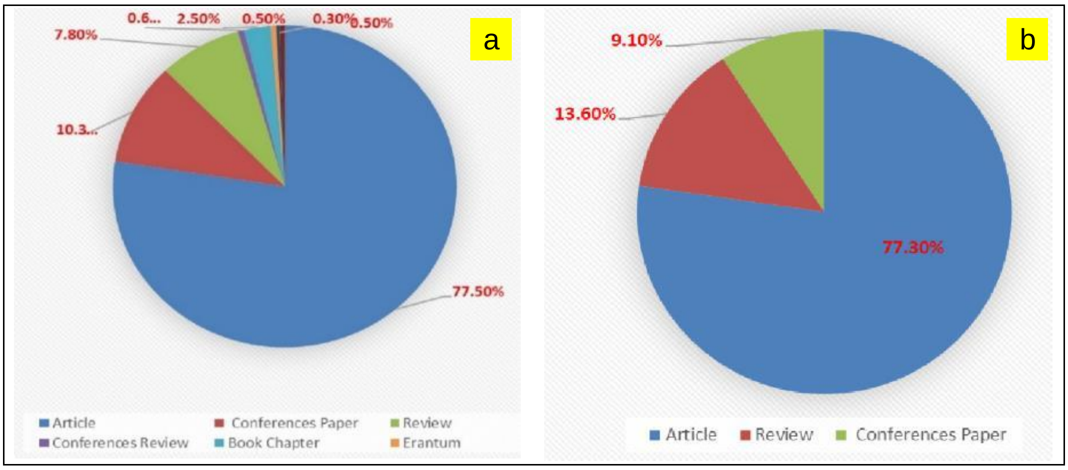


Figure 9. Distribution of scientific document types and their percentages: a) biolubricants from various types of feedstock and b) WCO bio lubricant

3.6. The Most Cited Articles of WCO Biolubricant

Table 1 presents a list of research titles and the number of citations related to WCO biolubricant. This list does not distinguish between review papers and research papers. The most cited paper on WCO biolubricant is 'Biolubricant synthesis from WCO via enzymatic hydrolysis followed by chemical esterification’, published in the Journal of Chemical Technology and Biotechnology in 2013 by Chowdhury et al. [35], which utilized enzymatic hydrolysis methods. The second most cited article, 'Synthesis and oxidative stability of trimethylolpropane fatty acid triester as a biolubricant base oil from WCO,' was published in Biomass and Bioenergy in 2014 by Wang et al. [36]. Besides the number of citations, the publication date of an article is a vital characteristic to consider, especially for those published within the last five years, indicating that the synthesis of WCO into biolubricant remains a high-interest topic (**Table 3**). The third most cited article was published in 2020 by Zhang et al. [37] with the title 'Green preparation of branched biolubricant by chemically modifying WCO with lipase and ionic liquid,' which was published in the Journal of Cleaner Production and has been cited 67 times.

Table 1. The most cited articles in the last 10 years regarding WCO biolubricant

No	Authors	Title	Year	Source	Cites	Ref
1	A. Chowdhury	Biolubricant synthesis from WCO via enzymatic hydrolysis followed by chemical esterification	2013	Journal of Chemical Technology and Biotechnology	78	[35]
2	E. Wang	Synthesis and oxidative stability of trimethylolpropane fatty acid triester as a biolubricant base oil from WCO	2014	Biomass and Bioenergy	76	[36]
3	W. Zhang	Green preparation of branched biolubricant by chemically modifying WCO with lipase and ionic liquid	2020	Journal of Cleaner Production	67	[37]
4	G. Sun	K_2CO_3-loaded hydrotalcite: A promising heterogeneous solid base catalyst for biolubricant base oil production from WCOs	2017	Applied Catalysis B: Environmental	54	[38]
5	Chowdhury, A.	Optimization of the production parameters of octyl ester biolubricant using Taguchi's design method and physicochemical characterization of the product	2014	Industrial Crops and Products	49	[33]
6	S. Bashiri	Chemical modification of sunflower WCO for biolubricant production through epoxidation reaction	2021	Materials Science for Energy Technologies	42	[39]
7	Foo, W.H	Recent advances in the conversion of WCO into value-added products: A review	2022	Fuel	40	[31]
8	R.Z.K. Hussein	Experimental investigation and process simulation of biolubricant production from WCO	2021	Biomass and Bioenergy	38	[28]
9	J.R. Guimarães	Immobilization of Eversa® Transform via CLEA Technology Converts it into a suitable biocatalyst for biolubricant production using WCO	2021	Molecules	34	[40]
10	Ghafar, F.	Study on the Potential of Waste Cockle Shell-Derived Calcium Oxide for Biolubricant Production	2019	Materials Today: Proceedings	28	[41]
11	M. Dehghani Soufi	Valorization of WCO-based biodiesel for biolubricant production in a vertical pulsed column: Energy efficient process approach	2019	Energy	28	[42]
12	A.K. Paul	In situ epoxidation of waste soybean cooking oil for synthesis of biolubricant basestock: A process parameter optimization and comparison with RSM, ANN, and GA	2018	Canadian Journal of Chemical Engineering	26	[43]
13	Perera, M	Bioprocess development for biolubricant production using non-edible oils, agro-industrial byproducts and wastes	2022	Journal of Cleaner Production	20	[44]
14	Chowdhury, A.	Esterification of Free Fatty Acids Derived from WCO with Octanol: Process Optimization and Kinetic Modeling	2016	Chemical Engineering and Technology	15	[45]
15	N. Singh	Natural Antioxidant Extracted WCO as Sustainable Biolubricant Formulation in Tribological and Rheological Applications	2022	Waste and Biomass Valorization	11	[46]
16	A. Chowdhury	Synthesis of biolubricant components from WCO using a biocatalytic route	2014	Environmental Progress and Sustainable Energy	11	[47]
17	J.R. Joshi	Chemical modification of WCO for the biolubricant production through transesterification process	2023	Journal of the Indian Chemical Society	8	[48]

No	Authors	Title	Year	Source	Cites	Ref
18	Kamarudin, N.S.B	Investigation on synthesis of trimethylolpropane (TMP) ester from non-edible oil	2020	Bulletin of Chemical Reaction Engineering and Catalysis	8	[49]
19	G. De Feo	Assessment of Three Recycling Pathways for WCO as Feedstock in the Production of Biodiesel, Biolubricant, and Biosurfactant: A Multi-Criteria Decision Analysis Approach	2023	Recycling	7	[29]
20	T.W. Putra	Intensification of biolubricant synthesis from WCO using tetrahydrofuran as co-solvent	2020	IOP Conference Series: Materials Science and Engineering	6	[50]
21	N. Singh	Evaluation of multifunctional green copolymer additives–doped WCO–extracted natural antioxidant in biolubricant formulation	2024	Biomass Conversion and Biorefinery	5	[51]
22	Abdullah, R.	Oil blends as biolubricant: Screening of effect factors influence to basestock	2014	Key Engineering Materials	4	[52]
23	Shamsuddin, N.H.A.	The improvement of screening the significant factors of oil blends as biolubricant base stock	2015	Malaysian Journal of Analytical Sciences	2	[53]
24	I. Sukirno	Utilization of WCO to synthesis trimethylolpropane ester as hydraulic biolubricant	2020	AIP Conference Proceedings	1	[54]
25	Xiang, S.	Physicochemical and tribological properties of triester derivatives from chemically modified WCO	2015	Biotechnology	1	[55]
26	Xiang, S.	Diester derivatives from chemically modified WCO as a substitute for petroleum based lubricating oils	2015	China Petroleum Processing and Petrochemical Technology	1	[34]

4. Systematic Literature Review Results

4.1. Characteristics of Biolubricants

Industrial machinery, cars, and agricultural equipment frequently use conventional petroleum lubricants [56]. Lubricating oils generally add 10% additives to the base oil. Base oil for conventional lubricants comes from petroleum that has been refined with high molecular weight and chemical modifications. Hydrogenated polyolefins, fluorocarbons, silicones, and esters belong to the base oil group [57]. The basic lubricant oil group includes processed oil, biomass, mineral oil, and synthetic oil. The base oil for biolubricants is an ester or a combination of natural and synthetic esters. Vegetable oils containing unsaturated fatty acids are used as base oils for biolubricants. This category includes lipids, plant-derived oils, agricultural waste, and animal fats processed through thermochemical and catalytic methods. Epoxidation, esterification/transesterification, and fatty acid condensation are fundamental chemical modification methods to increase the flow properties of vegetable oils, making them comparable to hydrocarbon-based mineral oils [57].

Lubricants are available in liquid, gas, solid, or semi-solid form. Lubricants are needed in the industrial sector because they function to prevent wear, corrosion, and machine failure. Furthermore, approximately 40-50% of used lubricants are improperly disposed of, harming both land and aquatic ecosystems due to their high levels of polynuclear aromatic hydrocarbons [58]. A higher viscosity index and superior lubrication properties are the advantages of lubricating oils from animal fats and vegetable oils. Additionally, the fatty acids in biolubricants create a more stable film layer, effectively preventing surface contact. Biolubricants are typically made through a transesterification reaction involving polyhydric alcohols, such as trimethylolpropane and ethylene glycol, derived from vegetable oils. The mix of saturated and unsaturated carbon chains in vegetable oils provides a range of unique properties [56].

4.2. Disadvantages of Biolubricants

While biolubricants provide numerous benefits and advantages, they also come with specific limitations that need to be considered. Biolubricants typically have higher production and procurement costs compared to traditional petroleum-based lubricants. Furthermore, biolubricants are not as widely available as traditional lubricants. They may also not be fully compatible with materials intended for petroleum-based lubricants, which could result in leaks or material deterioration [59]. Bio-based oils, with a flash point exceeding 300 °C, are considered non-flammable. Bio lubricants have poor fluidity and low oxidative stability, thus limiting their use. In addition, if worked at cold temperatures for a long time, this material tends to solidify [58]. This rapid oxidation process often results in changes to the properties of biolubricants. Moreover, bio-based lubricants are confined to a limited temperature range due to their low thermal stability at elevated temperatures and high pour points in colder conditions [9]. However, biolubricants made from vegetable oils exhibit insufficient oxidative stability and suboptimal performance at low temperatures [11]. Chemical modifications like acylation, hydrogenation, hydroformylation, transesterification, and oligomerization can be applied to mitigate these problems. According to Xie et al. [60], the limitations of vegetable oils in lubricant applications are mainly due to their low oxidative stability and high melting points. Processes such as hydrogenation, epoxidation, and transesterification are commonly used to improve these properties.

Other drawbacks of biolubricants include their relatively high production costs. The production process for biolubricants often requires specialized technology and raw materials, such as catalysts and complex chemical processes, which can significantly increase production expenses. Moreover, although biolubricants are more environmentally friendly, they often exhibit lower resistance to high temperatures and extreme pressures than conventional lubricants. This can limit their use in industrial applications that demand lubricants with high durability under harsh operating conditions [61], [62]. Hussein, et al. [28] stated that WCO is unlikely to serve as a substitute for mineral lubricating oil due to its high pour point low and oxidation stability.

4.3. Synthesis of Biolubricant

Several techniques, such as epoxidation, transesterification, ketonization, and estolide formation of vegetable oils to produce biolubricants [58]. Recently, techniques such as hydrolysis, hydrogenation, oligomerization, ozonolysis, ketone/fatty acid hydrodeoxygenation, decarboxylation, decarbonylation, and hydroisomerization have also been effectively utilized [63]. Using the transesterification technique, saturated fatty acids will be separated from vegetable oils, increasing oxidative stability and low-temperature properties. In this reaction, an alcohol radical interacts with an ester radical. The most efficient way to produce biolubricants is by esterifying pentaerythritol with straight-chain fatty acids (C_5-C_{11}) [63].

4.3.1. Hydrolysis Method

The synthesis of bio-lubricants using the hydrolysis method involves several steps. Firstly, vegetable oils or animal fats, chosen for their high fatty acid content, are heated to 60 °C and 100 °C to facilitate hydrolysis. Water and a catalyst, which can be a powerful base such as potassium hydroxide (KOH) or sodium hydroxide (NaOH), or a strong acid such as sulfuric acid (H_2SO_4), are introduced to the heated oil. This reaction breaks down triglycerides into glycerol and free fatty acids. The resulting glycerol is separated and purified, while the free fatty acids undergo further purification to remove any residual catalyst and water [47]. Subsequently, the free fatty acids can undergo optional chemical modifications such as esterification or transesterification, which involve reacting the fatty acids with alcohols like methanol or ethanol to produce esters, the primary components of bio-lubricants. Hydrogenation can also stabilize the fatty acids by reducing double bonds and improving oxidative and thermal stability. The final bio-lubricants are rigorously tested to ensure they meet desired physicochemical properties and performance standards. They are an eco-friendly substitute for petroleum-based lubricants, offering superior lubrication properties and environmental advantages [63].

The Homogeneous and heterogeneous catalysts are used to synthesize WCO into biolubricants using hydrolysis techniques. Triglycerides result from the hydrolysis process of free fatty acids and glycerol. To speed up the reaction, homogeneous catalysts such as sodium hydroxide (NaOH) and potassium hydroxide (KOH) were chosen because of their high effectiveness. Unfortunately, it is challenging to process liquid waste and separate and purify the product [64]. The best conditions for producing bio-lubricants from WCO are achieved at 60°C, using a base catalyst such as NaOH or KOH at 1% of the oil's weight, and a processing time of 2 hours. Under these conditions, the optimal molar ratio of methanol to oil is 6:1. Research indicates that these conditions result in a high yield of bio-lubricants with optimal reaction efficiency, as well as improved oxidative stability and lubrication properties of the biolubricant [62], [64], [65].

Further, using heterogeneous catalysts offers several benefits in the hydrolysis process of WCO. Heterogeneous catalysts, such as zeolites or transition metals supported on porous materials, can enhance reaction efficiency and simplify the separation of the catalyst from the final product. In addition, heterogeneous catalysts can be reused after the reaction process and are more environmentally friendly, reducing the liquid waste that has the potential to pollute the environment. Studies have shown that heterogeneous catalysts improve the final product's thermal and oxidative stability and minimize energy requirements in the production process [65]. The Optimal conditions were obtained in the synthesis of biolubricant from WCO with a heterogeneous catalyst with a catalyst amount of 2% by weight of the oil at a temperature of 65 °C and a reaction time of 3 hours. In studies utilizing heterogeneous catalysts such as CaO or zeolite, the optimal methanol-to-oil molar ratio is 12:1. These conditions have been proven to result in a high optimal yield while also enhancing the oxidative stability and lubricating properties of the final product [66].

4.3.2. Double Transesterification Method

The production process of biolubricants using the dual transesterification method involves two main stages to maximize conversion and product quality. In the first stage, vegetable oils such as castor or jatropha oil undergo a transesterification reaction with alcohol (e.g., methanol) under the influence of a base catalyst like NaOH or KOH. This reaction produces methyl esters and glycerol as by-products. In the second stage, the resulting methyl esters are further processed through a second transesterification reaction to improve the purity and stability of the product. This dual transesterification method effectively reduces free fatty acid content and enhances the physicochemical properties of biolubricants, such as oxidation stability, viscosity, and viscosity index [67]. Factors influencing the dual transesterification process include catalyst type and concentration, reaction temperature, alcohol-to-oil molar ratio, catalyst type and concentration, and reaction duration. Higher temperatures generally accelerate the reaction rate but can lead to product decomposition if it is too high. An optimal molar ratio of alcohol to oil ensures maximum conversion without wasting raw materials. The type and concentration of the catalyst significantly influences reaction efficiency and final yield. Additionally, reaction time must be sufficient to reach equilibrium without causing undesirable reverse reactions [68].

Several researchers have synthesized WCO into biolubricants using the dual transesterification method. Used cooking oil is synthesized into a biolubricant for investigations and simulations by Husein et al. [28]. The reaction was carried out using a heterogeneous calcium oxide (CaO) catalyst. It was found that the highest conversion was achieved at a processing time of 1.5 hours at a molar ratio of 3.5:1, 1.5 hours at a temperature of 130 °C, and a loading catalyst of 1.2% (w/w), resulting in a yield of 94%. Next, Wang et al. [36] derived WCO into a biolubricant by increasing its oxidative resistance from trimethylolpropane fatty acid tryster. The reaction parameters and oxidative stability of TFATE were investigated. The optimum yield was achieved at 85.7% using a potassium hydroxide catalyst at a reaction temperature of 128 °C, a molar ratio of 4:1, and a vacuum pressure of 200 Pa. After purification, the TFATE content in the final product reached 99.6% by molecular distillation at 120 °C.

4.3.3. Epoxidation Method

Epoxidation is one of the primary methods in synthesizing bio-lubricants from vegetable oils. In this stage, raw fats, such as crude palm oil or used cooking oil, undergo a chemical reaction with peroxides to form epoxides, crucial intermediate compounds in synthesizing bio-lubricants. The formed epoxides are then further processed to produce bio-lubricants with improved tribological properties and thermal stability. Research has shown that inedible mustard oil's frictional performance and oxidative stability can be enhanced through the epoxidation process, showing its considerable potential as an effective bio-lubricant [69]. The production process of bio-lubricants from WCO using the epoxidation method involves several crucial stages. First, WCO undergoes a chemical reaction with peroxides, such as performic acid, to produce epoxides, which are then converted into polyols through hydrolysis and transesterification reactions [70].

4.4. Evaluation of Methods and Reaction Conditions for Biolubricant Production from WCO

Table 2 outlines the different methods and reaction conditions employed in synthesizing biolubricants from WCO) using various catalysts. Several catalysts are used, including CaO, zinc acetate, KOH, CH3ONa, and Novozym 435, and multiple methods, such as transesterification, hydrolysis, and epoxidation. The reaction conditions vary in molar ratio, temperature, and time. The optimum yield can be achieved at 94% with the transesterification process using a CaO catalyst using oil molar ratio of 3.5:1 at a temperature of 130 °C with a methanol to for 1.5 hours. In contrast, employing zinc acetate for 3 hours with at 125 °C using a methanol-to-oil molar ratio of 6:1 yields 82.91%.

Table 2. Comparison of catalysts and methods in chemical reactions with reaction conditions and yields

Catalyst	Methods	Reaction condition				Yield (%)	Ref
		Temp. (°C)	Time (h)	Catalyst loading	Methanol to oil molar ratio		
CaO	Double Transesterification	130	1.5	1.2%	3.5:1	94	[28]
Novozyme 435	Hydrolysis	60	1.5	5%	2.5:1	95.19	[33]
Zinc acetate	Double Transesterification	125	3	1%	6:1	82.91	[48]
Novozym 435	Hydrolysis	150	24	5%	1:5.	81.22	[37]
TMP	Double Transesterification	128	1.5	4%	4:1	85.7	[36]
CaO	Double Transesterification	130	4	4%	3:1	97	[41]
Potassium carbonate	Double Transesterification	110	0.5	1%	4:1	83.33	[42]
KOH	Epoxidation	128	1.5	2.5%	1.1:0.5:1.	85.7	[34]
KOH	Double Transesterification	120	6	1%	3.9:1	91	[54]
MeONa	Double Transesterification	120	2	1%	6:1	90.18	[71]
CH_3Ona	Double Transesterification	120	6	1%	3.9:1	91	[53]
KOH	Double Transesterification	125	3	1%	1:4	94.42	[50]
TMP	Double Transesterification	150	4	2%	3:1	71	[49]
Novozyme 435	Hydrolysis	60	4.5	5%	3:1	95	[47]
Amberlyst 15H	Hydrolysis	81	4	1.85 g	3.2:1	99	[45]

Additionally, the table shows that Novozym 435 is used in several hydrolysis steps with varying reaction conditions, resulting in different yields. For instance, hydrolysis using Novozym 435 at 60 °C for 4.5 hours with a molar ratio 3:1 yields 95.19%. The catalyst Amberlyst 15H is used in the transesterification method at 81 °C for 4 hours with a methanol-to-oil molar ratio of 3.2:1, achieving an optimal yield of 99%. The variation in temperature, reaction time, and catalyst type underscores the necessity of optimizing reaction conditions to achieve high yields of biolubricants from WCO.

The optimal conditions for synthesizing biolubricants can be determined from WCO by involving the right choice of catalyst. The ideal reaction conditions include an optimal temperature, methanol-to-oil molar ratio, and adequate reaction time. Amberlyst 15H at 81 °C for 4 hours with a molar ratio of 3.2:1 shows the highest yield of 99%, making it the optimal condition in this table. The use of Novozym 435 in hydrolysis and transesterification also shows significant results, with yields reaching up to 95.19% and 81.22%, depending on the specific conditions applied.

4.5. Physicochemical of WCO Biolubricant

Table 3 shows the physical and chemical properties of biolubricants synthesized from WCO using various methods and catalysts. The transesterification method, utilizing catalysts like CaO, Trimethylolpropane TEATE, acetic acid, KOH, and sodium hydroxide, presents a broad range of outcomes. Significant variations in kinematic viscosity, oxidation stability, density, viscosity index, cloud point, and pour point evidence this versatility. Transesterification with CaO and Trimethylolpropane TEATE demonstrates high kinematic viscosity and oxidation stability, respectively. On the other hand, hydrolysis with Lipase (Novozym 435) and esterification using Novozym 435 provide strong results in viscosity and stability but vary in other properties like flash point and oxidation stability. Epoxidation, using acetic acid and hydrogen peroxide, shows moderate properties with distinct advantages under certain conditions.

Table 3. Comparison of methods and catalysts in chemical processes

Method	Catalyst	Density (20°C)	Flash Point (°C)	Cloud Point (°C)	Pour Point (°C)	Kinematic Viscosity (40°C)	Viscosity Index	Oxidation Stability (h)	Ref
Transesterification	CaO	895	235	2	-13	74.74	204	-	[28]
Hydrolysis	Lipase (Novozym 435)	-	303	-61	-	67.51	149	21	[37]
Transesterification	TrimethylolpropaneTFATE	-	240	-	−8	38.6	204	-	[36]
Esterification	Novozyme 435	-	324.4	-	1	32.35	218.47	1.18	[33]
Transesterification	CaO	-	-	-	-	30	179	-	[41]
Transesterification	Acetic acid	773	-	-	2.4	12.5	-	-	[72]
Epoxidation	Acetic acid	-	235	-	-30	11.91	135.12	-	[39]
Transesterification	KOH	895	198	-	−9	15.5	196	-	[42]
Epoxidation	Hydrogen peroxide	985	-	-	−6.5	7.51	-	-	[43]
Transesterification	Sodium Hydroxide	-	210	2	0	24.9	126.605	-	[48]

The choice of method and catalyst is crucial as it directly influences the biolubricant's properties, impacting its suitability for different applications. Depending on the catalyst used, transesterification methods offer a wide range of customizable properties, making them adaptable for various needs. Hydrolysis and esterification methods effectively achieve the desired viscosity and stability, making them suitable for applications requiring these traits. While offering moderate overall properties, epoxidation provides unique benefits, particularly in density and specific stability metrics. Therefore, selecting the appropriate method and catalyst combination is essential to tailor the biolubricant properties to meet specific performance requirements.

4.6. Techno-economic Analysis of WCO Biolubricants

With the increasing demand for sustainable and eco-friendly products, economies of scale are anticipated to lower biolubricant production costs, enhancing their competitiveness against traditional petroleum-based lubricants [59]. Several studies have conducted economic analyses on sustainability for biolubricant production. A techno-economic analysis of the biolubricant output from a mixture of used cooking oil and animal fat using Aspen Plus simulation has been conducted by Abdel Hamid, et al. [73]. They concluded that biolubricant production is economically feasible, featuring a 67.5% internal rate of return (IRR), a total capital investment of $12.7 million, and a payback period of 1.48 years. On the other hand, to enhance competitiveness and maintain a consistent minimum selling price (MSP), the simultaneous integration of biodiesel and biolubricant production can be considered. de Sá Parente Jr, et al. [74] stated that the selling price of biolubricants is lower than that of mineral lubricants, amounting to USD 3,000/ton and USD 6,000/ton, respectively, resulting in a Capex savings of 21%. Techno-economic analysis (TEA) on producing biolubricants from palm oil using Aspen Process Economic Analyzer (APEA). The economic analysis includes the capital and operational costs required to produce biolubricants utilizing MgO as a catalyst. The results show that the minimum selling price (MSP) of commercial synthetic poly alpha olefin (PAO) is 29% higher compared to the obtained results [75]. Two primary methods are employed to modify the properties of biolubricant: adding additives and chemical modification. Khan, et al. [76] indicate that estolide formation is the most effective among chemical modification routes. Additionally, chemically modified biolubricant production surpasses additive-based methods.

4.7. Analysis of Biodiesel and Biolubricant Production

VOSviewer is widely used for bibliometric reviews on biodiesel and bio-lubricants. Almeida et al. [77] reviewed trends in the use of lipase immobilization in the synthesis of biodiesel using bibliometric Web of Science data and patent analysis. Additionally, Chen et al. [78] performed a bibliometric analysis examining the sustainability and future challenges associated with synthesizing biodiesel from WCO, particularly emphasising the transesterification process. Apart from that, a review of the techno-economic and environmental potential of biodiesel in Brazil using bibliometric analysis has been carried out by Julio et al. [79]. Melo et al. [80] analyzed the prospects of magnetic biocatalysts and their current applications in biodiesel production.

Furthermore, Ahmad et al. [81] have used Vosviewer to analyse bibliometric data to review several aspects, such as challenges, physiochemical properties, and commercialization in producing non-edible oil biolubricants through various chemical processes, including transesterification. The paper highlights the importance of biolubricants as environmentally friendly substitutions to traditional lubricants derived from petroleum, noting their non-toxicity, biodegradability, and low greenhouse gas emissions. It also discusses the bibliometric analysis of research trends in biolubricant production, revealing significant publication growth over recent years. Furthermore, Delgado et al. [61] conducted A comprehensive review of biolubricants produced from vegetable oils through transesterification. Recently, a bibliometric review on the tribological performance of biolubricants has been performed by Nugroho, et al. [59]. Specifically in industrial applications, the performance improvement of biolubricants under high pressure and temperature conditions is achieved by incorporating nanomaterials such as graphene, maghemite (Fe_3O_4), and titanium dioxide (TiO_2), which results in better wear resistance and reduced friction.

This study examines as a promising resource for biolubricants to serve as an alternative to petroleum-based lubricants. The need for bio-lubricating oil is explained at length. In this review, VOSviewer was also used to analyze WCO biolubricant research on employing homogeneous and heterogeneous catalysts in the synthesis of WCO for bio-lubricants is linked to the physicochemical properties and the yield. The Methods for synthesizing WCO to bio-lubricants, such as double transesterification, hydrolysis, and epoxidation, are discussed in depth. This paper aims to fill that gap by presenting current knowledge on the obstacles and commercial considerations of producing environmentally friendly biolubricants. The primary goal is to understand the potential and key properties of various biolubricants.

Additionally, the study conducts a comprehensive bibliometric analysis employing rigorous research methods methodologies and data statistics. Bibliometric analysis is selected as it efficiently explores literature and publication trends using citation data. This method analyzes the connections between academic citations in biolubricants and underscores the dissemination of research findings. The article concludes with a discussion on prospects and challenges that need to be tackled to commercialize and apply biolubricants successfully. Furthermore, the methods for synthesizing WCO to bio-lubricants, such as double transesterification, hydrolysis, and epoxidation, are discussed in depth. In this review, the use of homogeneous and heterogeneous catalysts in synthesizing WCO for bio-lubricant is related to the physicochemical properties and yield presented in tabular form.

5. Conclusion

The research concludes that WCO is a viable feedstock for biolubricant production, offering an environmentally friendly substitute for conventional petroleum-derived lubricants. The study's bibliometric and experimental analyses reveal that biolubricants synthesized under optimal conditions demonstrate excellent physicochemical properties, such as lubricity and oxidative stability. Applying homogeneous and heterogeneous catalysts, particularly calcium oxide, effectively achieves high yield and quality biolubricants. These findings support the potential for large-scale adoption of WCO biolubricants, contributing to sustainable industrial practices and environmental conservation. Future research should focus on refining synthesis processes and exploring the full commercial potential of these biolubricants. The conclusion of this study highlights the critical role of bibliometric analysis, facilitated by VOSviewer, in understanding the trends and focal points of research on biolubricants derived from WCO. The visualization maps created using VOSviewer reveal interconnected research themes such as "biolubricant," "catalyst," "transesterification," and "oxidation stability," which are central to the field and exhibit significant co-occurrence in scientific literature.

Furthermore, biolubricant research will continue to increase and decrease slightly after 2022. The country contributing the most extensive research to biolubricant research is Malaysia, followed by India for biolubricants from the WCO and other feedstocks. The researcher with the most significant number of documents was Salimont, J, with 60 papers. Next, Universiti Kebangsaan Malaysia is the leading contributor, with around 65 documents. These clusters demonstrate the multidisciplinary approach necessary for advancing biolubricant development, showcasing areas like enzymatic catalysis and tribological properties. By identifying key areas and emerging trends, this analysis provides valuable insights for future research directions, emphasizing the need for continued innovation in biolubricant synthesis and application. Further studies are encouraged to evaluate and explore advanced nanocatalysts to improve reaction kinetics in biolubricant synthesis and apply low-power heating technology to reduce energy consumption in synthesizing biolubricants from WCO. On the other hand, exergy analysis is essential in biolubricant production to enhance energy efficiency and sustainability. Moreover, future studies should focus on economic analysis and life cycle assessment, which are necessary for the sustainability of biolubricant production to ensure commercial viability.

Acknowledgments

The authors gratefully acknowledge the financial support from Universitas Sumatera Utara through the Equity Project Program under the PKUU-Scheme for Article Review Writing, Fiscal Year 2023 (Contract Number 74/UN5.2.3.1/PPM/KPEP/2023). We also extend our appreciation to the reviewers for their invaluable insights and feedback, as well as to all technical staff and research assistants who provided essential support in equipment setup and data collection.

Author's declaration

Authors' Contributions and Responsibilities - Ilmi: Contributed significantly to the study's conception, design, and planning. Played a key role in the preparation of the manuscript and was involved in the overall supervision of the project. Suherman: Was responsible for the data collection, analysis, and interpretation of results. Provided critical revisions to the manuscript and helped finalize the statistical and bibliometric analysis. Erna Frida: Contributed to the literature review and drafted the discussion section. I also participated in revising and editing the manuscript. Nurin Wahidah Binti Mohd Zulkifli: Provided expert input on methodology, particularly in the bibliometric analysis, and contributed to the manuscript's results section. Jufrizal: Assisted with the technical review of the study and contributed to interpreting the findings, mainly focusing on the practical applications of the biolubricants discussed in the research.

Funding – This research was funded by Universitas Sumatera Utara through the Equity Project Program under the PKUU-Scheme for Article Review Writing, Fiscal Year 2023. The funding support was provided per Contract Number 74/UN5.2.3.1/PPM/KPEP/2023.

Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interest.

Additional information – No additional information from the authors.

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