A BIBLIOMETRIC ANALYSIS OF FATTY ACID METHYL ESTER (FAME) TRIBOLOGY (2010 TO 2019)

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Article history
Received
14th June 2023
Received in revised form
22nd October 2023
Accepted
23rd October 2023
Published
1st December 2023

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ABSTRACT

In the present study, a bibliometric analysis has been carried out with relation to the FAME research topic on its production, rheological and tribological studies for the last ten years (2010-2019). The scientific collaborations throughout this timespan were investigated according to different parameters in Web of Science (WoS). Based on the keyword search string, the top productive journals for the FAME research and their co-citation relationships were revealed in this study. Energy Fuels, Fuel and Wear are indicated to be the top three most influential journals of this research topic. Apart from that, the top productive countries, organizations, authors, funding agencies and their respective visualization networks were also investigated. A keyword co-occurrence analysis was conducted to reveal thematic areas in FAME research. A strong research interest in FAME oxidation stability and its tribological behaviour was one of the main findings of this analysis. FAME as biolubricant is recommended due to their ability to reduce wear and friction, also by adding a proper amount of additives, the poor oxidative stability characteristic of FAME could be resolved. These findings are expected to encourage more FAME-related research and communications in this field.

KEYWORDS

Bibliometric analysis; FAME; Oxidation stability

INTRODUCTION

The depletion of fossil fuel sources is expected to occur within the next 150 to 300 years, depending on the consumption scenario and technical possibilities of their extraction [1]. This concern has led to the increasing utilization of fuels derived from biological sources. One of the often-mentioned alternatives to diesel fuel in the automotive sector is Fatty acid methyl ester (FAME). FAME refers to the mono-alkyl esters of vegetable oils or animal fats, commonly obtained from commodity vegetable oil, namely soybean, rapeseed (canola), palm, and sunflower oil. Biodiesel production is typically through transesterification of vegetable oil, animal fat, or waste cooking oil with an alcohol and in the presence of a catalyst. The kinetics of the transesterification reaction can be represented by a three-stepwise reversible reaction as given below:

Step 1:

$$Triglyceride + Methanol \overset{catalyst}{\longleftrightarrow} Methyl\ ester + Diglyceride$$

Step 2:

$$Diglyceride + Methanol \overset{catalyst}{\longleftrightarrow} Methyl\ ester + Monoglyceride$$

Step 3:

$$Monoglyceride + Methanol \overset{catalyst}{\longleftrightarrow} Methyl\ ester + Glyceride$$

Overall,

$$Triglyceride + 3\ Methanol \xleftrightarrow{catalyst} 3\ Methyl\ esters + Glyceride$$

In recent years, FAME has been intensively studied due to the increasing demand for automotive applications with lower carbon footprint. Aside from the potential of being adopted as an alternative to diesel fuel, another aspect of FAME that has begun to attract attention is its superior lubrication properties compared to conventional lubricants. The importance of an effective lubrication system cannot be overlooked, as using new materials and implementing more advanced lubrication technologies can potentially reduce energy losses generated by friction and wear of machine elements by as much as 40% [2]. The advantages of utilizing FAME, namely its non-toxicity, biodegradability, and renewability, can be easily aligned to one of the core principles of Green Tribology [3], which is to implement a concept that refers to the science and technology of tribological aspects with relation to ecological balance and of environmental and biological impacts [4].

Saving resources and materials is one of the most important aspects of eco-tribology, which holds the meaning of environmentally acceptable tribological practices. On top of the depletion of crude oil, environmental concerns have also raised the importance of using environmentally acceptable lubricants. Thus, ecologically friendly alternative materials with better lubrication properties are essential. In engineering applications, optimum operation practices are a precursor for high efficiencies that could lead to reduced consumption of lubricants. As such, better oxidation stability and lesser contamination by liquid and solid matters can reduce the consumption of lubricants that would prolong oil change intervals. After lubricants are past their useful lifetime, they are often returned to the environment, which may cause significant damage due to their toxicity. Generally, for materials to be considered low or non-toxic, they should possess an LD50 value of more than 1000 ppm/kg. In toxicology, the LD50 value is the dose required to kill half the tested population members after a given test duration [1]. Hence, the term "ecotoxicity" was coined to represent the toxic effect of lubricants on plants and animals but not human health. To reduce the consumption of such lubricants, the popularity of the FAME has surged, leading to the exploration of several feedstocks that can meet the increasing demand for FAME.

The bibliometric analysis is a technique used among researchers in many science and engineering disciplines to investigate global emerging research themes along with significant scientific outputs reported in the literature. Using the bibliometric method, Zhang et al. studied global FAME's research activities and tendencies from 1991 to 2015 [5]. One of the significant points from their bibliometric analysis study is that FAME-related research has increased tremendously during those 25 years. They found out 1) Bioresource Technology and 2) Fuel are among the most prominent and influential journals. Other than that, Starbuck et al. carried out a bibliometric evaluation to map the research activities of the global biofuel from the year 1991 to 2012 [6]. Their analysis confirmed that biofuel field-related scientific outputs rocketed from 2003 to 2012.

Through bibliometric analysis, publications and citation trends in a given research topic across time could be identified, thus providing scientists and researchers with a thorough overview of the current research outlook in the specific area of interest. Based on the outcome of such an analysis, scientists and researchers can form impactful strategies to more effectively develop the research subject field. Regarding the search and retrieval of scientific publications, the Web of Science (WoS) is the most dominant database because it houses the largest number of indexed journal articles and conference proceedings papers. The Hirsch index is proposed as a useful method for characterizing the scientific output of researchers [7].

To determine the research trend of late, in this study, a bibliometric analysis was carried out to trace global trends in FAME research related to production, rheological, and tribological studies for the past ten years year 2010 to 2019). The publications and their citation characteristics across this duration in this field could then be further analyzed. In addition, the most productive journals, organizations, authors, funding agencies, and scientific collaborations at various levels could be investigated along with the co-citation relationships and keyword co-occurrence analysis.

Methodology

The bibliometric information used in this study was retrieved from the Thomson Reuters Web of Science (WoS) in October 2020. The following search string was used to perform an advanced search in WoS: “TS = ((FAME or fatty acid methyl ester*) AND (lubricity or friction or tribology)).” The asterisk in the string serves as a wildcard operator, expanding the search by considering the words that precede the asterisk. The retrieved publications from the WoS database were also restricted to be within ten years, from 2010 to 2019. The analysis was then performed on the selected publications related to the topics below:

1 Rheological properties of FAMEs produced from different feedstocks.
2 Types of catalysts involved in producing FAME.
3 Effects of additives on the performance of FAME as a lubricant.
4 Effects of different blends of feedstock on the lubrication performance of FAMEs.

Also, the following lists the themes that are not associated with the objective of this analysis and, hence, were removed from the subsequent analysis procedure.

1 Combustion and emission of FAMEs.
2 In-depth characterization of chemical isomers.
3 Production of non-FAMEs.

In short, this study focuses on publications related to FAME's production, rheological, and tribological studies. After filtering the publications, the total number of publications used in the subsequent analysis is 61. Figure 1 shows the search strategy adopted in the present analysis based on the number of publications remaining (n) at the end of each filtering stage.

The data for the selected publications were downloaded from WoS before being imported into Microsoft Excel. The publication information, namely document type, title, abstract, keywords, citations, and DOI, was also downloaded, along with the authors' names and affiliations. On the other hand, the journal impact factor (I.F.) and quartile ranking (Q) were taken from the Journal Citation Report (JCR) 2019. The most productive journals and their co-citation relationships could then be interpreted accordingly. The most productive countries, organizations, and authors, together with their scientific collaborations, could also be determined from the WoS data.

A keyword co-occurrence analysis was also conducted to determine the highest frequency of keywords across different periods. Based on the WoS data, VoS viewer, a text-mining software, was used to visualize the similarities among journals, authors, countries, organizations, keywords, and citations. The analysis of journal co-citation relationships, co-authorships, and keyword co-occurrence was finally presented as generated network visualization maps containing different-sized nodes. It is noted that the linkage strength between the nodes and their distance is proportional to the similarities shared by the nodes.

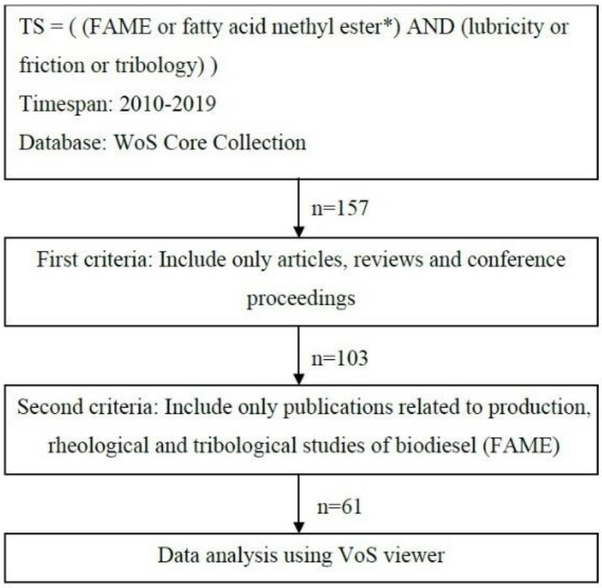


Figure 1: Filtering strategy to obtain relevant publications for bibliometric analysis (n denotes the number of publications at each stage)

Results and Discussion

General publication trend

The first paper on FAME was published by Graboski et al. [8]. The paper describes FAME being produced from vegetable oil and animal fats for fuel use in diesel engines. Moser et al. are among the early scientists who studied the properties of vegetable oil-derived FAME used as blend components in ultra-low sulphur diesel fuel [9]. On the other hand, Sulek et al. are among the first to present the tribological properties of fuel oil containing fatty acid methyl esters derived from rapeseed oil [10]. The 61 publications published in the year 2010 to 2019 consist of 46 articles (75.4%), 12 proceedings papers (19.7%) and three reviews (4.9%). The total number of citations received for the publications is

1,691, and the average number of citations per publication is 27.72. All publications were written in English. The total number of citations is seen to be increasing each year in Figure 2, which indicates a growth trend and an increasing exchange in the field of FAME research in the past ten years.

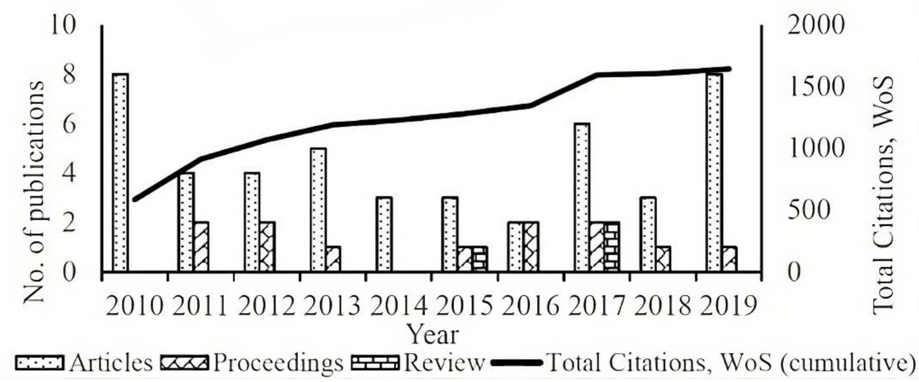


Figure 2: Publication and citation trend for biodiesels

Journal analysis

Table 1: Top productive journals on the topic of FAMEs

Journal	Category (Q, Rank) (2019)	*I.F. (2019)*	*T.P.*	%T.P. (%)	*Cumulative percentage*
Energy Fuels	Energy & Fuels (Q2/55/112) Engineering Chemical (Q2/49/143)	3.421	10	16.393	16.393
Fuel	Energy & Fuels (Q1/24/112) Engineering Chemical (Q1/18/143)	5.578	6	9.836	26.229
Wear	Engineering, Mechanical (Q1/19/130) Materials Science, Multidisciplinary (Q2/91/314)	4.108	4	6.557	32.786
Biomass Bioenergy	Agricultural Engineering (Q1/3/13) Biotechnology & Applied Microbiology (Q2/44/156) Energy & Fuels (Q2/53/112)	3.551	3	4.918	37.704
Revista De Chimie	Chemistry, Multidisciplinary (Q3/114/177) Engineering, Chemical (Q3/82/143)	1.755	3	4.918	42.622
Tribology International	Engineering, Mechanical (Q1/17/130	4.271	3	4.918	47.54
Bioresource Technology	Agricultural Engineering (Q1/1/13) Biotechnology & Applied Microbiology (Q1/12/156) Energy & Fuels (Q1/13/112)	7.539	2	3.279	50.819
Journal of the American Oil Chemists Society	Chemistry, Applied (Q3/36/71) Food Science & Technology (Q3/86/139)	1.659	2	3.279	54.098
Renewable Energy	Green & Sustainable Science & Technology (Q1/9/41) Energy & Fuels (Q1/19/112)	6.274	2	3.279	57.377
Advances in Mechanical Engineering	Thermodynamics (Q4/51/61) Engineering, Mechanical (Q4/106/130)	1.161	1	1.639	59.016

I.F.: impact factor; T.P.: total publications; %T.P.: percentage of total publication

Based on the search string, there was a total of 38 journals that were published related to FAME, with nine journals having published two or more publications. These nine journals have published 57.38% of all publications. The top journals are shown in Table 1, which cover the categories of energy and fuels, chemical engineering, mechanical engineering, and/or applied chemistry. Journals 1) Energy Fuels, 2) Fuel, and 3) Wear have been identified as the core journals for the research topic because these three journals publish 32.79% of publications. The co-citation relationship between journals is illustrated in Figure 3. The line connecting two nodes has different thicknesses, proportional to the co-citation strength of the linked journals. The node size refers to the total link strength of a journal. It is observed that Fuel, Energy Fuels, and Wear have a strong co-citation relationship with one another. The most probable reason for this is the focus on FAME production from mostly vegetable oils, modification of FAME composition for lubricity and fuel purposes, and oxidative stability of FAME. A distinct colour is used to categorize the journals into two separate clusters. The journals in Cluster 1 (red colour) emphasize the production of FAME from vegetable oils, considering the focus on alternative fuels by these journals. In contrast, the journals in Cluster 2, represented in green, mostly emphasized the lubrication properties of the FAME studied, while some journals focused on the oxidative stability of the FAME.

Top-cited publications analysis

Table 2: High-impact publications on FAMEs

Title of Publication	*References*	*TC*
Evaluation of alkyl esters from Camelina sativa oil as FAME and as blend components in ultra-low-sulfur diesel fuel	[9]	179
Castor oil FAME and its blends as alternative fuel	[11]	130
Okra (Hibiscus esculentus) seed oil for FAME production	[12]	108
Application of response surface methodology for optimizing transesterification of Moringa oleifera oil: FAME production	[13]	96
Oxidative stability of FAME: Causes, effects and prevention	[14]	92
Fatty acid methyl esters (FAMEs) from castor oil: Production process assessment and synergistic effects in its properties	[15]	84
Coriander seed oil methyl esters as FAME fuel: Unique fatty acid composition and excellent oxidative stability	[16]	78
Preparation of fatty acid methyl esters from hazelnut, high-oleic peanut, and walnut oils and evaluation as FAME	[17]	70
Tribology with FAME: A study on enhancing FAME stability and its fuel properties	[18]	62
Assessment of lubricity of compositions of fuel oil with bio components derived from rape-seed	[10]	62

T.C.: Total Citations

A total of 11 (18.0%) publications published from 2010 to 2019 have 50 or more citations. The papers listed as the top ten publications in Table 2 consist of eight articles and two review papers. Both review papers highlight the factors affecting the stability of FAME and the implications of oxidation on fuel properties, lubricity, and performance. Methods to enhance the stability of FAMEs have been discussed as well. Most of the top ten publications were published from 2010 to 2012, which allowed the publications to gain more citations. It is important to highlight that both review papers were published in 2017, signifying a great interest in the stability of FAME in recent years. This may be due to the increased utilization of FAME, which leads to interest in conducting a more comprehensive analysis to improve the stability of FAME for commercialization.

In the earlier research field, the search for alternative feedstocks has been given priority as intensive production of FAME from edible food-grade sources has raised concerns about its potential environmental effects. Different types of vegetable and seed oils, namely Camelina satvia oil, castor oil, okra seed oil, Moringa Oleifera oil, coriander seed oil, nut oils, and rapeseed oil, were investigated for their potential in producing FAME. The rheological properties of the FAME produced from these feedstocks were examined to see if they met the required ASTM D6751 and EN14214 standards. Emphasis was placed on applying these FAMEs as fuels or blend components, with only one publication from the top ten focused on the tribological behaviour of fuel oil with bio components derived from rapeseed oil as a potential lubricant. The Wear journal published this publication. The authors, Sulek et al., have found that as little as 5% of bio-additives from rapeseed oil can reduce the friction coefficient by 20% [10]. A total of 62 citations had been received by this article, indicating that it may be useful to other researchers in the investigation of vegetable oils, especially rapeseed oil, as a feedstock to produce FAME for lubrication applications.

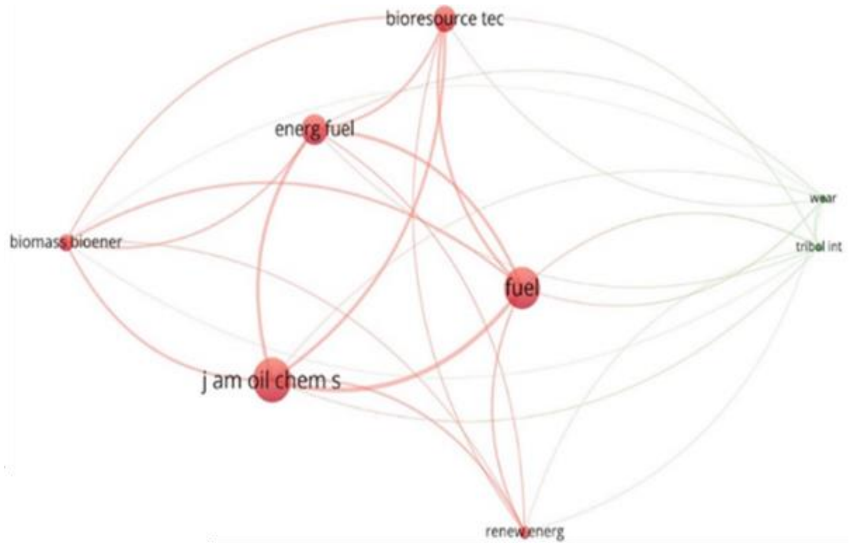


Figure 3: Co-citation relationship among top productive journals for research on FAMEs

Countries/Region analysis

Table 3: Top productive countries/regions on FAME research

Countries/ Regions	Years										T.P.	%T.P.	T.C.	h
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019				
USA	4	2	3	0	2	1	0	1	1	1	15	24.590	563	9
Malaysia	0	1	0	1	1	0	2	3	0	2	10	16.393	296	8
India	0	1	2	1	0	2	0	1	1	1	9	14.754	162	4
Spain	1	0	0	0	0	0	1	2	0	2	6	9.836	140	4
England	0	1	0	0	0	0	1	2	0	1	5	8.197	68	4
People’s R China	0	0	0	1	0	0	1	1	0	2	5	8.197	21	3
Thailand	0	0	0	0	0	0	1	2	0	1	4	6.557	44	4
Pakistan	1	1	0	0	0	0	0	0	0	1	3	4.918	207	3
Romania	0	0	1	1	0	1	0	0	0	0	3	4.918	29	3
Brazil	0	0	0	0	0	0	0	1	1	0	2	3.279	17	2

h: Hirsch index

Twenty-six countries are investigating FAME based on the search string, nine of which have produced three or more publications on the topic, as seen in Table 3. The USA, Spain, and Pakistan could be considered the senior country that has been contributing to this field since the year 2010, with a total of four publications from the USA and one from Spain and Pakistan. More publications were subsequently delivered by other countries, namely Malaysia, India, and England, in 2011. However, from 2011 to 2015, there was an absence of publications from Spain. Pakistan was also noted to have stopped publishing articles from 2012 onward until the sole publication in 2019.

In 2017, all countries, except for Pakistan and Romania, have published at least one publication on the topic, indicating a heightened interest in the field. Malaysia was the most productive country in the year 2017, with a total of 3 publications. However, in 2018, there was a sudden drop in productive countries, with only the USA, India, and Brazil publishing an article each. This drop did not last long, as the number of publications surged again in 2019. Interestingly, Pakistan received the third-highest number of total citations (207) despite not publishing at all from 2012 to 2018. Pakistan’s publications on FAME production from vegetable oil in 2010 and 2011 significantly contributed to the field after continuously receiving citations from other researchers.

The People's Republic of China was noted to have increased its research productivity on FAME since 2013 despite receiving fewer citations than countries with a lower frequency of publications, namely Thailand, Pakistan, and Romania. Figure 4 displays the network visualization map for the collaboration between countries. The countries on the map represent the top ten most productive countries in this field. These countries have produced at least two publications from research collaborations. There are two clusters linked to each other: the first cluster consists of Iraq, Malaysia, Pakistan, and Saudi Arabia, whereas the second cluster consists of England, Spain, and Thailand. The two clusters are linked through the collaboration between Malaysia and England. The USA, Romania, and India did not collaborate with other countries regarding publications. Interestingly, Malaysia has the largest node size as it has the most collaboration with other countries (a total of four countries).

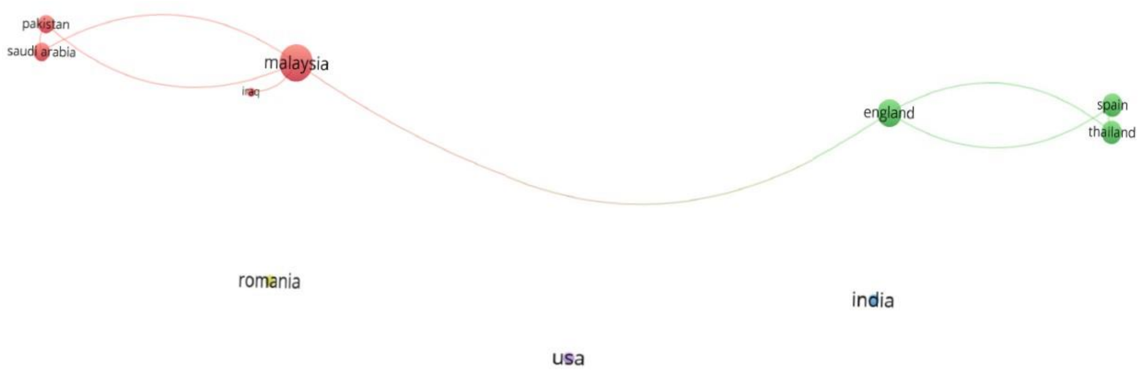


Figure 4: Co-authorship network among countries in research on FAMEs

Organizations

Table 4: Top productive organizations on FAME research

Organizations	Country	Years										T.P.	%T.P.	T.C.	h
		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019				
Agriculture Research Service	USA	3	2	3	0	1	1	0	0	0	1	11	18.03	514	9
University of Castilla-La Mancha	Spain	1	0	0	0	0	0	1	1	0	2	5	8.197	107	4
University of Malaya	Malaysia	0	0	0	0	1	0	1	1	0	1	4	6.557	123	4
Suranaree University of Technology	Thailand	0	0	0	0	0	0	1	1	0	1	3	4.918	26	3
University of Birmingham	UK	0	1	0	0	0	0	0	1	0	1	3	4.918	40	3
Universiti Kebangsaan Malaysia	Malaysia	0	1	0	0	0	0	0	1	0	1	3	4.918	40	3
Universidad Politécnica de Madrid	Spain	1	0	0	0	0	0	1	1	0	0	3	4.918	132	3
Universiti Teknologi Malaysia	Malaysia	0	0	0	0	0	0	1	1	0	1	3	4.918	38	3
Al-Nahrain University	Iraq	0	0	0	1	0	0	0	1	0	0	2	3.279	43	2
Anna University	India	0	1	0	0	0	1	0	0	0	0	2	3.279	15	1

A total of 74 organizations have contributed to the publication of FAME, but only 20 organizations have published more than one publication (27.0%). It can be seen from Table 4 that Agriculture Research Service is the top organization among other organizations due to its highest number of publications (11) and citations received (514). The high number of citations is due to the contributions of Moser et al. [9, 16]. The organization with the second highest number of citations (132) is Universidad Politécnica de Madrid, which produced only three (3) publications. The research collaboration network at the organizational level is shown in Figure 5. Three clusters are shown, where the University of Castilla-La Mancha, King Saud University, and University Kebangsaan Malaysia have the strongest total link strength in each cluster. Figure 5 also demonstrates the lack of collaboration between several institutions, the most significant being zero collaborations between the Agriculture Research Service and Anna University with the other institutions.

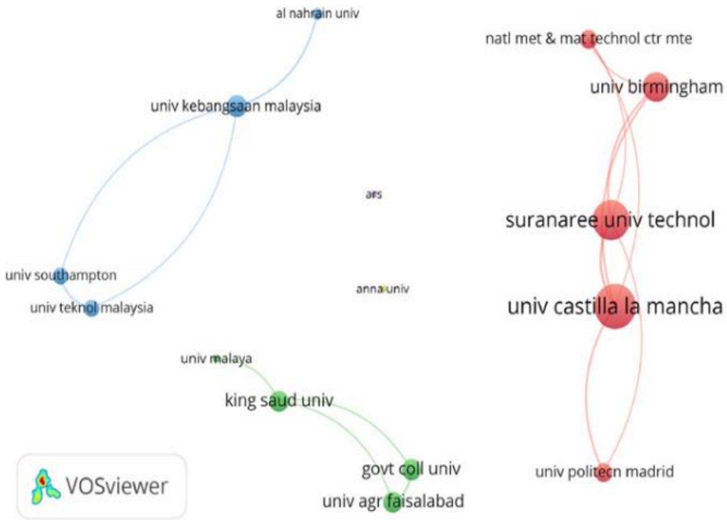


Figure 5: Collaboration network at the organizational level in research on FAMEs

Authors

Table 5: Top productive authors in FAME research

Authors	Country	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	T.P.	%T.P.	T.C.	h
Moser, Bryan	USA	3	2	3	0	1	0	0	0	0	0	9	14.754	485	8
Knothe, Gerhard	USA	2	0	0	0	1	1	0	0	0	1	5	8.197	96	4
Lapuerta, Magin	Spain	1	0	0	0	0	0	1	1	0	1	4	6.557	107	4
Masjuki, Haji H.	Malaysia	0	0	0	0	1	0	1	1	0	1	4	6.557	123	4
Sukjit, Ekarong	Thailand	0	1	0	0	0	0	1	1	0	1	4	6.557	56	4
Dearn, Karl D.	England	0	1	0	0	0	0	0	1	0	1	3	4.918	40	3
Kalam, M.A.	Malaysia	0	0	0	0	1	0	1	0	0	1	3	4.918	63	3
Sanchez-Valdepenas, J.	Spain	0	0	0	0	0	0	1	1	0	1	3	4.918	20	2
Vaughn, Steven F.	USA	2	0	1	0	0	0	0	0	0	0	3	4.918	296	3
Abdullah, Bashar M	USA	0	0	0	1	0	0	0	1	0	0	2	3.279	43	2
Anwar, Farooq	Pakistan	1	1	0	0	0	0	0	0	0	0	2	3.279	200	2
Ashraf, Muhammad	Pakistan	1	1	0	0	0	0	0	0	0	0	2	3.279	200	2
Barsari, Mahmoud A.N.	Iran	0	0	0	0	0	0	0	0	0	2	2	3.279	8	2
Bouchet, M. I. De Barros	France	0	0	0	1	0	0	0	1	0	0	2	3.279	22	2
Chollacoop, Nuwong	Thailand	0	0	0	0	0	0	0	1	0	1	2	3.279	24	2
Chong, William W.F.	Malaysia	0	0	0	0	0	0	1	1	0	0	2	3.279	34	2
Cursaru, Diana-Luciana	Romania	0	0	1	1	0	0	0	0	0	0	2	3.279	28	2
Forest, Cyrielle	France	0	0	0	1	0	0	0	1	0	0	2	3.279	22	2
Le Mogne, Thierry	France	0	0	0	1	0	0	0	1	0	0	2	3.279	22	2
Li, Mengmeng	China	0	0	0	0	0	0	1	1	0	0	2	3.279	7	2

From the defined search string, there are a total of 177 researchers that have explored the topic of FAME and its tribological properties. However, only 34 of the 177 researchers published two or more publications throughout the ten years. Table 5 shows the top 20 authors on this topic. Bryan Moser is the researcher with the most contributions to the topic, having nine publications and receiving 485 citations. This is evidenced by the author receiving a high Hirsch index (h) of 8. Gerhard Knothe, a notable researcher from the same country, had collaborated with Moser and written several publications on the derivation of FAME. Another highly cited author, Steven F. Vaughn, had collaborated with Moser on three publications, which focused on evaluating the fatty acid composition of plant seed oils for FAME production. It is to be noted that Moser and Vaughn are a few of the earliest researchers to investigate the oxidative stability of FAME produced from various feedstocks. These authors were stationed in the USA at the time of publication, indicating the country's strong interest in FAME usage.

The co-authorship network between authors is shown in Figure 6. There are, in total, 8 clusters. Nadia Salih, Emad Yousif, Bashar Mudhaffar Abdullah, and Jumat Salimon have formed the strongest co-authorship network with a total link strength of 6. The larger node size in the visualization map also evidences this. The publications by these authors focus on the chemical modification of plant fatty acid structures, which has great potential for improving the physicochemical and friction-reducing properties of these compounds as bio-lubricants [19]. The collaboration between Farooq Anwar, Muhammad Ashraf, and Umer Rashid is also significant, for they have authored research on the production of FAME from okra seed oil [12] as well as the application of response surface methodology for the optimization of transesterification of moringa oleifera oil [13].

From the visualization map, three clusters from Southeast Asian countries have produced prominent research from Malaysia and Thailand. This is because of the abundance of palm oil in these countries, which allows the production of FAME at a lower cost. The first cluster consists of researchers from the University of Malaya, whose

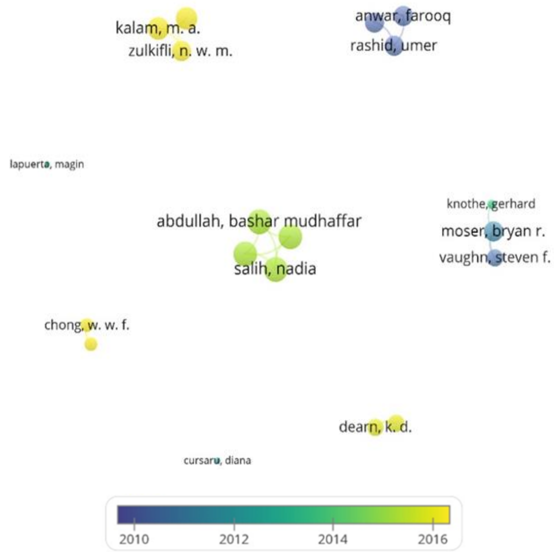


Figure 6: Co-authorship network visualization for authors in research on FAMEs

Research interests are on the tribological characteristics of chemically modified FAME. Kalam M.A., Masjuki H.H., and Zulkifli N.W.M. produced trimethylolpropane (TMP) and pentaerythritol ester (PE) from palm oil methyl ester and investigated the wear and friction characteristics of these samples [20]. These authors have also published a few significant papers on the oxidation and storage stability of FAMEs. Chong W.W.F forms the second cluster from Malaysia from Universiti Teknologi Malaysia and Ng J.-H. from the University of Southampton, who co-authored two publications. Their study uses lateral force microscopy to examine the boundary frictional characteristics of various FAMEs derived from various vegetable oils [21]. The frictional properties at various lubrication regimes for FAMEs derived from vegetable oils, hydrogenated vegetable oil, and animal fat were explored in another study [22]. The third cluster consists of the authors Dearn K.D. from England and Sukjit E. from Thailand. Their research is on the lubricity of diesel fuels and oxygenated compounds,s including esters. Finally, there are two clusters with one author each, namely Lapuerta M. and Cursaru D. These authors have co-authored with several other authors but did not belong to any cluster since there is no consistent collaboration with any of the authors.

Funding Agencies

Table 6: Funding agencies related to FAME research

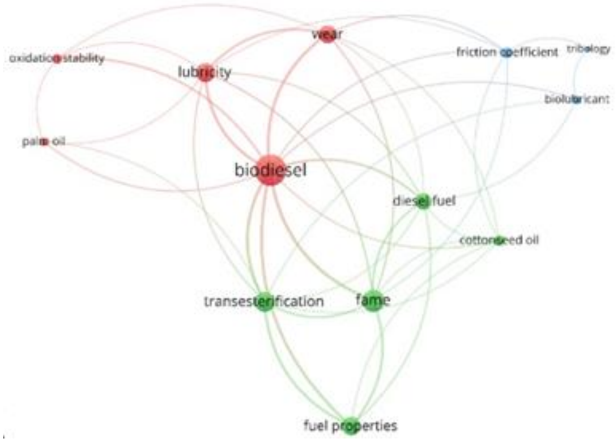
Funding Agencies	Country	Years										T.P.	%T.P.	T.C.	h
		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019				
University of Malaya	Malaysia	0	0	0	0	1	0	1	1	0	0	3	4.918	115	3
Department of Science & Technology	India	0	0	2	0	0	0	0	0	0	0	2	3.279	25	1
Universiti Kebangsaan Malaysia	Malaysia	0	0	0	1	0	0	0	1	0	0	2	3.279	43	2
Batman University (BAPCoordinatorsp)	Turkey	0	0	0	0	0	0	0	0	1	0	1	1.639	1	1
Complex Research Support Centers	Brazil	0	0	0	0	0	0	0	1	0	0	1	1.639	9	1
National University Research Council	Romania	0	0	0	1	0	0	0	0	0	0	1	1.639	14	1
Cotton Incorporated	USA	0	0	1	0	0	0	0	0	0	0	1	1.639	7	1
Council of Scientific & Industrial Research	India	0	0	1	0	0	0	0	0	0	0	1	1.639	25	1
Eco-Sol LLC	USA	0	0	1	0	0	0	0	0	0	0	1	1.639	7	1
Engineering and Physical Sciences Research Council	UK	0	0	0	0	0	0	0	1	0	0	1	1.639	20	1

Through the defined keyword string, 50 funding agencies have been acknowledged in published documents related to FAME research, with the top 10 funding agencies having published 22.95% of the total number of publications, as seen in Table 6. The University of Malaya is the top funding agency, having published three publications and receiving 115 citations, making it the most productive funding agency overall. This is evidenced by the higher Hirsch index (h) received, which is 3. The University of Malaya is noted to have collaborated with the University Putra Malaysia in one research publication. Still, it has no foreign collaborations on FAME research in the period investigated. University Kebangsaan Malaysia is the second most productive funding agency, with two publications that received 43 citations. It also has strong collaboration ties with Al Nahrain University in chemical sciences. Despite the low number of citations for its two publications, India's Department of Science and Technology is ranked higher than the University Kebangsaan Malaysia, with a Hirsch index (h) of only 1. Overall, Asian countries are observed to have contributed more funding to this research field, along with other Middle Eastern and Western countries.

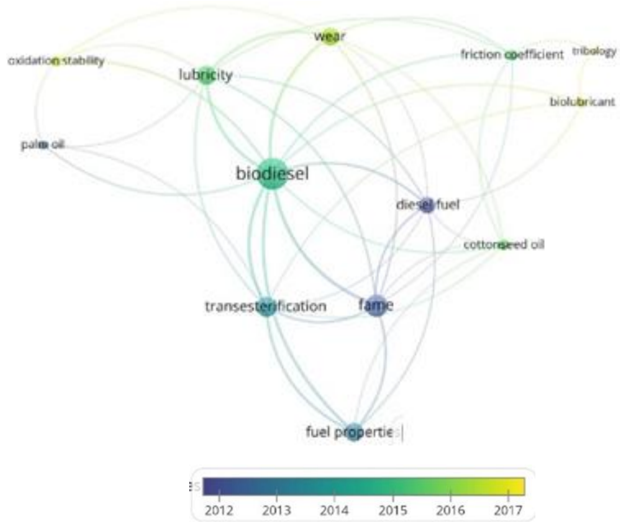
Keyword Co-occurrence Analysis

The co-occurrence of any two keywords explains their presence within the same scientific publication. The examination of the co-occurrence of keywords is capable of revealing the thematic areas in FAME research. A total of 29 keywords were extracted from 61 articles using VOS Viewer. Non-related and similar keywords were eliminated, refining the total to 13. These 13 keywords were included in the visualization map generated using VOS viewer. Figure 7 (a) shows the network visualization map, while Figure 7 (b) shows the overlay visualization map. The node size here is proportional to the number of occurrences for the specific keyword. As shown in Figure 7 (a), "biodiesel" appears to be the most frequently used or appeared keyword, followed by "FAME" and "transesterification," "lubricity," "fuel properties," and "wear." In Figure 7 (a), the keywords are categorized into three major clusters. Cluster 1, given in red, represents the wear characterization of FAME, which involves studies on its lubricity and oxidative stability. Palm oil was also one of the keywords linked to the cluster, indicating its popularity as a FAME feedstock. Cluster 2, given in green, is on the production of biodiesel or FAME.

The function of FAME as a diesel fuel and the study on its fuel properties were also highlighted. The appearance of "cottonseed oil" demonstrates that it was a popular feedstock among scientific researchers. Cluster 3, given in blue, focuses on bio-lubricants in general, where many studies explore the tribological behaviour of such lubricants.



(a) Network visualization map



(b) Overlay visualization map

Figure 7: Visualization map of the keyword co-occurrence network for research on FAMEs

Through the overlay visualization map of Figure 7 (b), it is demonstrated that keywords such as "Diesel fuel," "FAME," "biodiesel," and "transesterification" appeared on average in the publication year of 2012 to 2015. While, the keywords such as "oxidation stability," "biolubricant," and "tribology" show a more recent appearance which is around the year 2017. This has indicated that the research related to the FAME focus on its oxidation stability and tribology behaviour as a biolubricant has recently received significant attention. Hence, from the keyword co-occurrence analysis, it is identified that FAME research focuses on oxidation stability and tribological behaviour as a biolubricant is the research hotspot of this field, which might rise in upcoming years.

TRIBOLOGICAL BEHAVIOUR AND OXIDATION STABILITY OF FAME AS A LUBRICANT

During the early to the mid-span of the investigated period (2010-2019), rather than optimizing the transesterification process, the production of FAME generally focuses mostly on novel feedstocks that are mostly non-edible types. Several commonly selected feedstocks include rape seed oil, cotton seed oil, and jatropha. As time progressed, the emphasis shifted towards characterizing FAME for specific applications, mainly focusing on its lubricity. FAMEs generally have excellent lubricity, attributed to the ester group within the FAME molecules. The lubricity of FAME is contributed by its formation of a boundary-thin, protective anti-wear layer, which is adhered to the metallic surfaces. The boundary layer protects the surface from friction and wear.

For example, Hamdan et al. measured frictional properties of FAMEs derived from vegetable oils, hydrogenated vegetable oil, and animal fat at different lubrication regimes. The FAMEs derived were selected to fulfill the whole saturated-unsaturated and monounsaturated-polyunsaturated fatty acid methyl ester (FAME) spectrum based on a ternary plot. Based on saturation level, Hamdan et al. concluded that friction forces reduce with decreasing ratio of mono-unsaturated to total saturated FAME content. They observed that these improved frictional properties at both electrohydrodynamic and boundary lubrication regimes for the tested FAMEs are attributed to the enhanced friction modifier effect [22]. It was also reported that a lower ratio of mono-unsaturated to total saturated FAME content could reduce the load-carrying capacity of the lubricated contact at the mixed lubrication regime. Their study deduced soybean oil methyl ester as an optimum bio-lubricant/additive than the other tested FAMEs because it generates sufficiently low friction at a sufficiently high load-carrying ability [22].

In a study by Syahrullail et al., the performance of jatropha oil, Refined, Bleached, Deodorised (RBD) palm olein, and palm fatty acid distillate were compared with commercial stamping oil and hydraulic oil under increasing levels of pressure. It was found that, as compared to commercial stamping oil, the friction coefficient and wear scar diameter values were slightly larger for vegetable oils [23]. It is mentioned that adding proper additives may solve such an undesirable characteristic. Interestingly, it has also been noted that the good lubricity of FAMEs is primarily due to trace impurities in the FAME, particularly free fatty acids and monoglycerides. However, some of these impurities contribute to operational problems at lower temperatures. Therefore, improving low-temperature properties might worsen lubricity because of reduced impurities [24].

It is also commonly reported that vegetable oil-based lubricants outperform mineral-based oil in anti-wear and friction, scuffing load capacity, and fatigue resistance. However, vegetable oil-based lubricant tends to possess poorer thermal-oxidative stability and is less effective under extreme loads when compared with mineral-based oils. Thermal oxidative stability of the FAME is also an essential property, as it leads to the degradation of lubricant quality if it is unstable. Increased viscosity is one of the observations for low oxidation stability of FAME. Two factors that influence the oxidative stability of FAMEs are (1) FAME compositional properties and (2) storage and handling conditions [24]. Referring to the former, it has been reported that a high percentage of saturated fatty acids is known to improve the oxidation resistance of FAMEs [25].

When considered an additive, Arumugam and Sriram formulated a rapeseed oil-based bio-lubricant by mixing rapeseed oil methyl ester with a bio-additive package [26]. The additive package comprises 10% castor oil and 5% palm oil methyl ester. In their study, a 10% diesel contamination allowed the rapeseed oil-based bio-lubricant to form a diesel-contaminated rapeseed oil-based bio-lubricant. The purpose was to consider the fuel dilution effect commonly found in compression ignition-type engines. They reported that diesel-contaminated rapeseed oil-based bio-lubricant wear was lower (up to 91.5%) than diesel contaminated with SAE 20W40 [26]. Palm oil methyl ester was reported to contribute to the high affinity towards metal surfaces due to their polar functional groups.

Regarding storage, the induction period (IP) values are often used to measure storage life. For example, Serrano et al. reported that soybean and rapeseed methyl ester have the lowest induction period (IP) values [27]. In contrast, high oleic sunflower methyl ester and palm methyl ester possess the highest IP values before and after storage. Such an observed characteristic is attributed to the higher poly-unsaturation of soybean methyl ester and rapeseed oil methyl ester, leading to poorer stability than low poly-unsaturated oils, such as palm methyl ester and high oleic sunflower oil methyl ester. It has also been reported that by treating FAME with relevant additives, their IP values can be increased higher than the requirement of EN14214 even after the storage period, indicating that lower additive doses may be sufficient to ensure suitable oxidative stability regardless of the washing agent used [27, 28].

Conclusion

Based on the FAME and its tribological-related studies extracted from the WoS database during the past ten years (2010-2019), this bibliometric analysis study has provided an updated overview and current trend of research in FAME. Hence, here summarize some of the significant findings from this study:

- FAME research still shows a growth trend and an increasing exchange in the field for the past ten years (2010-2019), where the average citations per publication reached 27.72 in 2019.
- Energy Fuels, Fuel, and Wear are among the most influential journals in FAME research, and these three journals also possess strong co-citation relationships with one another.
- The upcoming countries demonstrating research interest in FAME are Malaysia, the People's Republic of China, Thailand, and Brazil. These findings can help to establish a stronger collaboration network between countries and increase research funding, which is expected to encourage more FAME-related research and communications in the scientific community.
- Most notably, the research hotspots in the current analysis are identified to be the oxidation stability and tribological study of FAME to be a biolubricant, as demonstrated by the keyword co-occurrence analysis.
- FAME as a lubricant can be recommended due to its ability to reduce wear and friction. Also, adding additives could solve the poor oxidative stability characteristic.

Limitations of this Study

The advanced search string designed in this bibliometric analysis was attempted to extract all the FAME publications related to production, lubricity, friction, and tribology indexed by WoS for the last ten years. It is well known that WoS can be considered the largest scientific publications network. However, including other databases, namely Scopus, Science Direct, PubMed, and

Google Scholar, might produce a varied dataset of publications. Those publications outside the database of WoS, which fulfill the search criteria, could not be retrieved via the search string and are neither included nor analyzed. Hence, analysis of research based on other databases to further validate the findings of this study will be worthwhile in further studies. Although the accuracy of this bibliometric analysis depends on the percentage of the total scientific publications extracted from WoS databases, the authors still believe that the presented bibliometric analysis based on the output from WoS is sufficient to illustrate the global trend of FAME research.

Acknowledgments

We thank Universiti Teknologi Malaysia for sponsoring our doctorate studies through UTM Zamalah.

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