THE TRIBOLOGICAL PERFORMANCE OF PERFLUOROPOLYETHER - BASED GREASE BIOLUBRICANT: A BIBLIOMETRIC ANALYSIS

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ABSTRACT

In response to the growing demand for environmentally friendly grease preparations, this study conducts a bibliometric analysis to examine the research trends surrounding the application of perfluoropolyether (PFPE) based grease biolubricants from 2010 to 2019. The analysis, based on 66 publications extracted from Web of Science (WoS), aims to narrow down the scope of interest in exploring the adoption of PFPE-based grease biolubricants in automotive applications. The analysis reveals that Tribology Letters emerged as the most productive journal, publishing 44.1% of the total publications on this topic. Italy was the initial contributor to this research, but no further studies were conducted after 2010. While, Singapore emerged as one of the main contributors, with 27 publications over the years. Keyword analysis demonstrates that the "friction and wear" keyword exhibited high significance with a total link strength of 25, followed by "lubrication" and "PFPE" with a total link strength of 16. Overall, this bibliometric analysis provides valuable insights into the research trend of PFPE-based grease biolubricants. The findings highlight the need for further exploration and development of PFPE-based grease biolubricants for automotive applications.

KEYWORDS

Bibliometric; Friction; Wear; Biodegradable; PFPE

1.0 INTRODUCTION

Friction plays a crucial role in our daily routines, allowing us to walk without slipping, handle objects securely, and bring vehicles to a stop using braking systems. However, in industrial applications, friction and wear often give rise to various challenges, including increased energy consumption, power loss, corrosion, reduced machinery lifespan, and compromised equipment safety and reliability [1]. Lubricants and greases are commonly employed to minimise friction and wear by providing a protective layer between moving surfaces.

Among the different types of greases, mineral oil-based grease is preferred due to its stable lubricating performance and cost-effectiveness [2, 3]. However, the use of non-biodegradable mineral oil-based grease poses significant environmental concerns. The discharge of such lubricants into terrestrial ecosystems can lead to the destruction of vegetation, agriculture, and soil organisms. Similarly, in aquatic ecosystems, the spillage of non-biodegradable lubricants causes oil contamination and negatively impacts aquatic life's growth and reproduction. As a result, alternative options, such as triglycerides derived from animal or vegetable oils, have gained attention as environmentally friendly alternatives [4, 5]. Consequently, the selection criteria for grease should encompass not only performance and cost considerations but also toxicity and biodegradability aspects.

Biodegradable-based grease lubricants, despite their environmental advantages, may suffer from certain disadvantages. One of the main drawbacks is their lower thermal and oxidative stability compared to non-biodegradable counterparts [6]. These biodegradable-based grease lubricants can degrade more quickly under high temperatures or prolonged use, resulting in reduced lubricating performance and shorter service life. Achieving a balance between biodegradability and performance can be challenging in these biodegradable-based grease lubricants.

However, the incorporation of perfluoropolyether (PFPE) into biodegradable lubricant formulations is found to be able to address these challenges [7]. PFPE is a synthetic fluorinated lubricant known for its exceptional thermal stability, chemical resistance, and low friction properties. By incorporating PFPE into biodegradable-based grease lubricants, it is possible to improve these biodegradable-based grease lubricants overall performance, such as enhancing their tribological properties, while still maintaining suitable level of biodegradability.

In the present work, motivated by the necessity of environmentally friendly and good tribological performance constituents in biolubricants preparation, this study aims to conduct a bibliometric analysis to examine the research trends related to the application of PFPE based grease biolubricants. By analysing the existing literature and research landscape, this study seeks to provide valuable insights into the development and potential of PFPE-based grease biolubricant. This analysis would also focus on the friction and wear behaviour of PFPE-based lubricants, narrowing down the scope of interest for exploring the adoption of PFPE-based lubricants in automotive applications.

2.0 METHODOLOGY

Bibliometric analysis is a quantitative analysis of written research papers. It presents an overview of the research field which can be categorised into publications, authors, countries and funding agencies. The method is widely utilised currently to study distinct science aspects and the ranking of relevant institutions or universities [8]. The accessibility of numerous search engines such as Google Scholar, PubMed, Science Direct, Scopus and Web of Science (WoS) substantially ease the search and retrieval of the academic databases and scientific publications. WoS is one of the most dominant search engine, providing global, consistent and accurate citation indexing services for more than 20,000 publications dealing with approximately 150 disciplines like art and humanities, science and social science [9]. Consequently, WoS database is selected in this study as the source of information for the bibliometric analysis.

On 16th November 2020, an advanced search was executed in WoS using the search string TS = ((PFPE or perfluoropolyether*) and (biodegradable or wear or grease)) and the time span was fixed to the 10 years (2010-2019). The asterisk functioned to enlarge the search scope for the terms preceding the asterisk. The search resulted in 128 papers, which contains journal articles, proceedings papers, books and reviews. Nonetheless, this analysis focused only on journal articles, proceedings papers and reviews, thus filtering the number of publications to 117. The results were then further reduced to 66 after filtering the topics related to the friction and wear properties of PFPE or biodegradable lubricants. The search strategy employed and the number of research papers remaining upon each stage is presented in Figure 1.

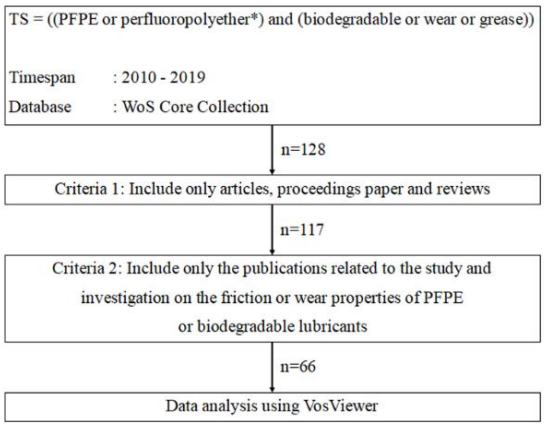

Figure 1: The search strategy employed for this bibliometric analysis

The relevant information, such as authors, title, source, document type, publication year and number of citations for the selected papers were extracted from the marked list. The information was downloaded from WoS and exported as Microsoft Excel file for further usage. Besides, the information like Hirsch index (h index), quartile ranking in Q and impact factor (IF) were retrieved from the citation report. Hirsch index is a single-number criterion to analyse the productivity and visibility of the publication [10]. According to Hirsch [11], the individual has index h if his or her papers reach minimum N_h number of publications,

each with minimum h citations. The IF is determined by dividing the total number of citations the paper received during the recent two years by the total publications released in that journal within the same duration. The IF represents the frequency of the papers cited in scientific literature [12].

VOSviewer is a freely available software developed by Van Eck and Waltman [13] for creating, visualising and analysing maps based on network data. The maps or networks of authors, countries, organisation, keywords, publications and journal categories can be generated using VOSviewer. In the present study, the bibliometric data were imported from WoS and transferred into bibliometric maps for the analysis of co-authorship, co-citation relationship and keyword co-occurrence. The network and overlay visualisation maps constructed are connected by the nodes of various sizes and each node has its label. The distance between the nodes depends on the similarities shared by the nodes. The nodes are connected with lines with different thickness based on the link strength [14].

3.0 RESULTS

General Publication Trend

The first publication on the friction and wear behaviour of perfluoropolyether (PFPE) was written by Scarati and Caporiccio [15] in year 1987. The topic gained quick responses and interests from many researchers as shown in Figure 2. It could be clearly seen that the number of publications was higher and the number of citations obtained increased drastically from 2010 to 2013.

There was a total of 66 papers found within the 10 years, from 2010 to 2019. The 66 publications included 61 articles (92.4%) and 8 proceedings papers (12.1%). The total citation received by the publications were 584 and the average citation per paper was 8.85. All the articles are published in English.

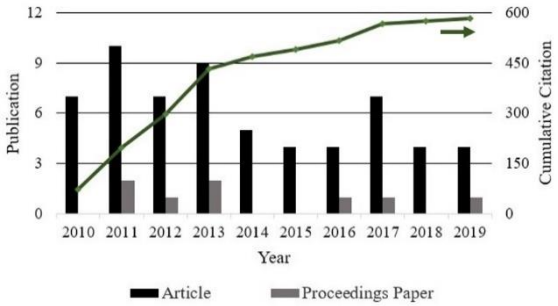

Figure 2: General publication trend on tribological performance of PFPE-based grease biolubricant topic

Journal Analysis

The top five productive journals with more than three publications, as depicted in Table 1, have published 82.4% of the total papers retrieved from WoS. Tribology Letters, concerning on the science of tribology and applications, produced the most publications (15 papers) with 44.1% cumulative percentage. While, Tribology International, reporting the investigations on tribology field, and wear, focusing on the fundamentals of wear, published the second most articles (5 papers) with 14.7% cumulative percentage.

On the other hand, Applied Surface Science, with the greatest impact factor of 6.182, published the first paper related to the tribological performance of PFPE grease in October 2010, primarily focusing on friction and wear characteristics and lubrication mechanism of PFPE. The co-citation network map among the journals is shown in Figure 3. Co-citation is a bibliometric indicator that measures the frequency of two publications being cited together, indicating a relationship or similarity between the two documents. The strength of co-citation relationship of the journals is indicated by the line thickness.

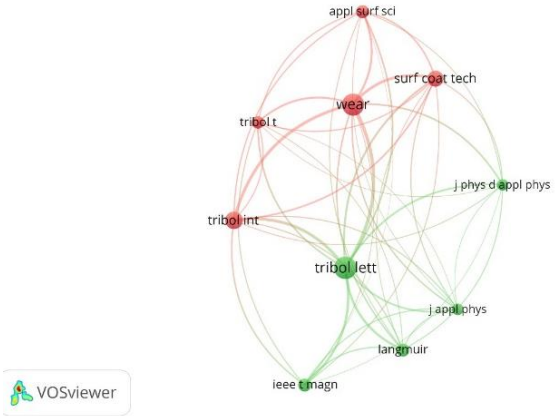

Figure 3: Co-citation network map among the journal

Table 1: Top productive journals on tribological performance of PFPE-based grease biolubricant topic

Journal	Q, Rank (2019)	IF (2019)	TP	%TP	Cumulative Percentage
Tribology Letters	Engineering, Chemical (Q2/66/143) Engineering, Mechanical (Q2/47/130)	2.566	15	44.1	44.1
Tribology International	Engineering, Mechanical (Q1/17/130)	4.271	5	14.7	58.8
Wear	Engineering, Mechanical (Q1/19/130) Materials Science, Multidisciplinary (Q2/91/314) Chemistry, Physical (Q1/37/159)	4.108	5	14.7	73.5
Applied Surface Science	Materials Science, Coating & Films (Q1/1/21) Physics, Applied (Q1/27/155) Physics, Condensed Matter (Q1/17/69)	6.182	3	8.8	82.4

IF=Impact factor; TP=Total number of publications; % TP=Percentage of total number of publications

Analysis of Top-cited Publications

A total of 20 (30.3%) papers published within the time span of 2010 to 2019 and received citations of 10 and above. The top-cited journals shown in Table 2, which studied on the friction and wear characteristics of PFPE or biodegradable grease comprised of a proceedings paper and ten articles. Samad et al. [16] were the first to study the friction coefficient and wear life of an air-plasma treated tool steel when the tool steel was coated with single film of Ultra-High Molecular Weight Polyethylene (UHMWPE) and dual film, UHMWPE and PFPE. The coating of PFPE over UHMWPE had been reported to highly improve the wear durability of the tool steel. Panjwani et al. [17] continued to investigate the effect of PFPE overcoat on UHMWPE on Ti6Al4V and the outcome of the experiment was similar to Samad et al. [16], where the wear life was enhanced. This was attributed to the molecules of PFPE being entrapped into the voids of UHMWPE in addition to its excellent tribological properties and thermal stability.

Polyether ether ketone (PEEK), an engineering thermoplastic with various outstanding properties, are useful in many applications like aerospace, biomedical and electrical. Nonetheless, it exhibited high friction coefficient and low wear durability. Loy and Sinha [18] attempted to cope with this issue by coating an ultrathin layer of PFPE and Multiply Alkylated Cyclopentane (MAC) lubricants on PEEK. The wear durability of PEEK has been shown to be enhanced at a rougher surface and higher concentration of lubricant. In their study, MAC is found to perform better in terms of friction coefficient and wear life.

Table 2: High impact publications on tribological performance of PFPE-based grease biolubricant topic

Title of Publication	Reference (author, publication year)	TC
Tool wear mechanisms and tool life enhancement in ultra-precision machining of titanium	Zareena and Veldhuis, 2012 [19]	50
Tribological characterization of a biocompatible thin film of UHMWPE on Ti6Al4V and the effects of PFPE as top lubricating layer	Panjwani et al., 2011 [17]	39
Wear performances and wear mechanism study of bulk UHMWPE composites with nacre and CNT fillers and PFPE overcoat	Liu and Sinha, 2013 [20]	38
Tribology of UHMWPE film on air-plasma treated tool steel and the effect of PFPE overcoat	Samad et al., 2010 [16]	32
Tribological studies of epoxy composites with solid and liquid fillers	Kumar et al., 2017 [21]	28
Self-lubricating SU-8 Nanocomposites for Microelectromechanical Systems Applications	Saravanan et al., 2013 [22]	26
Tribo-functionalizing Si and SU8 materials by surface modification for application in MEMS/NEMS actuator-based devices	Singh et al., 2010 [23]	22
Lubrication of polyether ether ketone (PEEK) surface by liquid ultrathin films for high wear durability	Loy and Sinha, 2012 [18]	18
Adhesion and Friction Properties of Molecularly Thin Perfluoropolyether Liquid Films on Solid Surface	Tani and Tagawa, 2012 [24]	15
Surface chemical modification for exceptional wear life of MEMS materials	Singh et al., 2011 [25]	14

TC=Total number of citations receive

Countries/Regions

The research on the friction and wear characteristics of PFPE or biodegradable grease has been conducted by fourteen countries. Five of the fourteen countries had published more than five papers related to the topic. The five top productive countries are displayed in Table 3. Navarrini et al. [26] were the first examine the friction and wear characteristics of PFPE in Italy, but no further research was done after the year 2010. Singapore is recognised as one of the main contributors to the topic, as indicated by the number of publications from 2010 to 2014, resulting the greatest total publication of 27 and highest h index of 11 developed.

China is in the second position in terms of publication and h index and follow by India. Nevertheless, China received citations of 109, less than India (140). It is worth mentioning that the number of articles released in 2013 is the most due to the concern of many researchers in modifying the tribological performance of SU-8. The material SU-8 is specially developed for micro-machines and micro-electronic applications but its poor friction and wear behaviour restricted its broader applications. The tribological properties of SU-8 had noticeable improved after PFPE has been introduced into it. The overlay visualisation of co-authorship network map of these countries is shown in Figure 4. The co-authorship relationship of the countries is indicated by the line connecting the nodes. Canada, England and Germany did not collaborate with other countries and strong co-authorship is only observed between Singapore and India.

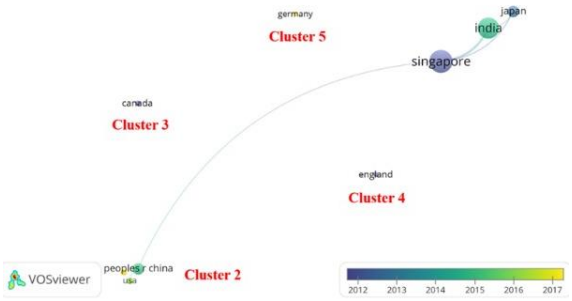

Figure 4: Overlay visualisation of co-authorship network among countries

Table 3: Five top productive countries/regions on tribological performance of PFPE-based grease biolubricant topic

Countries/ Regions	TP	%TP	Year										TC	h
			2010	2011	2012	2013	2014	2015	2016	2017	2018	2019		
Singapore	27	34.6	2	9	5	7	3	0	1	0	0	0	331	11
China	19	24.4	2	0	1	3	2	4	1	3	0	3	109	8
India	14	18.0	0	0	0	6	2	0	2	3	1	0	140	7
USA	8	10.3	0	1	0	1	0	1	1	0	3	1	22	3
Japan	5	6.4	1	0	2	0	1	0	1	0	0	0	47	5

TP=Total number of publications; % TP=Percentage of total number of publications; TC=Total number of citations received; h=h-index

Organisations

The publications on the friction and wear characteristics of PFPE or biodegradable grease were contributed by 29 organisations from various countries. A total of 15 organisations released more than one publication, as illustrated in Table 4. National University of Singapore is the most influential contributor to the research topic since 2010 with 321 citations obtained. Indian Institute of Technology is ranked second with 10 publications with the main contribution going to the authors, Sinha, Sujeet K. and Saravanan, Prabakaran. The co-authorship network of these organisations is depicted in Figure 5. Only two collaborations are noticed in China and between India and Singapore. In other words, other organisations are working individually.

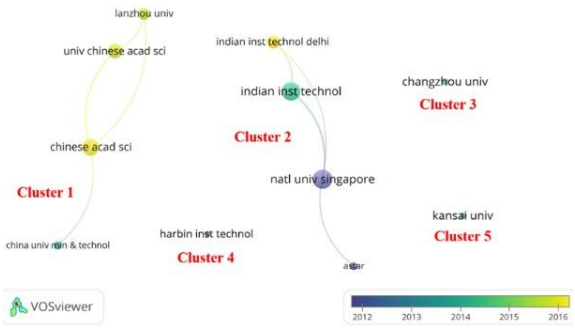

Figure 5: Overlay visualisation of co-authorship network among organisations

Table 4: Top productive organisations on tribological performance of PFPE-based grease biolubricant topic

Organisation	Country	Year										TP	% TP	TC	h
		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019				
National University of Singapore	Singapore	2	9	5	7	2	0	1	0	0	0	26	38.8	321	11
Indian Institute of Technology	India	0	0	0	6	1	0	1	2	0	0	10	14.9	124	6
Chinese Academy of Sciences	China	0	0	0	1	1	2	1	2	0	2	9	13.4	67	6
Indian Institute of Technology Delhi	India	0	0	0	0	1	0	2	2	1	0	6	9.0	58	5
University of Chinese Academy of Sciences	China	0	0	0	0	0	2	1	1	0	0	4	6.0	38	4
Changzhou University	China	0	0	0	2	0	1	0	0	0	0	3	4.5	14	2
Harbin Institute of Technology	China	2	0	0	0	0	1	0	0	0	0	3	4.5	14	2
China University of Mining and Technology	China	0	0	0	1	1	0	0	0	0	0	2	3.0	19	2
Agency for Science Technology Research	Singapore	0	2	0	0	0	0	0	0	0	0	2	3.0	33	2
Kansai University	Japan	0	0	1	0	1	0	0	0	0	0	2	3.0	23	2

TP=Total number of publications; % TP=Percentage of total number of publications; TC=Total number of citations received; h=h-index

Authors

A total of 155 researchers studied the effect of PFPE or biodegradable grease on the friction and wear characteristics of the contact surfaces. However, only 34 (21.9%) had produced more than one publication, as displayed in Table 5. Sinha, Sujeet K. is the most influential author that contributed to this research field, with 30 papers published and 364 citations received. A strong and wide collaboration network can be observed from the co-authorship network among authors in Figure 6 with the author, Sinha. In 2011, he had collaborated with Panjwani, Bharat and Satyanarayana, Nalam to produce one of the top-cited paper titled "Tribological characterization of a biocompatible thin film of UHMWPE on Ti6Al4V and the effects of PFPE as top lubricating layer".

Saravanan, Prabakaran and Minn, Myo are also significant contributors in the research field. They worked together with several scholars mainly on the enhancement of the tribological behaviour and application of SU-8 composite with PFPE.

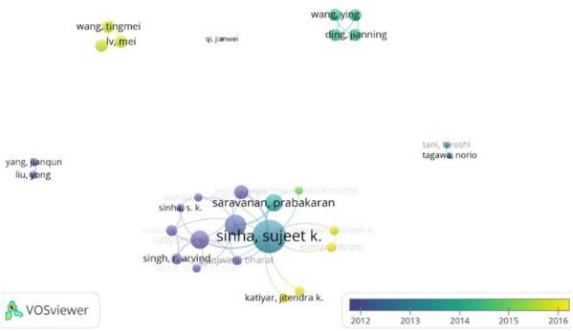

Figure 6: Overlay visualisation of co-authorship network among countries

Table 5: Top productive authors tribological performance of PFPE-based grease biolubricant topic

Author	Country	Year										TP	% TP	TC	h
		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019				
Sinha, Sujeet K.	India	2	9	5	7	2	0	2	2	1	0	30	39.0	364	12

Satyanaray ana, Nalam	Singapore	2	4	3	6	1	0	0	0	0	0	16	20.8	215	9
Saravanan, Prabakaran	India	0	0	0	4	1	0	1	0	0	0	6	7.8	54	4
Minn, Myo	Japan	0	4	1	1	0	0	0	0	0	0	6	7.8	48	4
Singh, R. Arvind	China	0	3	1	0	0	0	0	0	0	0	4	5.2	49	3
Ding, Jianning	China	0	0	0	2	0	1	0	0	0	0	3	3.9	14	2
Liu, Yong	USA	2	0	0	0	0	1	0	0	0	0	3	3.9	14	2
Lv, Mei	China	0	0	0	0	0	2	0	1	0	0	3	3.9	20	3
Panjwani, Bharat	India	0	1	2	0	0	0	0	0	0	0	3	3.9	47	3
Wang, Qihua	China	0	0	0	0	0	2	0	1	0	0	3	3.9	20	3

TP=Total number of publications; % TP=Percentage of total number of publications; TC=Total number of citations received; h=h-index

Funding Agencies

The 66 studies on the friction and wear characteristics of PFPE or biodegradable grease were sponsored by 25 funding agencies, where only 13 published two or more papers. Table 6 shows the funding agencies related to the relevant research with the funding agencies at national levels dominating the research on friction and wear of biodegradable greases. Singapore National Research Foundation supported 14, the greatest number of research, followed by NSFC, producing 10 publications. The support from these agencies also contribute to the higher number of journals released by the countries.

Table 6: Funding agencies related to tribological performance of PFPE-based grease biolubricant topic

Funding Agency	Country	Year										TP	% TP
		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019		
Singapore National Research Foundation	Singapore	1	8	2	3	0	0	0	0	0	0	14	29.2
National Natural Science Foundation of China NSFC	China	0	0	0	2	0	3	1	1	0	3	10	20.8
National Basic Research Program of China	China	0	0	0	1	0	2	1	2	0	0	6	12.5
Ministry of Education Culture Sports Science and Technology Japan MEXT	Japan	1	1	1	0	1	0	0	0	0	0	4	8.3
National Basis Research Foundation of China	China	2	0	0	0	0	1	0	0	0	0	3	6.3
National University of Singapore	Singapore	1	0	1	1	0	0	0	0	0	0	3	6.3
Fundamental Research Funds for the Central Universities	China	0	0	0	0	1	0	0	0	0	1	2	4.2
Grants in Aid for Scientific Research Kakenhi	Japan	0	1	0	0	1	0	0	0	0	0	2	4.2
IIT Delhi	India	0	0	0	0	0	0	1	0	1	0	2	4.2
Japan Society for the Promotion of Science	Japan	0	1	0	0	1	0	0	0	0	0	2	4.2

TP=Total number of publications; % TP=Percentage of total number of publications

Keyword Co-occurrence

The frequencies and co-occurrences of the keywords of 66 journals were examined. The shortened forms, singular and plural forms of the words with the same meaning were combined. Besides, the meaningless terms were ignored such as “composite”, “vacuum” and “epoxy”. Referring to Figure 7, the keyword “friction and wear” has been shown to be highly significant with the total link strength of 25, followed by “lubrication” and “PFPE” with the total link strength of 16. The ten keywords are categorised into four clusters with different colours. The first cluster is in red colour, indicating the earlier interest of the researchers in improving the properties of the material SU-8 with

PFPE. The improvement in the tribological performance of material SU-8 due to PFPE leads to the growth of cluster 2 (in red colour), cluster 3 (in blue colour) and cluster 4 (in yellow colour), representing the exploration of the scholars in enhancing the tribological behaviour of PFPE using polymer and composite. Wu et al. [27] reported that the MoS_2 is useful in decreasing the friction and wear of steel-to-steel contact lubricated with PFPE base oil. Besides, Huang et al. [28] stated that the tribological characteristics of the mixture of fluorinated candle soot and PFPE is better compared to pure PFPE. Wang et al. [29] also found that the combination of graphene oxide and PFPE possess better friction-reducing and anti-wear.

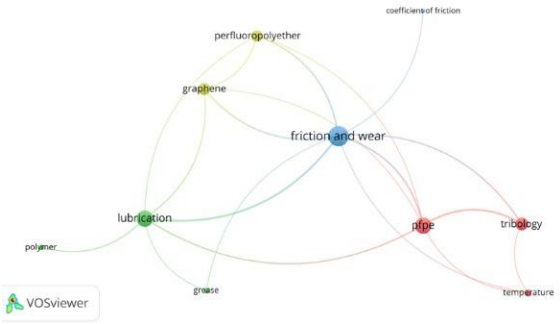

Figure 7: Overlay visualisation of co-authorship network among countries

4.0 CONCLUSION

In conclusion, this bibliometric analysis was conducted using the WoS database as the primary source of information. A total of 66 papers relevant to the topic of friction and wear properties of PFPE or biodegradable lubricants were included in this study. Previous research has focused on enhancing the tribological performance of materials such as DLC, SU-8, PEEK, and UHMWPE. The introduction of PFPE has shown significant improvements in the friction and wear behaviour of these materials. Additionally, researchers have explored methods to enhance the tribological properties of PFPE itself, including the use of graphene, MoS_2, and a mixture of CSP with perfluoro octanol. These additives have demonstrated the ability to reduce friction coefficients and improve wear life. Furthermore, the use of MAC and PFPE has been effective in extending the service life of MEMS. The results exhibit that MAC decreases friction and wear more effectively compared to PFPE. However, limited studies have been conducted on the potential automotive applications of PFPE-based biolubricants, highlighting a significant research gap that can be further explored in future studies.

Overall, this bibliometric analysis provides valuable insights into the current state of research in the field of PFPE-based grease biolubricants, emphasising the need for additional studies to bridge the gap in understanding their potential applications in the automotive industry.

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