TITANIUM OXIDE (TiO_2) NANOPARTICLE AS ADDITIVE FOR LUBRICANTS: A BIBLIOMETRIC ANALYSIS (1997-2022)

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ABSTRACT

Lubricant is a substance designed to minimize friction between surfaces in direct contact with each other, although it has certain limitations. To overcome these limitations, additives are generally added to the base oil to improve qualities like anti-wear, anti-friction, thermal properties, antioxidant properties, etc. Given this, recent advances have shown the great value of interest in nanoparticles as additives. Titanium dioxide nanoparticles as additives have emerged as a compelling addition to enhance engine efficiency. Its efficacy is evident in significantly reducing the coefficient of friction, antioxidant features, remarkable lubricating properties, cost-effectiveness, and non-toxic nature, along with economical, environmentally friendly and non-volatile characteristics. In this paper, a bibliometric analysis of the trend and application of metal oxide derivatives, i.e., titanium oxide (TiO_2) nanoparticles, as an additive for different base oils, has been done. The analysis is done on the data retrieved from Dimensions and Google Scholar, restricted to research articles only. The present analysis discusses various trends and co-relationships among authors, citations, and countries to understand the research trend. A total of 94 articles were examined and mapped using VOSviewer. Most of these articles were published in "Materials Today Proceedings" and the "Wear" journal. China emerged as the leading contributor in this research domain. An article from the "Wear" journal received the highest number of citations (1368). The highest number of articles was published in the year 2021.

KEYWORDS

Titanium oxide, Nanoparticle, Additive, Lubricant, VOSviewer

INTRODUCTION

Lubrication involves managing friction and reducing wear by inserting a film that minimizes friction between interacting surfaces in motion[1,2]. Various substances can be applied to surfaces for lubrication purposes, and such materials are commonly known as lubricants[2]. Thus, lubricant is a substance designed to minimize friction between surfaces in direct contact with each other. Lubricants are pivotal materials used in various applications ranging from home appliances to automotive to industrial equipment[2]. Fluids, solids, or plastic materials can serve as the lubricants employed, with oil and grease standing out as the most prevalent options.

Grease [3, 4] and Oil [5–7] (commonly known as base oil) used for lubrication purposes can be either synthetic, derived from vegetables, mineral-based, or a blend of these components. Base oils originating from vegetables and employed as lubricants are called biolubricants. Conversely, synthetic base oils predominantly consist of Polyalphaolefin, synthetic ester, mineral oil, polyglycol, and phosphate ester. The main roles of a lubricant encompass Minimizing friction, averting wear, shielding equipment against corrosion, and managing temperature by dispersing heat. Lubricants, whether natural or synthetic, have restrictions on meeting the requirements of various industrial applications. Pure base oils alone may not meet all the necessary lubrication criteria in specific situations. Therefore, supplementary substances must be introduced into the base oil, creating a blend known as a lubricant. Normally, this mixture consists of about 90% base oil and 10% additives.

The proportion of additives can vary from as low as 0.1% to as high as 30% and can be employed individually or in combination. These additives serve the purpose of imparting distinct qualities to the overall lubricant. Some key attributes that additives contribute to the base oil include antioxidation, anti-wear properties, corrosion inhibition, and excellent extreme pressure performance. The choice of additives is determined by the specific conditions of the application, as well as their compatibility with the base oil and other additives. Various additives are available, each serving distinct purposes [8–10].

With the progression of nano-sized technology, nanomaterials have emerged as a profoundly captivating subject in different fields of science. The minute dimensions of nanomaterial additives facilitate enhanced interaction between surfaces experiencing friction. Moreover, the heightened surface reactivity of nano additives contributes to the durability of the protective tribofilm layer by establishing a physical and chemical absorption layer. In recent years, numerous studies have focused on exploring the potential of lubricants infused with nanoparticles to regulate friction and minimize wear within systems. Various investigations have been employed on organic and inorganic nanoparticles within this context. Lubricant nano additives can be broadly categorized into carbon nanomaterials, composite compounds and metal nano additives. Carbon-based nanomaterials [11–14] include entities like carbon nanotubes [13, 15], nanodiamonds [13], fullerene [13] and graphene [13, 16]. On the other hand, composite compounds [13] comprise combinations such as TiO_2/SiO_2 and Al_2O_3/SiO_2, as well as graphene-based nanocomposites like FeS_2/G, Ag/G, and Cu/G. Metal nano additive [13] is a vast category which includes pure metals (Fe, Ni, Cu, Ag, etc.), metal oxide(CuO, TiO_2, ZnO, Al_2O_3, and ZrO_2, metal sulfides (MoS_2, CuS, WS_2, and ZnS), metal hydroxides ($La(OH)_3$), metal salts ($CaCO_3$, Zinc Phosphate and LaF_3). Lubricant additives based on metals have garnered significant interest from researchers [7, 14, 17, 18]. Among these, metal oxides have demonstrated noteworthy enhancements in properties [7, 13, 14, 18–21].

Titanium dioxide has emerged as a promising additive for improving engine efficiency. It has demonstrated its effectiveness by substantially decreasing friction coefficient through lubricant viscosity elevation [22]. This material has garnered attention due to its affordability, lack of toxicity, excellent dispersibility, stability in base lubricants, impressive lubricating qualities, and practical application potential in engineering [23–29]. Apart from these favourable attributes, it has been utilized to create cost-effective, environmentally friendly lubricants with antioxidant properties, relatively low toxicity, a pleasing odour, and non-volatility [30, 31]. To sum up, the exploration and advancement of TiO_2 nanoparticles have demonstrated considerable potential for application for lubricants. Nevertheless, research on the plausible uses of TiO_2 nanoparticles as additives is scarce. This underscores a substantial void in research that warrants investigation in upcoming investigations.

Bibliometric analysis is a statistical assessment of published scientific literature, including articles, books and book chapters. This method is extensively employed to scrutinize various aspects of scientific research. It thus serves as a potent approach for quantifying the impact and influence of publications within the scientific community. With this perspective, the current research has opted to conduct a bibliometric analysis on TiO_2 nanoparticle additives for lubricants. Titanium dioxide (TiO_2) can be employed in its original form or a coated variation. This study aspires to offer significant revelations regarding the advancement and prospects of lubricants having TiO_2 nanoparticles as an additive through a comprehensive examination of the available research literature.

Data Source and Methodology

The data for this study is derived from research articles published in journals indexed by Google Scholar and Dimensions. Both research platforms were chosen as the resources for this study due to their accessibility as free platforms. The search criteria involve the keywords "TiO_2" AND "nanoparticles", "lubricant", and "additive". The data collection for this study includes a time span of all years, and the filtering process includes considering the keywords in the fields, such as the title and abstract of the publications. One hundred seventeen relevant search results were identified in line with the topic. Subsequently, a more refined selection process was undertaken, focusing on research articles up to 2022, resulting in a final count of 94 articles. This subset of research articles is being utilized to implement bibliometric analysis.

Various data like citation no., h-index & quartile (Q rank) category were projected here from the data source taken by dimensions software and Scimago journal & Country rank (SJR) for accessing the research articles. VOSviewer is a software application designed to create and display bibliometric networks in a visual format[32]. The

present study uses the same software to construct visual representations, such as author networks, country affiliations, citation networks, publication patterns, and journal categorizations.

Results and Discussions

General Publication Trend

Throughout the comprehensive 25-year analysis from 1997 to 2022, 94 publications were identified, as depicted in **Figure 1**. The first publication regarding this topic emerged in 1997, authored by Qunji Xue et al.[27]. Following that initial publication, there's been a steadily increasing interest in the domain, evidenced by the growing number of articles centred on TiO_2 as an additive for lubricants. Notably, the peak in publications was observed in 2021. In the early stages, specifically during 1988, 1999, and 2005, no publication pertinent to the analysis topic was identified. Segmenting the entire duration since the onset of publications in 1997 into approximately five-year intervals reveals a noticeable uptrend in research related to the topic, as demonstrated in Table 1. The starting segment recorded five publications, followed by a consistent growth pattern, registering 7, 13, 23, and 46 publications in the successive segments (Groups 2, 3, 4, and 5). Notably, there was a marked increase in the publication trend in 2020, 2021, and 2022, with 10, 15, and 10 articles published, respectively. As the demand for lubricants with enhanced qualities and heightened efficiency continues to grow, research in this field has attracted escalating attention, as evidenced by the trend in paper publications over the years

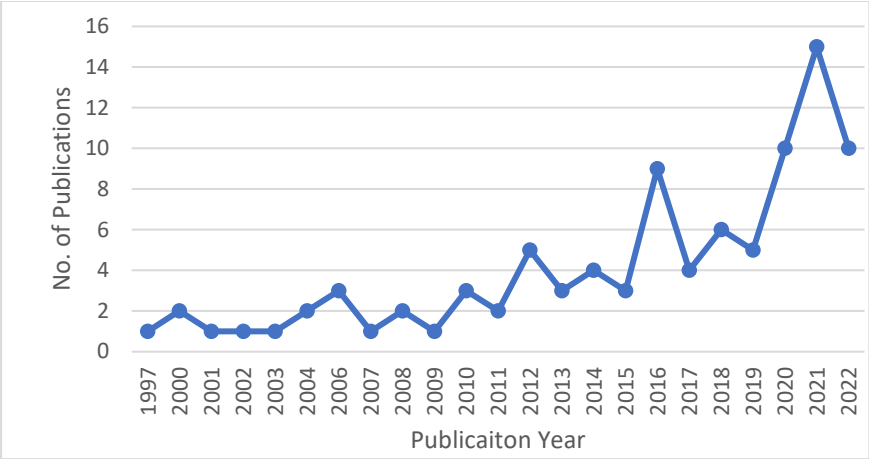

Figure 1: Articles publication trend over the years

Table 1: Groupwise article publication data chart

Groups (year range)	Publications	% of publications
Gr 1 (1997-2002)	5	5.32
Gr 2 (2003-2007)	7	7.45
Gr 3 (2008-2012)	13	13.83
Gr 4 (2013-2017)	23	24.47
Gr 5 (2018-2022)	46	48.94

Analysis of Publication Trends and Co-Citation Among Journals

A total of 50 distinct journals contributed to the publication of these articles. The publication trend shows that the spectrum is wide, and the topic is published in different journals. The five leading journals, each publishing five or more than five papers, collectively account for 32% of the overall publications. Most of the remaining journals typically contributed one or two articles each. The highest number of articles by a single journal is 7. Table 2 enumerates the top five journals, including specific metrics such as Q rank and H-index

Table 2. List of top 5 journals with their metrics

Journal title	Total Publications (TP)	% TP	Cumulative %	Q rank	H Index
Materials Today: Proceedings	7	7.45	7.45	Q2	69
Wear	7	7.45	14.89	Q1	179
Tribology transactions	6	6.38	21.28	Q2	73
Tribology International	5	5.32	26.60	Q1	140
IOP Conference Series Materials Science and Engineering	5	5.32	31.91	NA	54

Co-citation is a bibliometric metric used to determine how often two publications are jointly cited, suggesting a link or likeness between them. The thickness of the line denotes the intensity of the co-citation connection between journals. **Figure 2** shows the network visualization of co-citation of sources, keeping the criteria of minimum number of citations at 20.

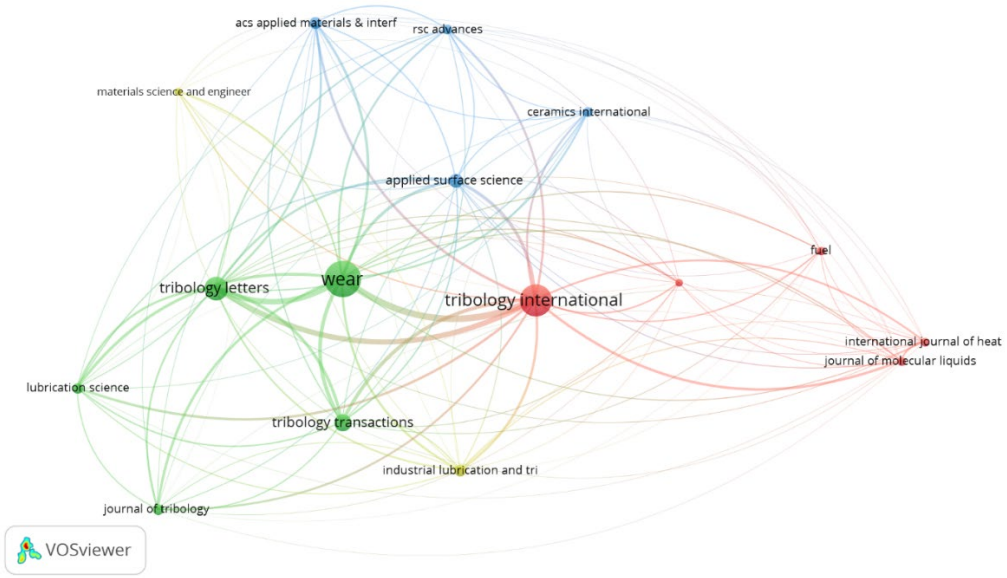

Figure 2: Network visualization of co-citation of publications

Citation Analysis of Source Titles

The cumulative citation count for all the titles included in the analysis amounted to 4785. The average number of citations per paper was 51%. Among the titles selected for analysis, approximately 59 of them received more than ten citations, while 26 articles garnered over 50 citations each. Impressively, 16 articles were cited more than 100 times. This trend highlights the significant influence and recognition of the title within the research community. Table 3 provides an overview of the top 10 most cited articles. Notably, the leading article[33] stands out with an impressive 627 citations, underscoring the pivotal role of TiO_2 nanoparticles as additives for biolubricants derived from palm oil-based TMP (trimethylolpropane) esters. The incorporation of TiO_2 nanoparticles into TMP ester yielded notable advantages. This included a significant 15% decrease in the friction coefficient and an 11% reduction in the wear scar diameter compared to the TMP ester without TiO_2 nanoparticles. The subsequent three articles on the list, each cited over 200 times, highlight the pivotal role of TiO_2 nanoparticles in various domains. These articles emphasize their significance in enhancing tribological properties, improving resistance to abrasive wear in coatings, and their pivotal function in reducing friction and enhancing anti-wear properties.

Table 3. List of top 10 cited articles

No.	Title	Journal	Publication Year	Authors	Times Cited
1.	Experimental analysis of tribological properties of lubricating oils with nanoparticle additives	Wear	2007	Y.Y. Wu, W.C. Tsui, T.C. Liu	627
2.	Improving the tribological characteristics of piston ring assembly in automotive engines using Al_2O_3 and TiO_2 nanomaterials as nano-lubricant additives	Tribology International	2016	Mohamed Kamal Ahmed Ali et. al.	259
3.	Abrasive wear characteristics of plasma sprayed nanostructured alumina/titania coatings	Wear	2000	You Wang et. al.	240
4.	Friction and wear properties of a surface-modified TiO_2 nanoparticle as an additive in liquid paraffin	Wear	1997	Qunji Xue, Weimin Liu, Zhijun Zhang	229
5.	Synthesis and Application of Inorganic Nanoparticles as Lubricant Components "a Review	Journal of Nanoparticle Research	2004	V.N. Bakunin et. al.	188
6.	Study on friction and wear behavior of polyphenylene sulfide composites reinforced by short carbon fibers and sub-micro TiO_2 particles	Composites Science and Technology	2008	Zhenyu Jiang et al.	165
7.	A study of the tribological behaviour of TiO_2 nano-additive water-based lubricants	Tribology International	2017	Hui Wu et. al.	164
8.	Application of TiO_2 nanoparticles as a lubricant-additive for vapor compression refrigeration systems "An experimental investigation	International Journal of Refrigeration	2012	R. Krishna Sabareesh et al.	154
9.	On the sliding wear of nanoparticle filled polyamide 66 composites	Composites Science and Technology	2006	L. Chang et al.	149
10.	Microstructure and tribological behavior of polymeric nanocomposites	Industrial Lubrication and Tribology	2001	Min Zhi Rong et. al.	143

A citation analysis of documents based on their citation numbers was also conducted using VOSviewer software. The criteria set for this analysis was a minimum of 100 citations per document. From this, a total of 8 clusters emerged. **Figure 3** visually presents the largest cluster, which comprises a collection of 12 interconnected items

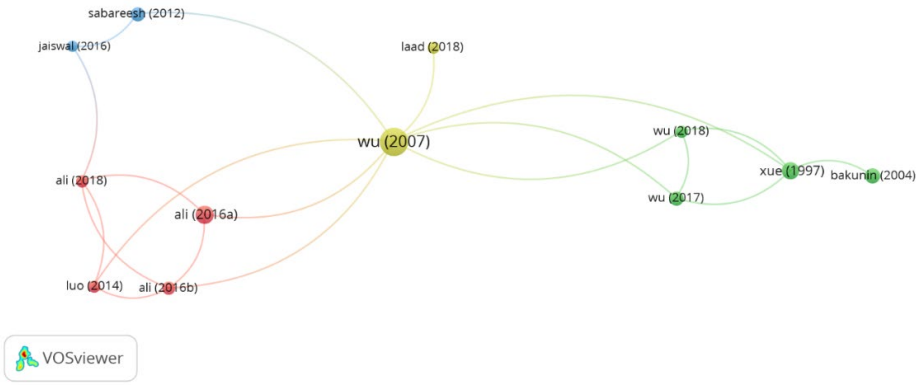

Figure 3: Citation cluster of most cited articles (largest set of connected items)

Citation Analysis of Journals

The citation analysis of journals illustrates their significance based on the number of citations these have received. Table 4 lists the top five journals, ranked according to the cumulative number of citations for all pertinent articles these have published. **Figure 4** visually represents the largest interconnected cluster among the most frequently cited ones, using a minimum document criteria 2.

Table 4. Top 5 journals with the highest citation

Journal name	Articles	Citation
Wear	7	1368
tribology international	5	656
composites science and technology	3	396
journal of nanoparticle research	3	245
industrial lubrication and tribology	4	218

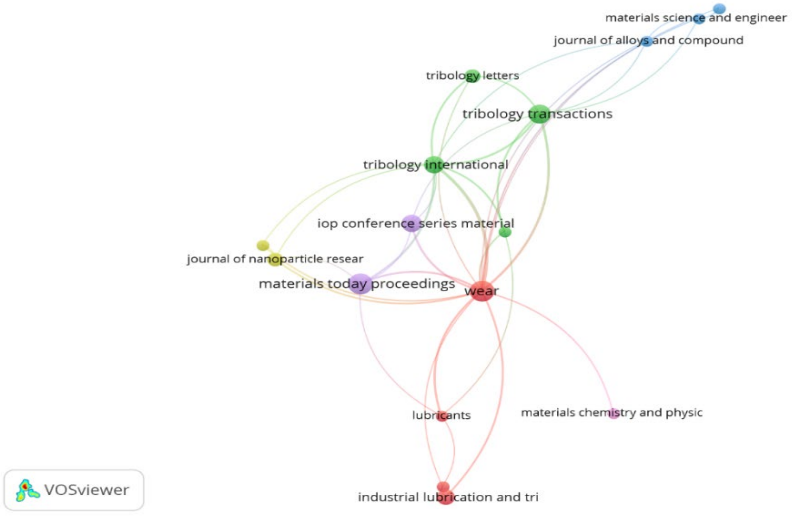

Figure 4: Citation cluster of most cited journals (largest set of connected items)

Authors and Co-authorship Analysis

A total of 379 authors contributed to the articles taken for analysis of the mentioned title. Out of this group, eight authors published three or more articles. Thirty-four authors contributed to 2 articles, while the remainder authored a single article each. Notably, Hui Wu[23, 25, 30, 34, 35] took the lead by co-authoring the most articles (5) in connection with other authors in the relevant search title. Mohamed Kamal Ahmed Ali and Hou Xianjun[36–39], in collaboration with other researchers, penned four articles. Zhijun Zhang[27, 40–42] contributed to 4 articles, of which he co-authored 3 with Qunji Xue[27, 41, 42]. Zhengyi Jiang, Wenzhen Xia, and Jingwei Zhao jointly authored three articles[23, 25, 35]. Table 5 lists those who published three or more articles, along with the respective years of publication. Notably, almost all the papers considered in this study resulted from the collaborative efforts of two or more researchers. **Figure 5** visually represents co-authorship patterns, with a minimum authorship criterion set at 2.

Table 5: Top 5 authors list with metrics

No.	Authors	Documents	citations	Publication years (Articles)
1	Hui Wu	5	314	2018 (1), 2017 (1), 2016(3)
2	Mohamed Kamal Ahmed Ali & Hou Xianjun	4	564	2018 (1), 2016(3)
3	Zhijun Zhang	4	441	2003(1), 2002 (1), 2000 (1), 1997(1)
4	Qunji Xue	3	348	2002 (1), 2000 (1), 1997 (1)
5	Zhengyi Jiang, Wenzhen Xia & Jingwei Zhao	3	348	2018 (1), 2017 (1), 2016 (1)

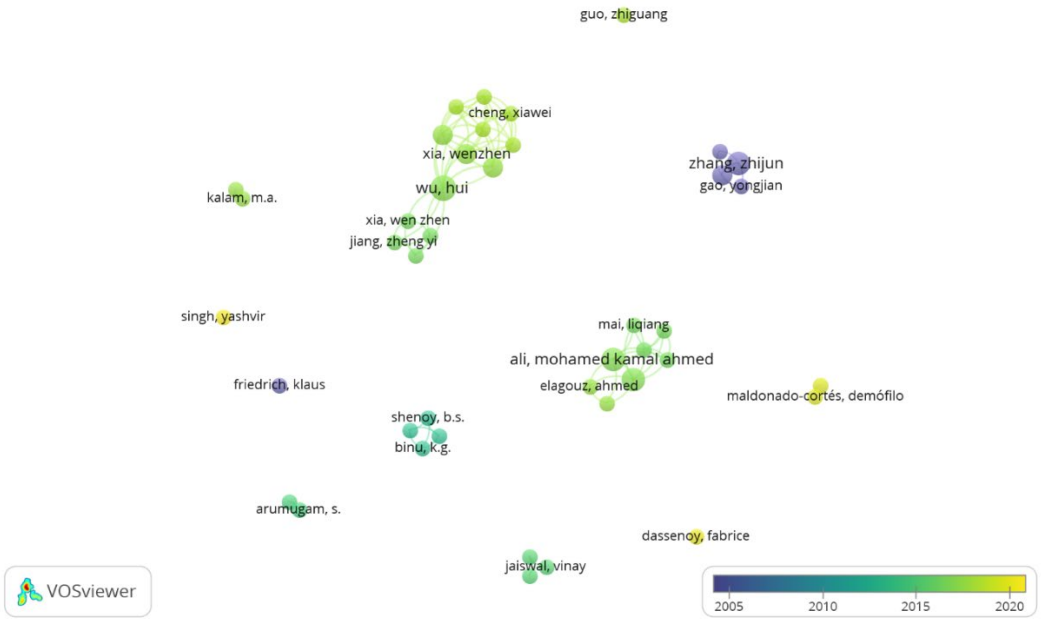

Figure 5: Overlay visualization of co-authorship among authors

Analysis of Published Articles among Countries and Citation of Countries

A total of 94 articles with author affiliations were published in 27 different countries. The list of five productive countries is displayed in Table 6, which reveals China as first place with the maximum number of article publications and a maximum citation total of 2,277. India acquires the second position in the list with a total publication of 24 with 841 citations. The potential justification for increased research activity in nations such as China and India could be attributed to the predominant influence of Asia-Pacific countries in the industrial lubricant market. This dominance stems from the escalating automotive production, ongoing construction and infrastructure development, and consistent demand from regional

manufacturing plants. Asia-Pacific stands out as the primary consumer of lubricants, accounting for approximately 14 million metric tons (MMT) annually. Within this total, China contributes 4 MMT, while India contributes 2.4 MMT. Australia and Malaysia share the third position with seven articles each and 494 and 175 citations, respectively. Taiwan, Germany, Mexico, and Egypt each published four articles, among which Taiwan has the most citations. **Figure 6** shows the network visualization of citations among countries; the cluster has the most interconnected countries.

Table 6. List of top 5 countries with the highest number of published papers

No.	Country	Documents	Citations	Year(article)
1	China	37	2277	2022(2), 2021(3), 2020(4), 2019(1), 2018(3), 2017(2), 2016(6), 2014(2), 2013(1), 2012(2), 2011(1), 2010(2), 2009(1), 2008(2), 2006(1), 2003(1), 2002(1), 2001(1), 2000(1), 1997(1)
2	India	24	841	2022(3), 2021(8), 2020(2), 2019(2), 2018(2), 2016(2), 2014(2), 2013(1), 2012(2)
3	Australia	7	494	2021(1), 2018(1), 2017 (1),2016(3), 2008(1)
4	Malaysia	7	175	2022(2), 2021(2), 2020(1), 2019(1), 2015(1), 2013(1)
5	Taiwan	4	720	2011(1), 2010(1), 2007(1), 2006(1)
	Egypt	4	564	2018(1), 2016(3)
	Germany	4	539	2008(1), 2006(2), 2001(1)
	Mexico	4	54	2021(1), 2018(1), 2017(1), 2015(1)

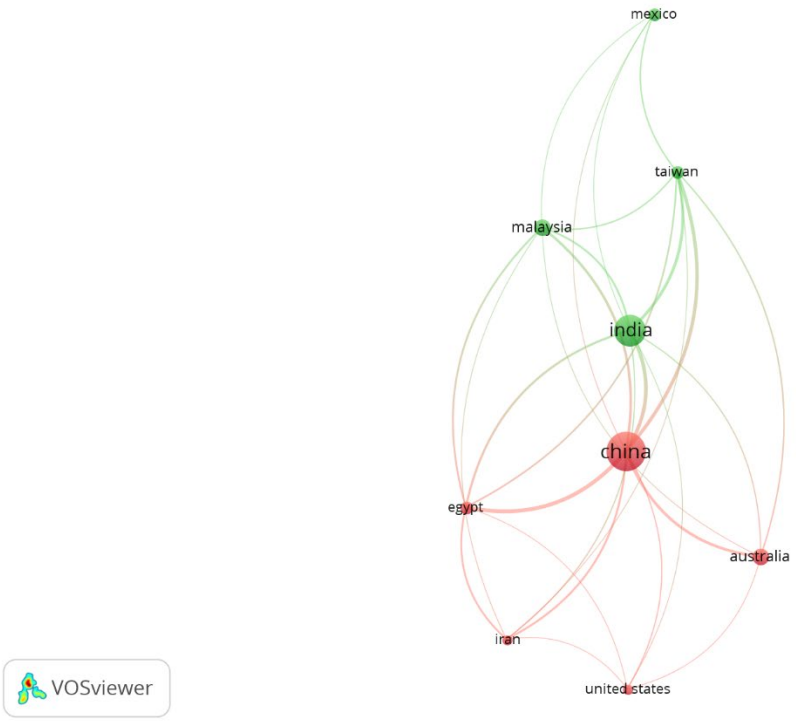

Figure 6: Network visualization of citations among countries

CONCLUSION

In total, 94 relevant articles were published from 1997-2022, highlighting the importance of TiO_2 nanoparticles as an additive for the lubricant. Such a high amount of research shows the potential of this nanoparticle. This bibliometrics study aims to combine the VOSviewer application's mapping in highlighting and analyzing the role of TiO_2 nanoparticles as an additive in lubricants. The study reveals the continuous growth in the research as the year passes with the no. of articles published.

Materials Today: Proceedings and Wear are the platforms where most articles are published. Title: "Experimental analysis of tribological properties of lubricating oils with nanoparticle additives", published in the journal Wear authored by Y.Y. Wu et al., in 2007, proved to be the most important article, as promised from its citation no. i.e. 627. Articles published in the journals Wear and Tribology International got the maximum number of citations, 1368 and 656, respectively. China showed the maximum contribution to the research, reflected in its affiliation in publishing 37 articles, followed by India, which showed research contribution in the field with association in the publication of 24 articles.

Furthermore, 2021 exhibited the most pronounced surge in research interest, as evidenced by the abundance of publications. Overall, this bibliometric assessment offers valuable perspectives on the present research landscape concerning incorporating TiO_2 nanoparticles as additives in lubricants. It accentuates the necessity for supplementary investigations to address the knowledge gap surrounding their potential roles in lubrication. Furthermore, it is recommended that more nations collaborate to delve into this subject, aiming to harness the potential of such materials as additives to enhance the deficient properties within lubricants.

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