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Global research trends in biodiesel production from palm fatty acid distillate (PFAD) using CaO, MgO, and TiO_2 heterogeneous catalysts: a bibliometric analysis (2015-2025)

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Abstract

This bibliometric study provides a comprehensive of global research on biodiesel production from palm fatty acid distillate (PFAD) using heterogeneous CaO, MgO, and TiO_2 catalysts during the period of 2015–2025. A total of 179 Scopus-indexed documents were analyzed by means of VOSviewer to examine publication trends, citation impact, co-authorship networks, and keyword co-occurrence. It is evident that Malaysia, Thailand, and Indonesia dominate both the publications and citations, reflecting their dominant palm oil production capacity. A substantial proportion of publications is concentrated on high-impact journals in the fields of energy and chemical engineering. A keyword clustering analysis reveals five main themes: process optimization, catalyst synthesis (including waste-derived CaO), feedstock diversification, activation/intensification techniques, and sustainability. The results demonstrate a predominance of laboratory-scale studies employing waste-based oxides, with a paucity of research addressing pilot-scale implementation, techno-economic assessment, and life cycle analysis. The findings provide a strategic roadmap for researchers, policymakers, and industry stakeholders to prioritize future developments in PFAD-based biodiesel production, particularly in catalyst scale-up, techno-economic assessment, and sustainable process integration. The primary benefit of this study is its capacity to systematically consolidate a decade of disparate research into a structured analytical framework, thereby enabling more targeted investment in under-explored areas such as pilot-scale implementation and life cycle analysis. In turn, this is expected to accelerate the transition of PFAD-based biodiesel from laboratory research to industrial application.

Keywords: Biodiesel production; palm fatty acid distillate (PFAD); heterogeneous catalysts; renewable energy; bibliometric analysis

1. Introduction

Global population growth and rapid industrialization have triggered a surge in global energy demand. Excessive reliance on fossil fuels not only has raised concerns about depleting oil reserves but also contributed significantly to greenhouse gas emissions and global climate change. In response to this challenge, renewable energy production, particularly biodiesel, has experienced rapid growth. Biodiesel is an attractive alternative due to its biodegradability, non-toxicity, and cleaner combustion emissions profile in comparison to conventional diesel fuel [1]. A significant challenge to the sustainable production of biodiesel is the cost of raw materials, which can account for 70-95% of total production costs. The utilization of edible vegetable oils has given rise to sparked debate. Consequently, the utilization of waste or byproducts from the palm oil processing industry, such as Palm Fatty Acid Distillate (PFAD), constitute a strategic solution. PFAD is abundantly available in palm oil-producing countries and has a much lower price than Crude Palm Oil (CPO). However, PFAD has a high free fatty acid (FFA) content, which complicates conventional transesterification processes due to the high risk of soap formation (saponification) [2].

The high FFA content of PFAD has driven a transition from homogeneous to heterogeneous catalytic systems. The catalysts comprise basic and acidic metal oxides, including calcium oxide (CaO), magnesium oxide (MgO), and titanium dioxide (TiO_2). CaO is popular due to its strong basic properties and low cost. MgO is attractive due to its thermal stability and affinity for the formation of magnesium salts, which can help to overcome FFA. TiO_2 is frequently employed to increase the catalyst surface area, enhance structural stability, and facilitate the distribution of the active phase when mixed with other oxides [3]. Experimental studies and several reviews have demonstrated that combinations or modifications of CaO–TiO_2 or TiO_2–MgO can enhance biodiesel conversion and catalyst resistance to leaching [4]. The primary advantages in the utilization of heterogeneous catalysts encompass ease of separation from the final product, reusability, and minimal wastewater generation in comparison to conventional methods [5]. Recent

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studies published in Communications in Science and Technology have demonstrated the growing development of sustainable heterogeneous catalysts derived from biomass waste, mesoporous silica, and metal-supported materials for biodiesel and biofuel production. These studies highlight the significance of catalyst design, surface modification, and bifunctional catalytic systems in enhancing fuel conversion efficiency and sustainability [83].

As the literature on PFAD and metal oxide catalysts continues to expand, a critical gap exists in the systematic quantitative mapping of its intellectual structure. While bibliometric studies have addressed biodiesel in a broad sense (Sulaiman et al., 2025; Das et al., 2025) or heterogeneous catalysts in general (Pratama et al., 2024), none has examined the tripartite intersection of PFAD with CaO, MgO, and TiO_2 simultaneously. This present study addresses this gap by means of three original contributions: (1) the initial bibliometric mapping of the PFAD-CaO/MgO/TiO_2 research landscape; (2) a research lifecycle classification framework assigning maturity status to each keyword cluster; and (3) a citation quality disparity analysis revealing research impact inequity between producer nations, with direct policy implications. Bibliometric results will facilitate the development of a more focused research agenda for the development of CaO, MgO, and TiO_2 catalysts for PFAD processing into biodiesel [6]. This objective of this study is to provide a comprehensive mapping of publications on biodiesel production from PFAD using CaO, MgO, and TiO_2 catalysts, identifying research trends, authors, and key application areas during the period 2015–2025. The data for this study were obtained from the Scopus database and analyzed using Vosviewer software.

The novelty of this study lies in three dimensions. Firstly, no prior bibliometric study has specifically mapped the intersection of PFAD as a feedstock with the three key metal oxide catalyst types (CaO, MgO, and TiO_2) simultaneously within a single analytical framework. Existing bibliometric works have addressed either biodiesel in general or heterogeneous catalysts in a broad sense, without the feed-stock specific focus adopted here. Secondly, the study introduces an interpretive research lifecycle framework that classifies the five identified keyword clusters into maturity stages (emerging, developing, and mature). This provides a new conceptual lens for understanding the evolutionary trajectory of PFAD biodiesel catalyst research. Thirdly, the present study quantitatively evaluates disparities in citation quality between countries, thereby revealing a significant research impact gap that carries direct policy implications for national research investment in palm oil-producing nations. Collectively, these contributions elevate the study beyond standard bibliometric mapping towards an analytical and policy-relevant study.

This study therefore contributes a forward-looking analytical overview that moves beyond descriptive trend mapping, thus supporting a more focused and evidence-based research agenda for CaO, MgO, and TiO_2 heterogeneous catalysts in PFAD biodiesel production.

2. Materials and Methods

This present study employed bibliometric analysis techniques to provide an overview of quantitative data and create a bibliometric map [7]. The research data was obtained using the Scopus database, the most widely used online reference source, encompassing a broader range of bibliometric data, broader journal coverage, and a faster indexing process [8].

The Scopus database was systematically searched on January 10, 2025, employing the following Boolean search string: TITLE-ABS-KEY ("biodiesel production" AND "palm fatty acid" AND ("heterogeneous catalyst" OR "CaO" OR "MgO" OR "TiO_2"). The initial search retrieved 204 documents. Having applied the inclusion criteria detailed as outlined in Table 1, a total of 179 documents were retained for analysis. The following criteria were used to identify the publications to be excluded from the analysis: (i) the publication were outside the 2015–2025 publication range, (ii) the publication were outside the designated subject areas, (iii) the publication were conference abstracts without full-text availability, or (iv) the publication were duplicates identified during data cleaning with OpenRefine. It is important to note that the citation analysis in Section 3.2 identifies the most frequently cited references within the 179 retained documents. Consequently, foundational studies published prior to 2015 may appear in this citation ranking, as they represent the primary reference anchors cited by the analyzed 2015–2025 publications. Their presence reflects citation patterns within the dataset, rather than constituting a breach of the inclusion criteria.

Scopus was selected as the exclusive bibliographic database for this study for several evidence-based considerations. Mongeon and Paul-Hus [8] demonstrated that Scopus provides broader journal coverage in engineering, chemical, and environmental sciences compared to Web of Science, thus making it the more appropriate primary database for this interdisciplinary topic. Furthermore, a higher number of journals from Southeast Asian countries are indexed by Scopus than by alternative databases, thereby reducing regional publication bias. Nevertheless, the use of a single database is acknowledged as a limitation of this study. Some relevant publications, which are indexed exclusively in Web of Science, Dimensions, or Google Scholar may not be represented in the dataset. It is recommended that future studies to conducted be to validate and extend these findings utilizing multi-database search strategies, including patent repositories such as Espacenet, to capture both academic and applied technological developments. Additionally, the English-language dominance of Scopus may result in an underrepresentation of publications in regional languages from Indonesian, Thai, and Malaysian institutions, which could introduce a language publication bias.

This study analyzes the development of research related to biodiesel from Palm Fatty Acid Distillate (PFAD) using heterogeneous catalysts based on CaO, MgO, and TiO_2 over the past decade. The analysis was conducted by reviewing publication trends, the most influential journal sources, dominant keywords, prolific authors and countries, and articles with the greatest citation impact [9]. To visualize the patterns and relationships in this data, this study employed VOSviewer software. VOSviewer is a bibliometric visualization software developed by Nees Jan van Eck and Ludo Waltman from Leiden University, the Netherlands [10,11]

The selection of VOSviewer over alternative bibliometric tools (e.g. CiteSpace, Bibliometrix, and Pajek) was made with a consideration of its superior capacity to facilitate multidimensional network visualization and its wide adoption in recent bibliometric studies in the domains of energy and biofuel

research [12].

Table 1. Inclusion criteria applied when retrieving data from Scopus

Option	Inclusion Criteria
Year	2015-2025
Subject Area	Chemical Engineering Energy, Chemistry, Environmental Science, Engineering, Physics and Astronomy Material Science
Source Type	Journal, Conference Proceeding
Document Type	Article, Conference Paper, Review

The filtered documents were then subjected to a process of cleaning using OpenRefine to reduce bias. This was achieved by substituting words with similar meanings but different spellings with terms with similar meanings and spellings to enhance the accuracy of the data analysis [13]. The OpenRefine data were then analyzed using VOSviewer (version 1.6.18) to visualize the final bibliometric data, and Origin Pro 2019 to visualize the data graphically.

3. Results and Discussion

This section provides a review of the bibliometric analysis conducted on the literature related to biodiesel production from Palm Fatty Acid Distillate (PFAD) using heterogeneous catalysts based on CaO, MgO, and TiO_2. Bibliometric analysis is a widely utilized method for systematic evaluation of research performance, intellectual structure, and collaborative patterns within a scientific field [14]. This present analysis illustrates the distribution of publication growth trends on an annual basis, the most influential primary publication sources, the occurrence of dominant keywords, leading authors in this field, articles with the highest number of citations, and countries that are major contributors to research on metal oxide catalysts for biodiesel production from PFAD. The bibliometric analysis reveals a relatively robust pattern of scientific collaboration among authors in this research domain.

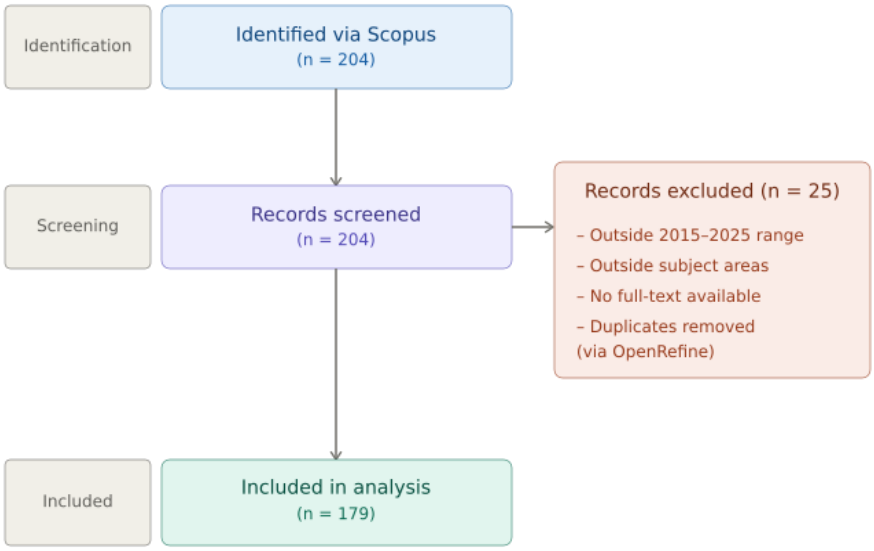

Fig. 1. PRISMA flow diagram illustrating document selection from 204 to 179 records

A visualization of publication data extracted from the Scopus database was conducted using VOSviewer with the objective of identifying several authors as occupying central positions in the co-authorship network. In bibliometric network analysis, authors with a high number of links and strong total link strength are typically regarded as key contributors who facilitate knowledge diffusion and interdisciplinary collaboration [10,36]. A bibliometric analysis of the 179 documents extracted from Scopus reveals distinct patterns across publication trends, authorship, citation impact, journal distribution, keyword co-occurrence, and country productivity, as detailed in the following sub-sections.

3.1. Publication trend

Data obtained from the filtered Scopus database reveal a total of 179 articles published between 2015 and 2025 using the keywords “Biodiesel Production,” “Palm Fatty Acid,” and “Heterogeneous Catalyst,” combined with “CaO,” “MgO,” or “TiO_2.” Bibliometric trend analysis is a well-established method to evaluate the growth, maturity, and research dynamics of a scientific field over time [9,14].

As demonstrated in Figure 2, there has been an increasing trend in number of publications focusing on biodiesel production from Palm Fatty Acid Distillate (PFAD) using CaO-, MgO-, and TiO_2-based catalysts. The data were extracted from the Scopus database and visualized using OriginPro 2019. From 2015 to 2017, the number of publications remained relatively low but stable, indicating that PFAD-based biodiesel research was still in an early development stage. During this period, research on biodiesel was largely dominated by feedstocks such as waste cooking oil (WCO) and conventional vegetable oils, which had been more extensively studied due to their availability and established processing routes [19,20]. Heterogeneous catalysts have attracted considerable attention in view of their high catalytic activity, reusability, and environmentally friendly

characteristics. Previous studies reported that the application of heterogeneous catalysts can enhance the efficacy of biodiesel production while reducing purification requirements and process costs [37]. Consequently, the application of CaO, MgO, and TiO_2 heterogeneous catalysts in PFAD conversion had not yet gained significant attention.

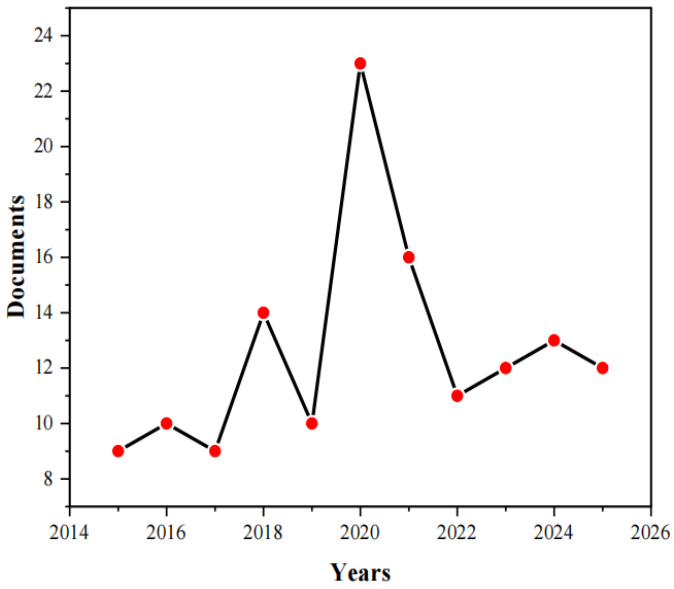

Fig. 2. Annual publication trend and cumulative publications

A significant increase in the number of publications was observed during the 2018 and 2019 periods. This growth can be attributed to several factors, including the recognition of PFAD as a low-cost and abundant feedstock with high free fatty acid (FFA) content, as well as the increasing number of studies focusing on the development of heterogeneous solid-base catalysts, particularly CaO and other metal oxides, for esterification and transesterification reactions [18]. In addition, global efforts to reduce dependence on fossil fuels and promote renewable energy sources further accelerated research interest in biodiesel technologies during this period [21] The peak in publication output was observed around 2020, representing the highest research activity within the 2015–2025 timeframe. This surge can be partly associated with the increased emphasis on renewable energy research during the COVID-19 pandemic, which provided researchers with greater opportunities to complete experimental work, data analysis, and manuscript preparation. Moreover, by this time, the development of CaO-, MgO-, and TiO_2-based heterogeneous catalysts had attained a more advanced stage, resulting in enhanced catalytic performance, reusability, and economic feasibility [22,23].

From 2021 to 2023, a decline in publication numbers was observed, reflecting a temporary shift in global research priorities towards emerging topics such as green hydrogen, sustainable aviation fuel (biojet fuel), and carbon capture and storage technologies. Nevertheless, research interest in CaO, MgO, and TiO_2 catalysts for biodiesel production remained relatively stable, as these catalysts continue to be regarded as cost-effective and environmentally friendly options for industrial-scale applications [24].

The publication trend observed in this study is consistent with patterns reported in analogous bibliometric studies in the biofuel catalyst domain. Sulaiman et al. [38] reported in their bibliometric analysis of AI-driven biodiesel catalyst optimization that similar publication peak was identified around 2020 followed by a moderate decline, attributing this to a redistribution of research funding toward green hydrogen and carbon capture technologies. Pratama et al. [61] reported in their bibliometric assessment of green diesel research that the same growth-and-plateau pattern had been identified, with the observation that mature research fields often exhibit such cycles when foundational knowledge stabilizes and researchers shift towards adjacent emerging topics. The slight recovery observed in 2024–2025 in the present study, which was not reported in earlier bibliometric reviews is an original finding that can be attributed to renewed governmental mandates in Indonesia (B40 blending policy) and Malaysia (B20+ implementation programs). These have reinvigorated applied research interest in PFAD-derived heterogeneous catalysis.

In the 2024 and 2025 periods, the publication trend demonstrated a slight upward movement, indicating renewed interest in PFAD-based biodiesel research. This increase is primarily driven by the development of more innovative catalyst activation and modification techniques, as well as strong governmental support in major palm oil–producing countries such as Indonesia and Malaysia to enhance the value-added utilization of PFAD. Furthermore, growing emphasis on low-emission biofuels and circular economy strategies has served to reinforce the relevance of PFAD as a sustainable feedstock for biodiesel production [25,26]

3.2. Top author and citations

A bibliometric analysis of the authors indicates that research on biodiesel production from Palm Fatty Acid Distillate (PFAD) using CaO-, MgO-, and TiO_2-based heterogeneous catalysts is dominated by a limited number of key researchers. Author-level bibliometric indicators, including the number of publications, citation counts, H-index, and total link strength, are widely used to evaluate research productivity, scientific influence, and collaboration intensity within a scientific field [9,14]. A study of the Scopus dataset reveals that Rashid, Umer is the most productive author, with a total of 20 publications, 820 citations, and the highest total link strength (52). These metrics indicate that he has a very strong international collaboration network. High total link strength values in co-authorship networks reflect an author's central role in facilitating scientific collaboration and knowledge dissemination across institutions and countries [11,17].

In contrast, Yap, Taufiq Yun Hin has recorded the highest total citation count (883) and the highest H-index (79), indicating greater scientific influence despite having a slightly lower number of publications compared to Rashid. Citation-based metrics such as the total number of citations and the H-index are frequently employed as proxies for the long-term research impact and scholarly visibility of an academic journal [15,27]. Other researchers who have made significant contributions include Faungnawakij, Kajornsak, with 928 citations and an H-index of 47, and Viriya-Empikul and Nawin, with a total of 820 citations. The high citation rates associated with these authors indicate that their work is frequently referenced and plays a crucial role in advancing the development of heterogeneous metal oxide catalysts based on CaO, MgO, and TiO_2 for PFAD esterification and transesterification processes. It is widely acknowledged that highly cited publications are of foundational studies that shape research directions and technological progress in a given field [9,16].

The substantial bibliometric influence of Rashid, Umer is further corroborated by the technological significance of his experimental contributions; his group has developed bifunctional magnetic CaO-based nanocatalysts achieving biodiesel yields in excess of 98%, with catalyst designs that address reusability and separation challenges critical to industrial-scale PFAD biodiesel production [28].

The total link strength values as reported in Table 2 also highlight the extent of collaboration among researchers. Rashid Umer, exhibits the highest total link strength, demonstrating his active involvement in multinational and cross-institutional collaborations. In the context of applied research domains such as renewable energy and catalysis, where multidisciplinary approaches are essential for addressing complex technological challenges, the establishment of robust collaborative networks assumes paramount importance [17].

Researchers from Southeast Asian countries, including Malaysia, Thailand, and Indonesia, dominate the list of top authors. This regional prominence is closely linked to the high availability of PFAD as a by-product of the palm oil industry and the strategic importance of biodiesel development in these countries. Previous studies have identified Southeast Asia as a major hub for research activities pertaining to palm oil–based biodiesel in consideration to abundant feedstock availability, supportive government policies, and pronounced industrial relevance [29]. As demonstrated in Table 2, the results indicate that the advancement of PFAD-based biodiesel research is significantly determined by several influential researchers who combine high productivity, substantial citation impact, and extensive collaboration networks. The presence of these key authors plays a crucial role in promoting innovation and accelerating the development of heterogeneous catalyst technologies for sustainable biodiesel production.

As illustrated in Figure 3 the co-authorship network is derived from a minimum of 200 citation-linked publications, as retrieved from the Scopus database and visualized using VOSviewer. In this network, each node represents an individual author, with the size of the node corresponding to the number of publications, while the connecting lines indicate co-authorship relationships. The thickness of the links reflects the strength of collaboration, with different colors representing distinct collaboration clusters, grouping authors who frequently publish together on similar research topics. This visualization approach is widely applied in bibliometric studies to identify influential authors, collaboration intensity, and research communities within a specific scientific field [14,30].

The bibliometric analysis of biodiesel production from Palm Fatty Acid Distillate (PFAD) using heterogeneous catalysts such as CaO, MgO, and TiO_2 reveals a highly interconnected and collaborative research landscape. The co-authorship network is clearly divided into several major clusters, indicating the presence of well-established research groups that have a consistent record of contributions to advancements in PFAD-based biodiesel catalysis. Similar collaboration patterns have been reported in recent bibliometric assessments of heterogeneous catalyst development for biodiesel production [31].

Table 2. Authors with most publication

Author	Documents	Citations	Average of Citation	Total link	H Indeks
Rashid, Umer	20	820	41.0	52	67
Yap, Taufiq Yun Hin	13	883	67.9	22	79
Hidayat, Arif	7	59	8.4	5	18
Faungnawakij, Kajornsak	6	928	154.7	18	47
Jusoh, Mazura Amin M.	6	106	17.7	12	22
Ngamcharussrivichai, Chawalit	5	139	27.8	10	36
Soltani, Soroush	5	131	26.2	12	19
Sutrisno, Bachrun	5	38	7.6	5	11
Viriya-Empikul, Nawin	5	820	164.0	17	21
Zakaria, Zaki Yamani	5	17	3.4	11	27
Hameed, Bassim H.	4	211	52.8	3	140
Hazmi, Balkis	4	39	9.8	15	8
Ibrahim, Mohd Lokman	4	262	65.5	9	38
Lim, Steven	4	237	59.3	11	41
Nehdi, Imededdine Arbi	4	122	30.5	11	41

Among these clusters, the Rashid, Umer cluster (purple) emerges as the most dominant, characterized by the largest node size and extensive linkages to multiple authors. This central position indicates both high publication productivity and strong collaborative influence. Authors closely connected within this cluster include Hazmi, Balkis; Ibrahim, Mohd Lokman; Nehdi, Imed; and Yunus, Roslinda. The research produced by this group primarily is chiefly concerned with the development of CaO-based and multifunctional heterogeneous catalysts, including CaO-MgO and CaO-TiO_2 systems, as well as magnetic CaO-supported catalysts for high free fatty acid feedstocks. These studies have significantly contributed to the improvement of catalyst reusability, separation efficiency, and biodiesel yield from PFAD and other low-cost feedstocks [32,33].

The Yap and Taufiq cluster (yellow) represents the second largest collaboration group. This cluster involves frequent cooperation with authors such as Ishak, Noor; Tee, H. S.; and Ramli, I. R. M. Research within this group emphasizes catalyst activation strategies, surface modification of CaO-based catalysts, and detailed physicochemical characterization techniques. Their work also addresses reaction optimization

parameters, including methanol to oil ratio, catalyst loading, and reaction temperature, which are critical for achieving high biodiesel yields from PFAD feedstocks. The scientific contributions of this cluster are consistent with recent trends that emphasize the significance of catalyst structure-activity relationships in the context of heterogeneous biodiesel catalysis [34].

A separate collaboration cluster led by Ngamcharussrivichai (brown–orange) focuses on the synthesis of CaO catalysts derived from natural minerals and waste materials, catalyst stability, and regeneration performance in PFAD transesterification. This research direction supports sustainability goals by promoting low-cost and environmentally benign catalyst sources, a topic that has gained increasing attention in recent biodiesel catalyst studies [35].

The Hosseini-Choong cluster (green) concentrates on reactor level studies, esterification-transesterification integration, and the application of heterogeneous catalysts for non-edible and high acid value feedstocks. This cluster has been demonstrated to contribute to scaling perspectives and process integration, thereby addressing challenges related to mass transfer limitations and catalyst deactivation. Such system level approaches are increasingly recognized as essential for the industrial viability of PFAD-based biodiesel production [3]. Additionally, smaller yet well-connected clusters, including the Soltani group (light blue), illustrate international collaboration in the development of multiphase and composite catalysts where MgO and TiO_2 are employed as structural promoters to enhance catalyst stability and basicity. These collaborative efforts signify the growing trend towards multifunctional catalyst design, with the objective of enhancing performance under harsh reaction conditions [32]. The present bibliometric study demonstrates an increasing interest in heterogeneous and bifunctional catalysts, which is consistent with recent CST publications reporting biomass-derived catalysts, mesoporous silica-supported catalysts, and metal-modified catalytic systems for biodiesel and biofuel production [85].

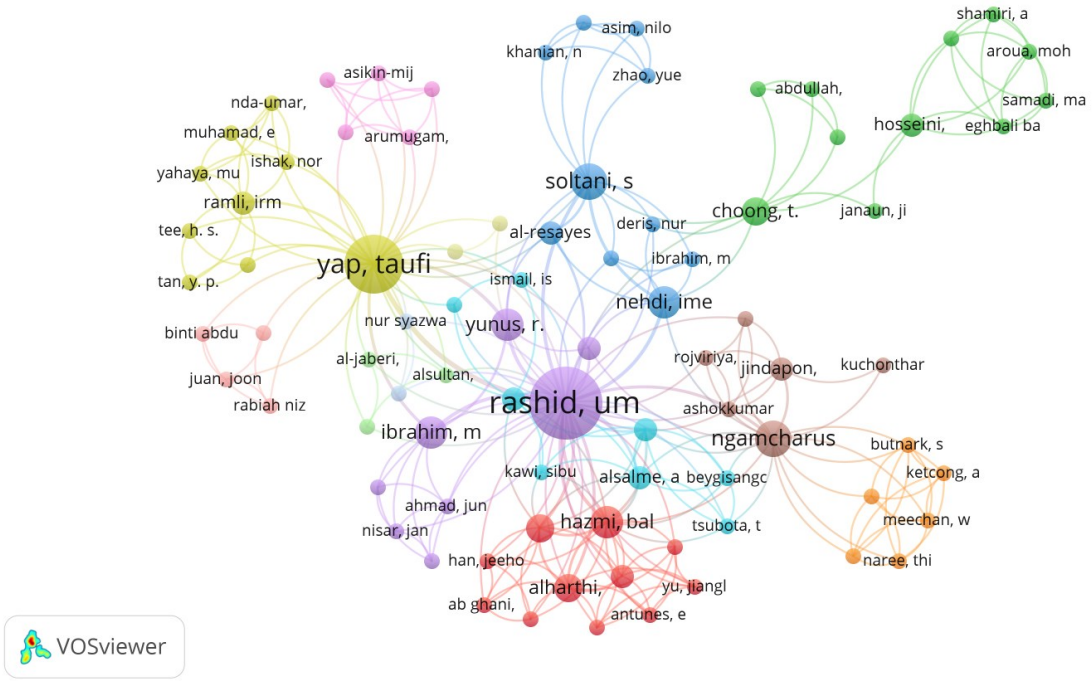

Fig. 3. Visualization of authors with at least 200 citations

3.3. Publication contribution

As presented in Table 3, 15 publications have been identified as the most highly cited in the field of biodiesel production from palm fatty acid feedstocks using heterogeneous catalysts based on CaO, MgO, and TiO_2. These publications have been indexed in the Scopus database and analyzed using VOSviewer and complementary bibliometric tools. This analysis highlights seminal works that have significantly influenced the scientific development of heterogeneous catalyst design, feedstock utilization, and process optimization in biodiesel research. Similar bibliometric approaches have been extensively adopted for the identification of foundational contributions in the domains of renewable fuel and catalysis research [9,38]. Overall, the most cited publications are dominated by four major research themes utilization of solid waste and biogenic materials as CaO catalyst precursors, biodiesel production from palm oil derivatives, including PFAD, optimization of biodiesel synthesis using statistical methods such as Response Surface Methodology (RSM), and comprehensive review articles on heterogeneous base catalysts.

These dominant themes indicate that the synthesis of waste-derived catalysts and the optimization of processes remain central research priorities given their direct relevance to sustainability, cost reduction, and the implementation of circular economy in biodiesel production [35,39]. The two frequently cited articles by Viriya-Empikul et al. (2010, 2012) occupy the first and second positions, with 378 and 230 citations, respectively. The utilization of mollusk shells, eggshells, and industrial waste as the sources of CaO catalyst was pioneered in both studies. Their exceptionally high citation counts confirm their status as landmark studies that established biogenic $CaCO_3$-derived CaO as a viable, cost-effective, and high-performance heterogeneous catalyst for biodiesel production. Recent studies continue to cite these works as foundational research for waste-based catalyst development, thereby underscoring their long-term scientific impact [34,40].

Table 3. Document with most citations

S/N	Title	Author	Citations	Year	Ref
1	Waste shells of mollusk and egg as biodiesel production catalysts	Viriya-Empikul, N.; Pitakjakpipop, P.; Puttasawat, B.; Yoosuk, B.; Chollacoop, N.; Faungnawakij, K.	378	2010	[46]
2	Biodiesel production over Ca-based solid catalysts derived from industrial wastes	Viriya-Empikul, N.; Pitakjakpipop, P.; Nualpaeng, W.; Yoosuk, B.; Faungnawakij, K.	230	2012	[47]
3	Heterogeneous base catalysts: Synthesis and application for biodiesel production – A review	Mani, M.; Karmegam, N.; Gundupalli, M.P.; Gebeyehu, K.; Tessema Asfaw, B.; Chang, S.W.; Ravindran, B.; Awasthi, M.	212	2021	[48]
4	Industrial eggshell wastes as the heterogeneous catalysts for microwave-assisted biodiesel production	Khemthong, P.; Luadthong, C.; Nualpaeng, W.; Changsuwan, P.; Tongprem, P.; Viriya-Empikul, N.; Faungnawakij, K.	204	2012	[42]
5	Optimization of heterogeneous biodiesel production from waste cooking palm oil via response surface methodology	Wan Omar, W.N.N.; Amin, N.A.	199	2011	[49]
6	Kinetics of transesterification of palm oil and dimethyl carbonate for biodiesel production at the catalysis of heterogeneous base catalyst	Zhang, L.; Sheng, B.; Xin, Z.; Liu, Q.; Sun, S.	181	2010	[50]
7	Ultrasonic-assisted production of biodiesel from transesterification of palm oil over ostrich eggshell-derived CaO catalysts	Chen, G.-Y.; Shan, R.; Shi, J.-F.; Yan, B.-B.	178	2014	[51]
8	Biodiesel production from palm oil via heterogeneous transesterification	Kansedo, J.; Lee, K.T.; Bhatia, S.	155	2009	[52]
9	Kinetics and optimization studies using Response Surface Methodology in biodiesel production using heterogeneous catalyst	Latchubugata, C.S.; Kondapaneni, R.V.; Patluri, K.K.; Virendra, U.; Vedantam, S.	146	2018	[53]
10	Biodiesel production from palm oil using sulfonated graphene catalyst	Nongbé, M.C.; Ekou, T.; Ekou, L.; Yao, K.B.; Le Grognec, E.; Felpin, F.-X.	137	2017	[54]
11	Biodiesel production using heterogeneous catalysts including wood ash and the importance of enhancing byproduct glycerol purity	Uprety, B.K.; Chaiwong, W.; Ewelike, C.; Rakshit, S.K.	128	2016	[55]
12	Preparation of sulfonated carbon-based catalysts from murumuru kernel shell and their performance in the esterification reaction	da Luz Corrêa, A.P.; Bastos, R.R.C.; Rocha Filho, G.N.D.; Zamian, J.R.; Conceição, L.R.V.	125	2020	[56]
13	Synthesis of biodiesel from palm fatty acid distillate using sulfonated palm seed cake catalyst	Akinfalabi, S.-I.; Rashid, U.; Yunus, R.; Yap, Y.H.	119	2017	[57]
14	Biodiesel production via transesterification of palm oil by using CaO-CeO2 mixed oxide catalysts	Wong, Y.C.; Tan, Y.P.; Yap, Y.H.; Ramli, I.; Tee, H.S.	118	2015	[58]
15	Methyl ester production from palm fatty acid distillate using sulfonated glucose-derived acid catalyst	Ibrahim, M.L.; Rashid, U.; Yap, Y.H.; Yunus, R.	114	2015	[59]

It is noteworthy that the two most-cited studies in this dataset Viriya-Empikul et al. (2010, 2012) with 378 and 230 citations respectively were published prior to the commencement of the analysis window of this study in 2015, yet they rank first and second in citation frequency. This anomaly is not a dataset error; rather, it is a bibliometric indicator of foundational knowledge consolidation. Papers that established key methodological or conceptual frameworks continue to accumulate citations long after publication as subsequent researchers utilize them as reference anchors. This pattern is consistent with Price's law of citation concentration, which predicts that a limited number of seminal papers receive disproportionately high citation shares within any established research domain. The implication for this field is that waste-derived CaO catalyst synthesis, the topic of both Viriya-Empikul studies, has become the canonical reference point for the broader heterogeneous PFAD biodiesel catalyst literature, confirming its status as the most influential subdiscipline within this research domain.

The review article by Mani et al. (2021) has received 212 citations, thus occupying third position in the relevant ranking. This outcome lends further support to the hypothesis that well-structured review papers have a significant impact in terms of consolidating and guiding research directions. This review systematically mapped advancements in heterogeneous base catalysts, including CaO, MgO, and TiO_2, and has served as a key reference for both experimental researchers and process engineers. The rapid accumulation of citations within a relatively short time frame reflects the growing demand for integrative reviews addressing catalyst performance, stability, and scalability in biodiesel production [38,39]. The study by Khemthong et al. (2012), ranked fourth, lends further support to the prominence of eggshell-derived CaO catalysts. Eggshell waste remains one of the most widely explored CaO precursors, owing to its high calcium carbonate content, minimal pretreatment cost, and favorable catalytic activity. Recent publications continue to expand on this concept by incorporating advanced

activation techniques, such as microwave and ultrasonic assistance, to further enhance catalyst performance [41,42]. It is evident from several publications that have received significant citation, including those by Wan Omar and Saidina Amin (2011) and Latchubugata et al. (2018), that Response Surface Methodology (RSM) is extensively utilized for the optimization of biodiesel process. RSM has been proven to be an effective statistical tool for maximizing biodiesel yield while minimizing experimental runs by simultaneously optimizing key parameters such as reaction temperature, time, alcohol-to-oil ratio, and catalyst loading. Recent studies have confirmed that RSM remains the most widely applied optimization technique in heterogeneous biodiesel research, particularly for PFAD and other high-FFA feedstocks [43,44].

Research by Zhang et al. (2010) and Chen et al. (2014) demonstrates the integration of conventional transesterification with non-conventional process intensification techniques, such as ultrasonic-assisted biodiesel synthesis. These studies made a significant contribution to the enhancement of reaction kinetics, mass transfer efficiency, and overall process productivity. Contemporary research continues to adopt and refine these activation strategies, thus confirming their relevance in the development of technologies for rapid and energy efficient biodiesel production. Publications focusing explicitly on PFAD-based biodiesel, such as those by Akinfalabi et al. (2017), Wong et al. (2015), and Ibrahim et al. (2015), remain highly relevant to the present research scope. These studies emphasize the suitability of PFAD as a low-cost, high-FFA feedstock for esterification-dominated biodiesel processes utilizing sulfonated catalysts, mixed metal oxides, and bifunctional systems. Recent literature confirms a sustained global research interest in PFAD due to its abundance in palm oil-producing countries and its strategic role in enhancing the economic value of palm oil industry by-products [45].

3.4. Publication sources

Table 4 depicts the 15 publication sources with the highest number of documents and citations related to the topic of biodiesel production from PFAD using CaO, MgO, and TiO_2 catalysts. The data were obtained from the Scopus database and analyzed to demonstrate the quality and influence of each publication outlet based on the number of documents, total citations, H-Index (2024), Scimago Journal Rank (SJR), and Impact Factor (IF 2024). Overall, the dominant publication sources originate from highly reputable journals in the fields of renewable energy, chemical process technology, biomass conversion, and catalysis.

This finding indicates that research on biodiesel from PFAD using heterogeneous metal oxide catalysts is a highly cited topic within the fields of energy and fuels, chemical engineering, environmental engineering, catalysis and materials science. This trend confirms the multidisciplinary nature of the topic and its extensive relevance, both scientifically and practically, to sustainable energy development. A study of the publication sources revealed that research related to biodiesel production from PFAD using CaO, MgO, and TiO_2 catalysts is primarily published in highly reputable journals in the fields of renewable energy, biomass, and catalysis.

Table 4. Publication sources with the most documents

S/N	Source	Document	Citations	H Index (2024)	SJR (2024)	Impact Factor (2024)
1	Renewable Energy	10	640	270	2.08	9.1
2	Bioresource Technology	9	1270	383	2.4	9.0
3	AIP Conference Proceedings	9	35	90	0.15	0.37
4	Fuel	8	748	273	1.61	7.5
5	Journal of Cleaner Production	6	214	354	2.14	10
6	Energy Conversion and Management	5	275	274	2.92	10.9
7	Catalysts	5	46	105	0.75	4.0
8	Bulletin of Chemical Reaction Engineering and Catalysis	5	7	29	0.31	1.3
9	Fuel Processing Technology	4	197	185	1.6	7.7
10	Applied Catalysis A: General	4	195	244	1	4.8
11	Waste and Biomass Valorization	3	102	79	0.65	2.8
12	Process Safety and Environmental Protection	3	87	128	1.47	7.8
13	Journal of Environmental Chemical Engineering	3	61	151	1.45	7.2
14	Bioenergy Research	3	56	78	0.67	3.0
15	Materials Today: Proceedings	3	53	112	0.59	1.78

Renewable Energy was the most productive source with a total of 10 articles and 640 citations. This was followed by Bioresource Technology, which, despite having a slightly lower number of articles, recorded the highest total citations wat 1,270 citations. Renewable Energy maintains a robust Impact Factor of 9.1 and SJR of 2.08 in 2024, thus positioning it within the Q1 quartile for the research in renewable energy. The journal serves as a leading international, multi-disciplinary platform for renewable energy engineering and research. Meanwhile, Bioresource Technology demonstrates exceptional scientific influence with an Impact Factor of 9.0 and SJR of 2.4 in 2024, reflecting its position as one of the most cited journals in the field of biomass conversion and bioresource technology [62,63]. It is evident that journals such as Fuel, Journal of

Cleaner Production, and Energy Conversion and Management have been recognized for their significant contribution to the scientific advancement in the domains of biofuels and heterogeneous catalyst technology. This is underscored by their attainment of commendable Impact Factor of 7.5 and SJR of 1.61 in 2024, maintaining its Q1 status in the energy and fuels category. The Journal of Cleaner Production, for instance, recorded an Impact Factor of 10 and SJR of 2.14 in 2024, reflecting its strong position in environmental engineering and sustainable production research. The journal of Energy Conversion and Management demonstrates the highest Impact Factor among the top sources with 10.9 and SJR of 2.92 in 2024, indicating its exceptional influence in energy conversion research [64,65].

The majority of highly cited journals focus on energy conversion technology, base catalyst synthesis, and waste utilization for renewable fuel production, which align well with the characteristics of PFAD-based biodiesel research. Recent studies have demonstrated that heterogeneous metal oxide catalysts, particularly CaO and TiO_2-based materials, exhibit substantial potential for the efficient production of biodiesel from PFAD and other waste feedstocks. The application of these catalysts is pivotal in addressing critical challenges associated with sustainable biofuel production, including catalyst reusability, high conversion efficiency, and reduced environmental impact [66,67]. Concurrently, several publications from international conferences, including the AIP Conference Proceedings, were also identified in large numbers, although their citation rates were lower than those of Q1 and Q2 journals. The presence of 9 documents in AIP Conference Proceedings a Q4 outlet with a low SJR of 0.15 alongside predominance in Q1 journals such as Renewable Energy (SJR 2.08) and Bioresource Technology (SJR 2.40) reveals a dual-track publication pattern characteristic of Southeast Asian research communities.

High-quality studies from well-funded groups at institutions such as Universiti Putra Malaysia and Chulalongkorn University are more likely to be published in top-tier international journals, while studies from earlier-career researchers or resource-limited groups are more frequently published in conference proceedings. This bifurcation in the standard of publication quality within a single research field has been identified in bibliometric analyses of other applied science domains in developing regions [61]. From a strategic perspective, this pattern underscores the necessity for targeted mentorship programs and international research partnerships to raise the overall publication quality standard in PFAD biodiesel research, particularly from Indonesian and Nigerian institutions where the average citation rate is comparatively lower. The quartile classification system in Scopus divides journals into four categories based on citation impact and scientific influence: Q1 journals represent the top 25% with highest citation impact, Q2 journals occupy the 25-50% range, Q3 journals fall within 50-75%, and Q4 journals constitute the bottom 25%. This classification is determined on an annual basis with metrics including CiteScore, SJR, citation impact, and global reputation [68,69].

The distribution of these publication sources indicates that research related to the topic of PFAD biodiesel has strong relevance and has received significant attention in various scientific fields including energy, chemical engineering, and catalyst materials. The multidisciplinary nature of biodiesel research is evident in the diverse range of publication outlets, ranging from specialized catalysis journals to more extensive environmental and energy engineering platforms. The broad dissemination of this research across multiple high-impact journals reflects the mounting global interest in the development of sustainable biofuel production technologies that utilize heterogeneous catalysts and waste-derived feedstocks. This dominance of Q1 renewable energy journals as the primary publishing outlets is consistent with the findings reported by Sulaiman et al. (2025) and Pratama et al. (2024) that confirm that biofuel catalyst bibliometric studies across different feedstock and catalyst types converge on the same top-tier journal ecosystem. This reflects the maturity and interdisciplinary integration of the bioenergy research field.

3.5. Co-occurrence of keyword

The figure presents a keyword co-occurrence network generated using VOSviewer, which illustrates the conceptual structure, thematic relationships, and research trends in the field of biodiesel. In this visualization, the size of the node represents the frequency of keyword occurrence, while the thickness and distance of the connecting lines indicate the strength of relationships between keywords. The use of different colors corresponds to distinct thematic clusters that reflect the major research directions within the biodiesel domain. Such VOSviewer-based co-occurrence mapping has been extensively utilized in recent bibliometric studies to identify dominant themes and emerging topics in the domain of renewable energy and biofuel research [70,71].

Cluster 1, labelled Chemical Reactions and Processes (red and pink), encompasses a range of keywords including esterification, transesterification, kinetics, reaction mechanisms, modeling, and optimization. This cluster depicts research aims to understand the reaction mechanism of converting PFAD to FAME, investigate reaction kinetics, optimize operating conditions (temperature, methanol-to-oil molar ratio, reaction time), and apply experimental design methods such as ANOVA and response surface methodology (RSM). These topics highlight the significance of chemical reactions as a core aspect of the biodiesel production process from PFAD, particularly in feedstocks characterized by high levels of free fatty acids [72,73]. The keyword *biodiesel* is identified as the largest and most central node in the network, thus indicating its dominant role in establishing connections between various research themes. The strong links with transesterification, esterification, heterogeneous catalyst, and optimization demonstrate that biodiesel research is highly interdisciplinary, encompassing feedstock selection, catalytic reaction mechanisms, process optimization, and reactor design. Recent reviews confirm that heterogeneous catalysis, particularly using metal oxide-based catalysts, has become a central pillar in modern biodiesel research due to its advantages in reusability, separation, and environmental performance [73,74].

Cluster 4, related to Synthesis Methods and Catalyst Activation (yellow and orange), contains several keywords such as calcination, impregnation, ultrasonic and microwave, hydrothermal, and sol–gel method. The focus of research in this cluster is on the development of synthesis and activation strategies to enhance catalyst activity, refine crystal structure, enhance basicity in CaO and MgO, and optimize TiO_2 dispersion. Recent studies have reported that tailored calcination, impregnation, and sol–gel or hydrothermal treatments significantly influence the acid–base properties, surface area, and stability of heterogeneous catalysts used for

biodiesel production [75,76]. Cluster 5, which is associated with Environment, Energy, and Products (purple and brown), contains keywords such as biofuel, renewable energy, glycerol, value-added products, and waste valorization. This cluster indicates an evolution in PFAD biodiesel research, with a shift towards the utilization of by-products, particularly glycerol, in conjunction with broader sustainability, circular economy, and environmental impact themes. The current literature emphasizes the significance of converting biodiesel by-products and residues into value-added chemicals and materials, purposely to enhance the overall sustainability of biodiesel production chains [77].

Cluster 3, related to Feedstock and High-FFA Processing, is centered on esterification, palm fatty acid distillate (PFAD), and free fatty acid, highlighting the intensive research focus on feedstocks characterized by high free fatty acid content. The strong association between PFAD and esterification confirms that esterification is a critical step in converting PFAD into biodiesel, thereby avoiding soap formation during subsequent base-catalyzed transesterification. The presence of keywords such as solid acid catalyst, heterogeneous acid catalyst, sulfonation, and post-sulfonation treatment indicates that the development of solid acid catalysts is a key strategy to overcome saponification issues commonly encountered with homogeneous base catalysts, reflecting a clear shift toward more environmentally friendly and sustainable catalytic systems [66,75].

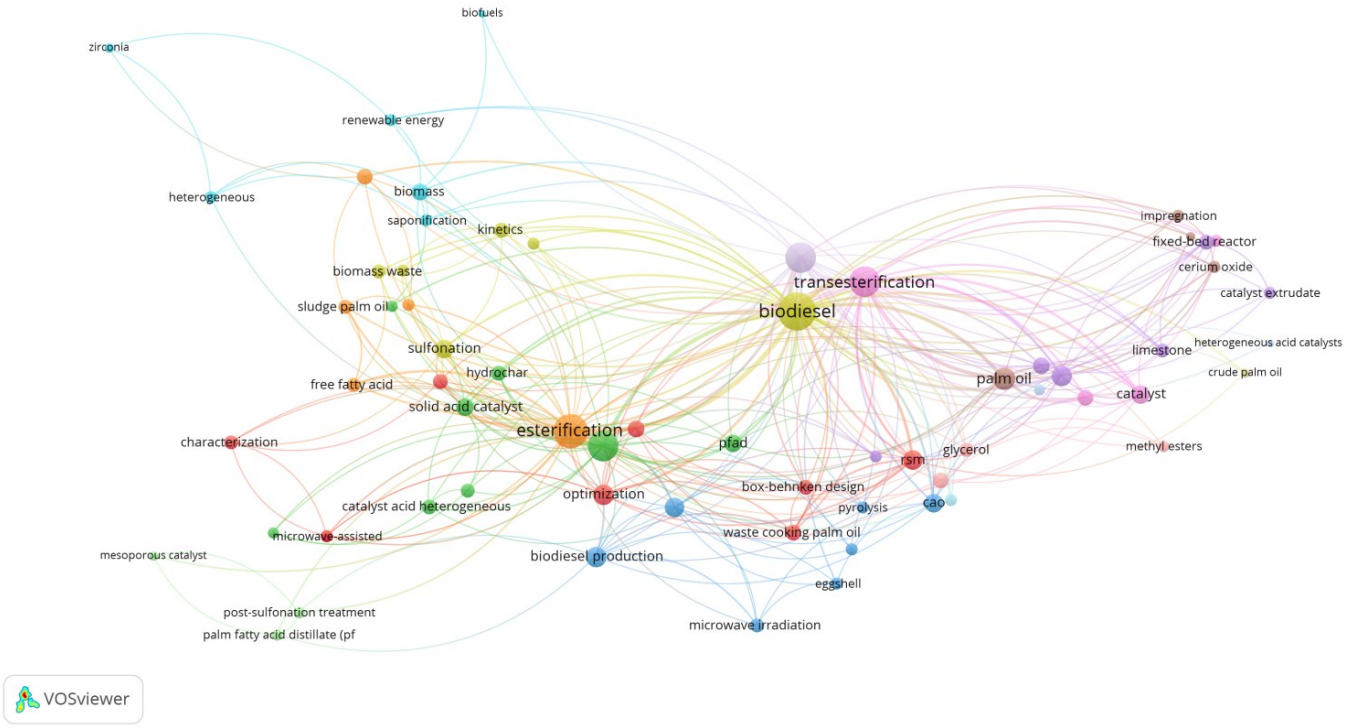

Fig. 4. Visualization of publication sources with the most documents

The utilization of keywords such as heterogeneous catalyst, catalyst, calcium oxide (CaO), cerium oxide (CeO_2), and limestone results in the formation of a distinct cluster. This cluster serves to emphasize the significance of metal oxide-based heterogeneous catalysts. CaO has been shown to be strongly associated with transesterification due to its strong basicity and high catalytic activity. In contrast, other metal oxides such as CeO_2, MgO, and TiO_2 have been demonstrated to contribute to improved catalyst stability, bifunctionality, and resistance to deactivation. The linkage between heterogeneous catalysts and fixed-bed reactors suggests a growing trend in research towards continuous reactor systems, highlighting a transition from laboratory-scale batch processes to industrially relevant technologies for biodiesel production [75,78]. The presence of keywords such as optimization, response surface methodology (RSM), and Box Behnken design reflects the increasing use of statistical and mathematical tools to optimize biodiesel production processes. These approaches are widely employed to determine optimal reaction conditions including reaction temperature, alcohol-to-oil molar ratio, catalyst loading, and reaction time. The objective is to maximize biodiesel yield while minimizing energy consumption and operating costs. In parallel, the utilization of keywords such as biomass, biomass waste, waste cooking oil, sludge palm oil, and hydrochar indicate extensive exploration of renewable and waste-derived feedstocks for biodiesel production, underlining the global emphasis on waste valorization, renewable energy generation, and circular economy principles [77,79]

The emergence of keywords including microwave assisted, microwave irradiation, and pyrolysis highlights the development of process intensification techniques that are designated to accelerate reaction rates and enhance energy efficiency. Advanced technologies such as microwave heating and thermo-catalytic pyrolysis are increasingly investigated as alternatives to conventional heating methods. It has been reported that these technologies enhance conversion, reduce reaction time, and in some cases reduce overall energy demand in biodiesel and biofuel production. The observed keyword co-occurrence patterns are consistent with recent literature trends that emphasize heterogeneous metal oxide catalysts, high-FFA feedstocks such as PFAD, waste valorization, and process intensification as key pillars of sustainable biodiesel research

[76,80].

Synthesizing the five keyword clusters identified in this study (1) Chemical Reactions and Process Optimization, (2) Catalyst Synthesis and Activation, (3) Feedstock and High-FFA Processing, (4) Sustainability and By-product Valorisation, and (5) Process Intensification within an interpretive research lifecycle framework reveals the maturity status of each research direction. Cluster 1 (process optimization, RSM, kinetics) and Cluster 3 (PFAD esterification, solid acid catalysts) represent well-established research themes. These two clusters are characterized by a high frequency of keyword, dense co-occurrence networks, and declining marginal novelty per publication. The development of Cluster 2 (novel synthesis methods: sol-gel, hydrothermal, magnetic catalysts) and Cluster 4 (glycerol valorization, circular economy) is characterized by active growth and unresolved technical challenges. Recent studies have also demonstrated increasing interest in biomass-derived heterogeneous catalysts as sustainable alternatives for biodiesel production, including the utilization of *Moringa oleifera* leaf ash as a green catalyst for transesterification reactions [82]. Cluster 5 (microwave-assisted intensification, pyrolysis integration) constitutes an emerging theme, as evidenced by the lower frequency of keywords and sparse network connections. This indicates that this area is a frontier area with high growth potential. This lifecycle classification represents an original analytical contribution of this bibliometric study, providing a forward-looking roadmap for researchers and funding agencies to prioritize resources towards developing and emerging themes where marginal scientific returns are highest.

3.6. Collaboration and country productivity

The visualization of co-author countries in Fig. 5 demonstrates the pattern of international collaboration in scientific publications related to biodiesel production from PFAD using heterogeneous catalysts based on CaO, MgO, and TiO_2. In VOSviewer-based country maps, the size of the node represents the number of documents, while the thickness of the links and their number reflect the intensity of co-authorship relationships among countries. This type of mapping is increasingly utilized in recent bibliometric studies to identify collaboration hubs and regional research networks in the domains of energy and biofuel [70,81]. The Malaysia node emerges as the largest node in the network, indicating that Malaysia contributes the most publications and acts as a hub for international collaboration on PFAD-based biodiesel. This is consistent with Malaysia's status as one of the world's largest palm oil producers and a leading country in palm-oil-derived biodiesel development.

Malaysia has strong co-publishing relationships with several countries, including Indonesia, Thailand, China, India, Nigeria, Iran, the United Arab Emirates, Pakistan, Spain, France, and Morocco. These relationships supports Malaysia's role as a regional research center for heterogeneous catalysts and oil-based waste utilization such as PFAD. Collectively, this Southeast Asian trio (Malaysia, Thailand, and Indonesia) accounts for 79.4% of global publications on this topic, thus forming a geographically concentrated research ecosystem. The collaboration intensity (reflected in shared co-authorship links) of this ecosystem reflects both shared industrial resources and coordinated regional bioenergy policy frameworks.

It is also evident that other countries, including China, India, and Japan, become significant contributors to the network. This indicates that biodiesel conversion from low-cost feedstocks is gaining global importance, particularly in countries with substantial and growing energy demand. The European cluster, comprising the United Kingdom, France, Spain, Belgium, Germany, and Hungary, exhibits smaller node sizes, suggesting a more limited publication output. Nevertheless, these countries continue to contribute to international collaboration in catalysis and renewable energy research. This collaboration pattern confirms that the production of biodiesel from PFAD using heterogeneous catalysts is predominantly led by developing countries that produce and develop palm-oil and are seeking cost-effective renewable energy technologies. This multi-continental collaboration reflects the strategic interest of many countries in advancing research in the field of CaO-, MgO-, and TiO_2-based catalyst for the purpose of sustainable biofuel production [34,60].

Bibliometric data obtained from the Scopus database demonstrates Malaysia's dominance as the country with the highest research productivity in biodiesel production from PFAD using CaO, MgO, and TiO_2 catalysts, contributing 36.3% of the total publications. This finding is in line with Malaysia's position as the world's second-largest palm oil producer and its robust policy support for sustainable bioenergy development. The analysis indicates a positive correlation between raw material availability and research intensity in palm-oil-producing countries, where PFAD, as a by-product of palm oil refining, provides a stable and abundant feedstock for biodiesel research [84].

As demonstrated in Table 5, an analysis of data indicates a clear hierarchy in the distribution of publication. Malaysia is ranked first with 65 publications (36.3%), followed by Thailand with 42 publications (23.5%), and Indonesia in third place with 35 publications (19.6%). Collectively, these three Southeast Asian countries contribute 79.4% of the total global publications on this topic, which aligns with their status as the main global palm oil producers. Malaysia and Indonesia are widely recognized as the two largest producers of palm oil on a global scale. The primary feedstock for biodiesel production is palm oil and the production of PFAD is a significant by-product of refining, with large quantities of research being driven by this factor [83].

The publication percentage represents each country's relative contribution to total scientific output in this research field. Malaysia's 36.3% share indicates that more than one-third of global research on biodiesel from palm fatty acids using heterogeneous catalysts originates from Malaysian institutions and researchers, reflecting substantial investment in research infrastructure and supportive governmental frameworks for bioenergy. Total citations, as a fundamental bibliometric indicator, are widely accepted as a reliable measure of the impact and visibility of research. Malaysia, with 2,518 citations, and Thailand, with 1,960 citations, demonstrate that publications from these two countries are not only quantitatively prolific but also qualitatively influential within the global scientific community. This pattern is consistent with the findings of bibliometric studies that demonstrate that leading producer countries within specific commodity chains

frequently dominate citation impact within related technological fields.

The Average of Citations parameter provides important insight into the relative quality and influence of publications from each country. The analysis demonstrates substantial variation, with China recording the highest average citation rate (67.3 citations/document). This finding suggests that, despite its relatively modest publication volume (13 documents), China's research outputs are highly impactful. Thailand (46.7 citations/document) and Nigeria (44.2 citations/document) also demonstrate robust strong citation performance, reflecting high visibility and influence of their work on heterogeneous catalysts and waste-based biodiesel. In contrast, Indonesia exhibits the lowest average citation rate (8.7 citations/document), suggesting a potential for enhancement of research quality, international collaboration, and visibility. This tendency is consistent with previous bibliometric findings that demonstrate that a high publication volume does not always translate into proportionally high citation impact.

This citation quality disparity warrants critical examination. China's exceptional average citation rate (67.3 citations/document) despite its modest publication volume (13 documents) suggests that Chinese researchers contribute highly influential studies that advance methodology. This pattern is consistent with China's broader bibliometric profile in applied catalysis. The finding that Indonesia has an average citation rate of 8.7 citations per document suggests that, while this country is a highly active producer of PFAD research, its outputs are predominantly disseminated in lower-impact regional journals (e.g., AIP Conference Proceedings, Bulletin of Chemical Reaction Engineering and Catalysis) rather than in Q1 international journals. This phenomenon reflects a structural challenge that is commonly observed in research system of emerging-economy. In such context, the publication pressure and funding constraints channel researchers towards faster, lower-bar publication outlets. Addressing this gap requires strategic investment in international collaboration, English-language academic writing capacity, and incentives for publishing in high-impact journals. This citation analysis constitutes an original contribution of this study, as prior bibliometric reviews on PFAD or heterogeneous biodiesel catalysts have not specifically quantified and interpreted the citation quality gap between producer nations.

In the context of VOSviewer, Total Link Strength (TLS) represents the overall strength of collaborative links between one country and other countries in the bibliometric network. This parameter indicates the extent to which a country engages in international co-authorship and joint research. The link strength analysis demonstrates that Malaysia (TLS: 58) possesses the most robust collaboration network, thus underscoring its role as a regional research hub and its capacity to attract international partners. Saudi Arabia (TLS: 37) has been found to exhibit high link strength relative to its number of publications (13 documents). This finding suggests the presence of an effective international collaboration strategy and focus on co-authored research in the field of bioenergy and catalysis. Thailand (TLS: 30) maintains a solid collaborative position as the second most productive country, whereas Indonesia (TLS: 13) and China (TLS: 11) show comparatively lower TLS values. This may indicate a predominance of domestic or intra-regional collaborations rather than broader global networks.

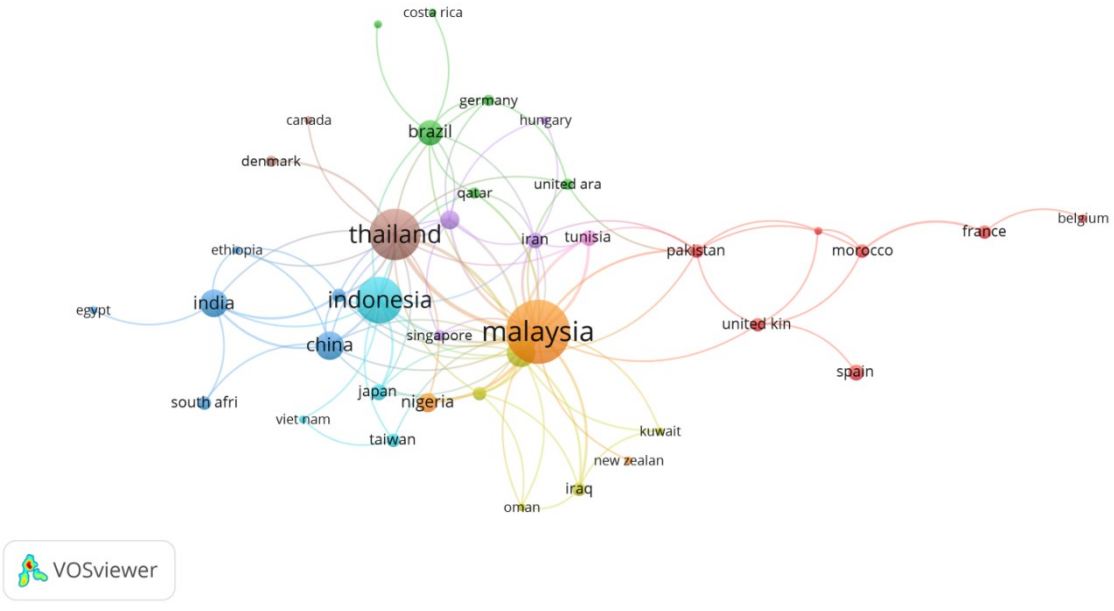

Fig. 5. Visualization of countries with the most documents.

India (12 publications, 6.7%) and Brazil (10 publications, 5.6%) have demonstrated active involvement in biodiesel research using heterogeneous catalysts. India's average of 42.7 citations per document reveals competitive research quality, despite the comparatively smaller size of its palm oil industry in comparison to that of Southeast Asia. Brazil, a major producer biofuels that relies predominantly on non-palm oil feedstocks, illustrates diversification of the application of CaO, MgO, and TiO_2 catalysts to a range of oils and biomass-derived feedstocks. These findings provide a valuable roadmap for researchers and policymakers aiming to enhance the productivity and impact of biodiesel research, particularly by strengthening international collaboration networks and improving the scientific quality and visibility of publications in this field.

Table 5. Country productivity in publications

Country	Publication	Percentage	Citations	Average of Citations	Total Link Strength
Malaysia	65	36.3%	2518	38.7	58
Thailand	42	23.5%	1960	46.7	30
Indonesia	35	19.6%	305	8.7	13
China	13	7.3%	875	67.3	11
Saudi Arabia	13	7.3%	223	17.2	37
India	12	6.7%	512	42.7	9
Brazil	10	5.6%	228	22.8	8
Nigeria	6	3.4%	265	44.2	5
United States	6	3.4%	150	25.0	15
Iran	4	2.2%	141	35.3	12
Spain	4	2.2%	132	33.0	1
Tunisia	4	2.2%	122	30.5	11
Japan	4	2.2%	118	29.5	5
South Korea	3	1.7%	214	71.3	10
Taiwan	3	1.7%	184	61.3	3

3.7. Institutions and highest publications

Figure 6 presents the distribution of academic institutions with the highest publication output in research on biodiesel production from Palm Fatty Acid Distillate (PFAD) using CaO, MgO, and TiO_2 heterogeneous catalysts. The data were retrieved from the Scopus database and visualized using VOSviewer. The horizontal bar chart displays the number of documents contributed by the ten most productive institutions. A study of the Scopus database indicates that research contributions are dominated by universities in Southeast Asia and West Asia, in line with the regional concentration of the palm oil industry and related biodiesel research.

Universiti Putra Malaysia (UPM), Serdang, Selangor emerges as the most productive institution, contributing approximately 14 documents, followed closely by a second UPM-affiliated entry with approximately 12 documents. It is important to note that the multiple appearances of UPM in the chart reflect variations in the formatting of institutional names within the Scopus database. These variations caused VOSviewer to register them as separate entities. When consolidated, UPM's total contribution substantially exceeds that of any other single institution, confirming its leading role as a research hub for PFAD-based biodiesel catalysis. The dominance of UPM reflects Malaysia's pronounced commitment to research and development in the field of palm oil and its derivatives as renewable energy sources, a commitment that is consistent with the country's position as a leading global palm oil producer and biofuel developer. This can be evidenced by numerous publications on PFAD esterification/transesterification and CaO-based heterogeneous catalysts produced by UPM researchers.

Beyond UPM, other Malaysian institutions also demonstrate notable contributions. Universiti Tunku Abdul Rahman (UTAR), Kajang, Selangor contributed approximately 6 documents, while Universiti Malaya, Kuala Lumpur contributed approximately 5 documents, and Universiti Sains Malaysia, Gelugor, Penang contributed approximately 4 documents. The sustained contributions from multiple Malaysian universities indicate a strong and coordinated research ecosystem in heterogeneous catalysis, supported by collaborative efforts in catalyst synthesis, characterization, and process optimization for biodiesel production.

Regional contributions are also evident from non-Malaysian institutions. Chulalongkorn University, Bangkok, Thailand contributed approximately 7 documents, which serve to reinforce Thailand's position as the second most active research country in this domain, a position that is consistent with the country-level findings presented in Table 5. Universitas Islam Indonesia, Yogyakarta, Indonesia and College of Sciences, Riyadh, Saudi Arabia each contributed approximately 8 documents. The involvement of Universitas Islam Indonesia reflects Indonesia's growing research engagement in PFAD-based biodiesel, while the participation of the College of Sciences in Saudi Arabia demonstrates that interest in heterogeneous catalysts for biodiesel extends beyond palm oil-producing regions to countries pursuing energy diversification and sustainable fuel development from waste-derived feedstocks.

The institutional distribution depicted in Figure 6 is consistent with the country-level analysis as presented in Table 5, wherein Malaysia, Thailand, and Indonesia collectively accounted for 79.4% of global publications. The concentration of high-output institutions in palm oil-producing countries reflects the direct linkage between feedstock availability, industrial relevance, and research intensity. The findings of this study confirm that research into PFAD-based biodiesel utilizing catalysts such as CaO, MgO, and TiO_2 is driven at the regional level. The predominant role of Asian institutions in this field is evident as these institutions are the main centers of scientific and technological development. At the same time, the growing participation of institutions from Saudi Arabia and other non-producing regions indicates the augmentation in global interest, thus presenting significant opportunities to strengthen cross-institutional collaboration in the domains of catalyst engineering, process scale-up, techno-economic assessment, and life cycle analysis in future studies.

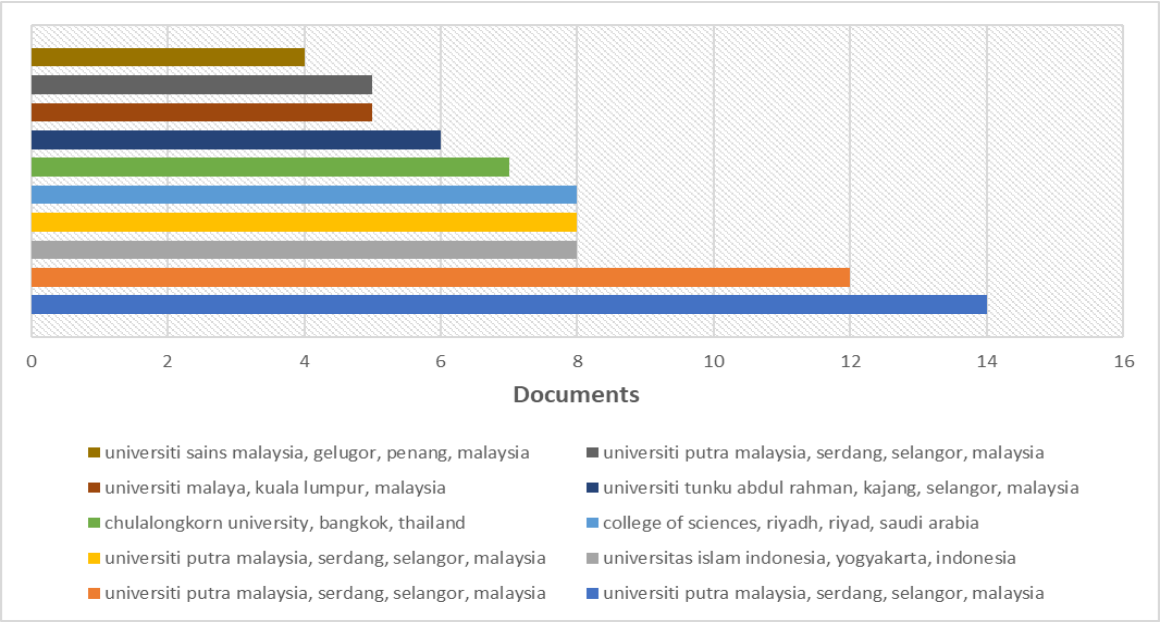

Fig. 6. Institutions with the most publications

Table 6 presents a comparative overview of the findings of this study compared to two recent bibliometric analyses conducted in closely related domains, namely Sulaiman et al. [38] and Pratama et al. [61]. This benchmarking exercise contextualizes the present findings within the broader bibliometric literature on biofuel catalyst research and validates the analytical contributions of this study.

In terms of research focus, the three studies address distinct but complementary dimensions of biodiesel and biofuel catalyst research. The present study exclusively focuses on the tripartite intersection of PFAD as a specific feedstock with three key metal oxide catalyst types of CaO, MgO, and TiO_2 simultaneously within a single analytical framework. This focus that is a novelty in the field and has not been adopted in any prior bibliometric work. In contrast, Sulaiman et al. [38] examined the broader integration of artificial intelligence-driven optimization in biodiesel catalyst research without restricting the analysis to a specific feedstock, while Pratama et al. [61] focused on green diesel production, a distinct biofuel pathway that encompasses a wider range of hydroprocessing catalysts and feedstocks beyond palm-based materials.

Table 6. Bibliometric study comparison

Aspect	This Study (2026)	Sulaiman et al. [38]	Pratama et al. [61]
Focus	PFAD + CaO/MgO/TiO_2 catalysts	AI-driven biodiesel catalyst optimization	Green diesel production
Database	Scopus (179 docs)	Scopus + WoS	Scopus
Peak year	2020	2020	2021
Top country	Malaysia (36.3%)	Malaysia	Indonesia
Top journal	Renewable Energy	Bioresource Technology	RSC Advances
Novel contribution	Research lifecycle framework; citation quality gap analysis	AI optimization integration	Country collaboration network

This differentiation in scope confirms that the present study fills a specific and previously unaddressed gap in the bibliometric literature. Regarding database and document coverage, the present study employed Scopus exclusively, yielding 179 documents after systematic filtering. This approach is deemed appropriate since Scopus boasts a broader coverage of Southeast Asian engineering and chemical journals in comparison to Web of Science [8]. While Sulaiman et al. [38] adopted a dual database approach combining Scopus and Web of Science, and Pratama et al. [61] relied solely on Scopus, the present study's single-database methodology remains methodologically consistent with established practice All three studies converge on a similar peak publication year: the present study and Sulaiman et al. [38] both identified 2020 as the highest output year, while Pratama et al. [61] reported a slightly later peak in 2021. This consistency suggests that 2020-2021 represented a broader global surge in bioenergy research, likely driven by increased productivity during the COVID-19 pandemic and heightened policy emphasis on renewable fuels. The slight recovery observed in 2024-2025 in the present study, which was not present in either of the comparative studies, constitutes an original temporal finding attributable to renewed governmental biofuel mandates in Indonesia and Malaysia. Regarding the leading countries, all three studies identify Southeast Asian nations as the dominant contributors. In the present study, Malaysia was ranked first (36.3%), a position also held by the country in the study of Sulaiman et al. [38]. However, Pratama et al. [61] identified Indonesia as the top

contributor in the green diesel domain. This convergence across independent analyses strongly confirms Southeast Asia as the global epicentre of research into palm-based biofuel and heterogeneous catalyst, driven by the region's abundant feedstock availability, supportive government policies, and well-established research infrastructure.

The leading academic journals identified across the three studies demonstrate a notable degree of overlap. The present study identified Renewable Energy as the most productive source, Sulaiman et al. [38] highlighted Bioresource Technology, and Pratama et al. [61] identified RSC Advances for green diesel research. The consistent targeting of high-impact Q1 journals reflects the maturity and global visibility of the bioenergy research domain. In terms of novel contributions, each study offers a distinct analytical advancement. Sulaiman et al. [38] integrated AI-driven optimization perspectives into bibliometric analysis, while Pratama et al. [61] contributed a country collaboration network analysis for green diesel research. The present study advances the field through two original contributions: a research lifecycle framework classifying five keyword clusters into maturity stages (emerging, developing, and mature), and a quantitative citation quality gap analysis revealing significant research impact disparities between palm oil-producing nations, with direct policy implications for national research investment strategies. Collectively, these contributions position the present study as an analytical and policy-relevant work that moves beyond standard bibliometric description.

3.8. Future research

It is recommended that future research on biodiesel from palm fatty acid distillate (PFAD) using CaO, MgO, and TiO_2-based catalysts focus on several strategic and emerging areas that build on current advances in heterogeneous catalysis and waste valorization. Recent studies have demonstrated that waste-derived CaO and mixed oxide catalysts can achieve biodiesel yields comparable to commercial materials while supporting circular economy principles. Consequently, there is a necessity to prioritize the development of catalysts derived from alternative materials and wastes, including eggshells, seafood shells, industrial sludge, palm oil mill byproducts, and metallurgical residues. This should be accompanied by systematic comparison of their physicochemical properties, stability, and catalytic activity against commercial CaO/MgO/TiO_2-based catalysts. Secondly, comparative studies on mixed and doped oxide systems are required to elucidate the synergistic interactions between CaO, MgO, and TiO_2.

The investigation of metal–support interactions, the balance between surface acidity and basicity, and the effect of TiO_2 crystal phase (anatase versus rutile) on PFAD esterification–transesterification performance will provide a deeper mechanistic understanding and facilitate the rational design of catalysts that are more active and stable. Benchmarking these mixed oxides against other heterogeneous catalyst systems under standardized reaction conditions, including feedstocks with high free fatty acid content, will also enable identification of the most efficient formulations for PFAD upgrading. Thirdly, future research should explore advanced modification and structuring strategies such as surface functionalization, sulfonation, incorporation into mesoporous or hierarchical frameworks, and the use of ionic liquids or surfactants to tune particle size, morphology, and pore architecture.

These approaches have the potential to enhance catalyst reusability, suppress metal leaching, and improve catalytic activity towards high-FFA feedstocks such as PFAD, while maintaining low-cost and scalable preparation routes. The coupling of CaO–MgO–TiO_2 systems with supports such as biochar, metal–organic frameworks, or precipitated calcium carbonate also offers opportunities to improve dispersion, accessibility of active sites, and resistance to deactivation.

Furthermore, the expansion of the application of CaO–MgO– TiO_2 catalysts beyond conventional synthesis of biodiesel should be considered, particularly in the context of renewable-energy-related reactions such as glycerol reforming and oxidation, bio-oil upgrading, CO_2 utilization, and photocatalytic processes. Recent reviews have highlighted the potential of TiO2-based and mixed-oxide catalysts for photocatalytic CO_2 reduction and glycerol valorization, thereby linking biodiesel production with broader integrated biorefinery concepts and low-carbon fuel pathways. The integration of PFAD-derived biodiesel systems with downstream catalytic routes can facilitate a more sustainable and comprehensive bioenergy framework.

Ultimately, it is pivotal that future bibliometric and techno-scientific assessments integrate multiple scientific databases and patent repositories, including Web of Science, Dimensions, Google Scholar, and Espacenet, in addition to Scopus. The combination of publication and patent data will provide a more comprehensive overview of research fronts, intellectual property development, commercialization potential, and global collaboration dynamics in PFAD-based biodiesel and heterogeneous catalyst technologies. The integration of these analyses will facilitate the identification of emerging hotspots, guide the allocation of funding priorities, and ensure that academic research is aligned with industrial and policy requirements in the domain of sustainable biofuel development.

4. Conclusion

This bibliometric study successfully mapped the global research landscape of biodiesel production from palm fatty acid distillate (PFAD) using CaO, MgO, and TiO_2 heterogeneous catalysts over the period 2015–2025. The analysis was based on 179 Scopus-indexed documents, which were analyzed using VOSviewer. The findings revealed that Malaysia, Thailand, and Indonesia collectively contribute 79.4% of global publications, reflecting their dominant position as palm oil-producing nations. The publication output demonstrated a peak in 2020, subsequently exhibiting a slight recovery in 2024–2025, driven by renewed governmental biofuel mandates. The most influential authors and institutions are concentrated in Southeast Asia, with Rashid, Umer and Yap, Taufiq Yun Hin identified as the most productive and highly cited researchers, respectively. A thorough investigation into keyword co-occurrence analysis identified five thematic clusters. Process optimization and esterification representing established research themes, while microwave-assisted intensification and glycerol valorization have been identified as emerging areas with significant growth potential. A notable citation quality disparity was observed, with China recording the highest average citation rate (67.3 citations/document) despite modest publication volume. In contrast, Indonesia, though highly productive, exhibited the lowest average citation rate (8.7

citations/document), indicating a structural challenge in achieving international visibility. The findings of the present study provide a comprehensive evidence base and forward-looking roadmap to guide future research priorities, funding strategies, and policy decisions in sustainable PFAD-based biodiesel development.

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