

Review Paper

Two Decades of Biodiesel Research from Waste Cooking Oil: A Bibliometric and Literature Review of Heterogeneous Catalysts

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Abstract

Waste cooking oil (WCO) represents an abundant yet underutilised feedstock for biodiesel production, constrained primarily by challenges related to catalyst performance and recyclability. Conventional homogeneous catalysts, such as sodium hydroxide (NaOH) and potassium hydroxide (KOH), often suffer from deactivation after several reuse cycles due to leaching and sensitivity to impurities. In contrast, heterogeneous catalysts, including calcium oxide (CaO) and biomass-derived materials, offer promising, reusable, and environmentally benign alternatives for WCO-based biodiesel synthesis. This study presents a comprehensive bibliometric and literature review examining global research trends in biodiesel production from WCO using heterogeneous catalysts. As environmental concerns and fossil fuel depletion intensify, biodiesel has gained increasing attention as a sustainable and renewable energy substitute. A total of 974 publications indexed in the Scopus database between 2006 and June 2024 were systematically analysed to identify key research trends, influential authors, geographical distribution, and thematic clusters. Data retrieved from the Scopus database were exported in RIS format and subsequently processed using VOSviewer for bibliometric visualisation. Keyword analysis revealed dominant clusters around “WCO biodiesel” and “heterogeneous catalysts”, encompassing research topics such as transesterification, oxidation stability, performance optimisation, and corrosion behaviour. The bibliometric mapping highlights strong interconnections among research themes, particularly those associated with catalysts, transesterification mechanisms, engine performance, and emission reduction. The literature review further evaluates various types of heterogeneous catalysts including CaO, biochar, and metal- and biomass-based catalysts focusing on their synthesis routes, physicochemical properties, and optimal operating conditions. Research productivity on WCO biodiesel peaked during 2020–2021 but declined after 2022, suggesting research saturation or shifting interest toward emerging renewable technologies. Co-country analysis identified India and Malaysia as leading contributors, while Tabatabaei et al. and Bae et al. were the most prolific authors. This study offers a holistic overview of research progress and future directions, providing valuable insights for advancing cleaner, more efficient, and sustainable biodiesel production technologies.

Keywords: Biodiesel; Bibliometric; Heterogen catalyst; SLR; VosViewer; WCO



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1. Introduction

1.1. Background

The depletion of nonrenewable energy supplies has occurred in recent decades, driven by the growing demand for fossil fuels caused by population growth [1]. Natural gas, coal, and crude oil are examples of fossil fuels that provide the world's energy needs [2]. Fossil fuels could potentially meet around 80% of the world's energy requirements, and 20% by renewable energy. Oil makes up approximately 35% of the total energy produced, with the remaining sources coming from solar and supplemental energy, coal (29%), natural gas (24%), nuclear energy (5%), and hydropower (6%) [3]. Finding fuel or energy from renewable sources has been the focus of some recent research [4]. The extensive utilization of fossil fuels, including coal, petroleum, and natural gas, to meet our requirements for carbon-based chemicals and energy has led to the emergence of worldwide environmental issues, including the issue of climate change and concerns regarding energy security [5]. To mitigate the aforementioned issues, there is a strong push to utilize unconventional materials like microalgal lipids and waste cooking oil as the primary raw materials for biodiesel synthesis. This approach has led to the emergence of second-and third-generation biodiesel concepts [5].

Vegetable oil and used vegetable oil can produce biodiesel that has a positive environmental impact, particularly in converting waste into energy, energy fulfillment, and the global and national economy [4]. The utilization of both used and The production of biodiesel using vegetable oils that have not been utilized can yield several favorable outcomes in terms of environmental impact, waste utilization, energy provision, and the overall global and national economy [4].

Biodiesel, an auspicious alternative to traditional fossil fuels, exhibits characteristics comparable to those of diesel fuel while concurrently mitigating the release of greenhouse gases. It possesses the commendable qualities of a high calorific value, is non-toxic to ecosystems, is biodegradable [1], has low carbon emissions, has higher lubrication, and is environmentally friendly. Additionally, it demonstrates environmental compatibility, heightened lubricity, and diminished carbon [6]. From a

technical standpoint, it showcases exceptional lubricity and viscosity, complemented by the additional benefits of a high cetane number and flash point [7].

Figure 1 shows the demand for biodiesel in several countries. Total biofuel consumption in the United States and the European Union is expected to gradually increase. It is expected that biodiesel consumption in Brazil will increase. To address the rising consumption of fossil fuels, Indonesia launched the B30 program in 2020. Currently, Argentina has implemented a policy of a 10% biodiesel blend, with demand still small compared to other countries.

In biodiesel production, the expense of the main feedstock plays a vital role in the advancement of biofuels, as it constitutes over 70% of the overall production cost [8]. Waste oil can be sourced from households, restaurants, and industries, typically containing a high level of free fatty acids (FFA) [9]. Several countries, such as Malaysia, the United States, and China, produce 16.5 million tons of waste cooking oil (WCO) annually. Typically, it is discharged as waste and disposed of in water or soil, resulting in not only resource wastage but also environmental contamination [6]. WCO serves as one of the feedstocks that can be utilized as a source for the production of biodiesel. The utilization of WCO helps in reducing the costs associated with biodiesel production and mitigating environmental pollution [10]. The Waste cooking oil (WCO) can be utilized as an alternative fuel for diesel engines [11].

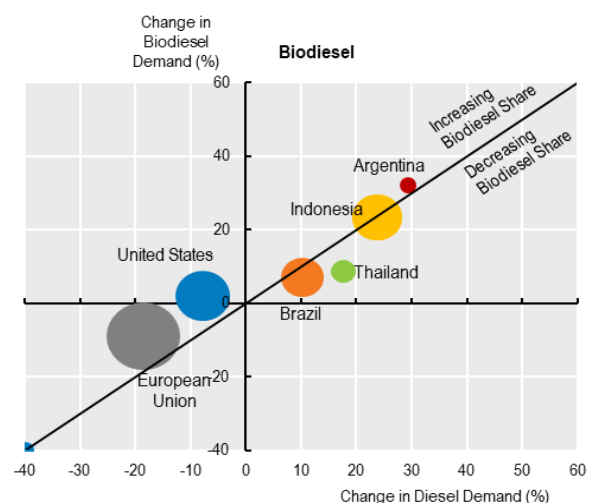


Figure 1. Development of demand for biodiesel in several countries [8]

In Indonesia, the use of biodiesel as an alternative fuel has been steadily growing year by year, almost on par with major countries such as the United States and Brazil. However, there was a slight decrease during the COVID-19 pandemic (2020-2022). It is predicted that biodiesel consumption will rise again in line with economic growth and the increasing number of vehicles each year. By 2030, biodiesel consumption is projected to reach 9.49 million kiloliters, while global demand for biodiesel is estimated to be 50 billion liters (Figure 2).

Biodiesel may be synthesised from waste cooking oil (WCO) via the transesterification process, employing alkali, acid, or enzyme catalysts [12]. Catalysts have been employed to expedite the process of esterification and transesterification, thereby facilitating the conversion of glycerides into biodiesel. The utilization of catalysts augments the solubility of alcohol, consequently elevating the rate of the ensuing reaction [10]. Homogeneous catalysts exhibit rapid reaction rates within a short duration; however, they pose challenges in downstream separation and reusability [13]. Moreover, they presented several drawbacks, including challenges in catalyst recovery after the reaction, a pronounced tendency to form stable emulsions, saponification, and the generation of toxic wastewater [14].

To overcome the issues associated with homogeneous catalysts, solid heterogeneous catalysts are now widely employed in biodiesel production, as they offer several advantages such as ease of separation, freedom from saponification and emulsion formation, and reusability. Solid heterogeneous catalysts can be basic CaO-based catalysts derived from various sources such as egg shell [15], snail shell [16], as well as magnetic catalysts MCNT@CdO [17], ZnAl₂O₄ [18]. On the

other hand, several studies have also reported the utilisation of catalysts derived from agricultural waste such as coconut chaff [20], rice straw [21] and empty fruit bunch [22].

1.2. Bibliometric Analysis

Bibliometric analysis is a research method that offers a comprehensive overview of past and present studies while also identifying key areas for future development within developing areas of research. Bibliometrics continues to be developed to quantitatively evaluate the key elements of written communication, such as titles, authors, and publication periods. Presently, bibliometrics is widely applied to examine thematic categories, the sequential progression of systematic output, collaborative networks among countries and institutions, and the geographical distribution of authors [23].

A summary of several reviews published previously (2020–2024) in the Scopus database related to trend publication biodiesel bibliometric analysis is presented in Table 1. It is apparent that numerous review papers have sought to capture recent developments in specific aspects of WCO biodiesel research. As outlined in Table 1, these studies have addressed a wide range of topics, including biodiesel production under supercritical conditions, sustainable biodiesel, and factors influencing its adoption.

Through a comprehensive bibliometric investigation using the Elsevier Scopus database, this research explores the utilisation of bibliometric analysis and literature review in biodiesel studies over the last decade [24]. By analysing emerging trends, recognising key contributors and institutions, and illustrating patterns of collaboration, the study delineates the development of this interdisciplinary domain while highlighting the pivotal influence of bibliometric in driving innovations within sustainable energy technologies.

The scientific novelty of this research lies in the integration of bibliometric analysis and literature review methods applied to available scientific data to evaluate the utilisation of heterogeneous catalysts in biodiesel production from waste cooking oil. To date, no studies have combined bibliometric and literature review approaches in the investigation of WCO biodiesel production employing heterogeneous catalysts.

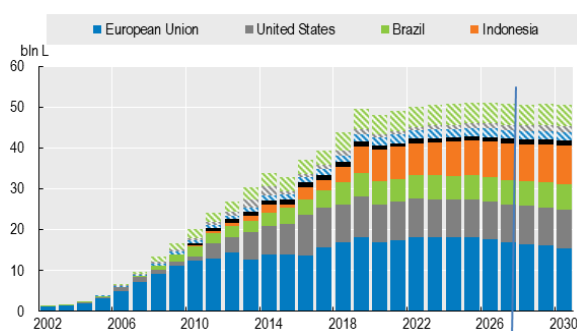


Figure 2. Biodiesel consumption in the world [19]

This work uses a dual approach, combining a bibliometric analysis of research trends and a literature review of WCO biodiesel production. This research aims to address the lack of bibliometric studies on biodiesel production based on WCO. In this study, 975 publications from the Scopus Core Collection database, spanning the years 2006 to June 2024, were analyzed to explore the development trends and future directions in this field.

2. Methods

2.1. Bibliometric Analysis

A bibliometric analysis of WCO biodiesel production was carried out with the Scopus database (<https://www.scopus.com>, Elsevier). As

one of the biggest citation and abstract databases for peer-reviewed literature, Scopus provides more reliable and consistent data for bibliometric analysis. Biodiesel." It begins with the search criteria for documents, which includes the keyword "WCO Biodiesel," covering the period from 2006 to June 2024. The search is conducted in the Scopus database, focusing on documents in English and selecting articles and reviews. This search yields 974 articles. The bibliometric analysis then examines various aspects such as the annual distribution of publications, the distribution across scientific journals, contributions from different countries and institutions, the most cited articles, and the overall distribution of scientific documents (Figure 3).

Table 1. Overview of recent bibliometric studies on biodiesel production (2020-2024)

Author	year	Title	Journal
Andreo-Martínez, et al. [25]	2020	Production of biodiesel under supercritical conditions: State-of-the-art and bibliometric analysis	Applied energy
Chen, et al. [23]	2021	Sustainability and challenges in biodiesel production from waste cooking oil: An advanced bibliometric analysis	Energy Reports
Osman, et al. [26]	2021	Bioethanol and biodiesel: Bibliometric mapping, policies and future needs	Renewable and Sustainable Energy Reviews
Almeida, et al. [27]	2021	Trends in lipase immobilization: Bibliometric review and patent analysis	Process Biochemistry
da Silva Dutra, et al. [28]	2022	How the biodiesel from immobilized enzymes production is going on: An advanced bibliometric evaluation of global research	Renewable and Sustainable Energy Reviews
Nabgan, et al. [29]	2022	Sustainable biodiesel generation through catalytic transesterification of waste sources: a literature review and bibliometric survey	RSC Advances5
Arista, et al. [30]	2024	Bibliometric analysis and visualization for revealing publication trends, research mapping of solid acid catalyst for biodiesel and biofuel production based on VOSviewer	Science Talks
Kombe [31]	2024	Exploring the landscape of ultrasonic transesterification: Unveiling priority research areas through bibliometric insights	Energy Conversion and Management X
Kusuma, et al. [32]	2024	Unlocking the potential of agricultural waste as biochar for sustainable biodiesel production: A comprehensive review	Bioresource Technology Reports
Purba, et al. [33]	2024	Bibliometric insights into microalgae cultivation in wastewater: Trends and prospects for biolipid production and environmental sustainability	Journal of Environmental Management
Hamed, et al. [34]	2024	Thermochemical conversion of oil palm biomass and its applications: A bibliometric exploration of global trends over two decades	Journal of Analytical and Applied Pyrolysis
Alagumalai and Song [24]	2024	Exploring the landscape of machine learning-aided research in biofuels and biodiesel: A bibliometric analysis	Green Energy and Resources

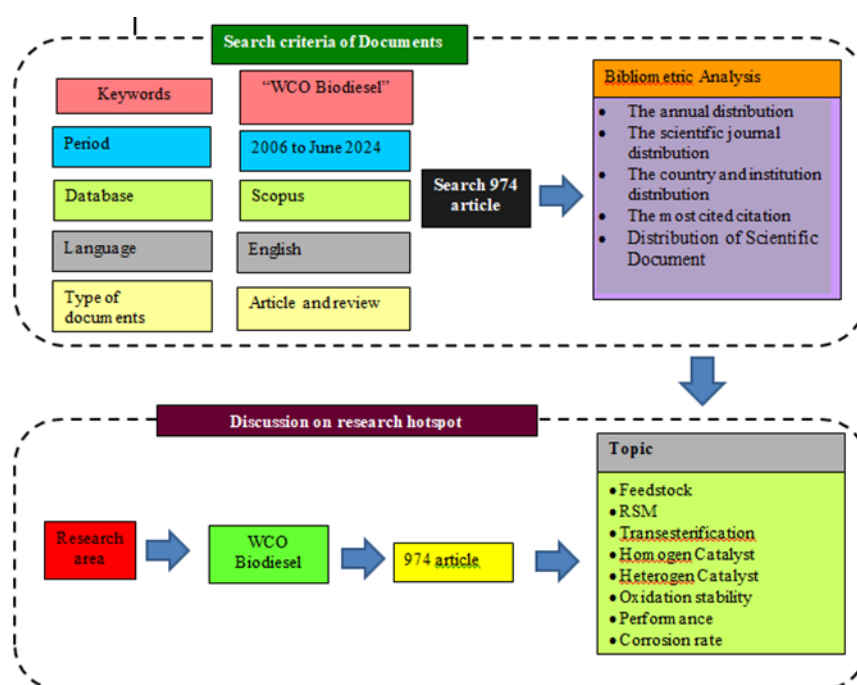


Figure 3. Steps of research and bibliometric analysis for wco biodiesel

Following this, the discussion on research hotspots centers on WCO Biodiesel, utilizing the 974 articles identified. The key topics of discussion include feedstock, Response Surface Methodology (RSM), transesterification, heterogeneous catalysts, oxidation stability, performance, and corrosion rate. This thorough method offers an in-depth evaluation of the current research landscape and identifies key areas of focus and interest within the field of WCO Biodiesel, highlighting both technical and methodological aspects of biodiesel production from waste cooking oil.

On the other hand, the literature review specifically examines biodiesel production utilizing heterogeneous catalysts such as CaO, metal catalysts, biomass catalysts, and egg shells, employing various types of heating methods. This section identifies factors affecting yield, including pretreatment, processing time, the amount of catalyst, temperature, and the methanol-to-oil ratio. Furthermore, the literature review examines various technologies employed in the production of biodiesel from WCO using heterogeneous catalysts.

3. Results

3.1. VosViewer Analysis

The image is a network visualization generated by VOSviewer, depicting the co-

occurrence of terms related to Waste Cooking Oil (WCO) research (Figure 4). The visualization reveals distinct clusters representing various research themes. The central term "WCO" is prominently linked to several key topics. The red cluster on the left is associated with catalyst-related studies, emphasizing terms like "catalyst," "transesterification," "homogeneous catalyst," and "optimization." This indicates a significant focus on the optimization of catalyst types and transesterification processes in converting WCO into valuable products, such as biodiesel. Key techniques such as "response surface methodology" and various types of catalysts like "sulfuric acid" and "heterogen catalyst" are also highlighted, suggesting a comprehensive investigation into catalyst efficacy and process parameters. On the other hand, topics related to the use of catalysts, engine performance, exhaust gas emissions, and optimization have been extensively studied by many researchers. However, methods of biodiesel production have not been widely compared in the context of WCO biodiesel production processes.

The green cluster on the right pertains to performance-related studies, highlighting terms like "performance," "rate," "emission characteristics," and "thermal efficiency." This cluster suggests an emphasis on evaluating the performance and environmental impact of WCO

acid" and "heterogen catalyst" are prominently featured, indicating comprehensive investigations into catalyst effectiveness and process parameters.

Furthermore, the color differences indicate the novelty of research topics related to WCO biodiesel from 2018 to 2021. From Figure 5, it is shown that yellow represents more recent research compared to purple. The topics of using nanocatalysts and optimization with RSM are relatively newer. In general, it can be concluded that the topic of WCO biodiesel production is no longer of significant interest.

The green and yellow clusters on the right pertain to performance-related studies, featuring terms like "performance," "rate," "emission characteristics," and "thermal efficiency" (Figure 6). These clusters highlight the research interest in calculating the performance and environmental effect of WCO-derived biodiesel, particularly concerning emissions and efficiency in internal combustion engines. Terms like "NO_x," "CO₂," and "thermal efficiency" underscore the focus on enhancing the environmental performance of biodiesel. The blue and green clusters, showing connections to terms such as "water content," "microwave," and "supercritical methanol," indicate additional research areas focused on alternative processing methods and the physicochemical properties of WCO. Overall, the visualization encapsulates a comprehensive landscape of WCO research, spanning catalyst optimization, performance evaluation, and environmental impact assessment, with a clear indication of the temporal progression of these research topics.

3.2. Trends in Annual Research Publications: A Two-Decade Analysis (2004-2024)

Figure 7 shows that the chart illustrates the annual quantity of published documents from 2004 to 2024, revealing distinct trends over these two decades. Initially, from 2004 to 2014, the number of publications showed a consistent and gradual rise each year. This period is followed by a sharp acceleration between 2014 and 2016, indicating a surge in interest or significant developments within the field. From 2016 onwards, the number of published documents continues to rise steeply, peaking around 2020-2021 with approximately 120 documents. This substantial growth period highlights the heightened research activity and output during these years.

Following the peak, the graph shows a noticeable decline in publications post-2021, dropping to around 80 documents by 2024. This decrease may suggest a shift in research focus, the completion of major studies, or external factors impacting the rate of publication. The significant growth observed between 2014 and 2020 could be attributed to advancements in the field, increased funding, or heightened interest in the topic. Conversely, the decline after 2021 might result from research saturation, changes in funding priorities, or global events influencing research activities. Overall, the graph underscores the dynamic nature of research outputs over time, reflecting both the growth and subsequent decline in scholarly activity.

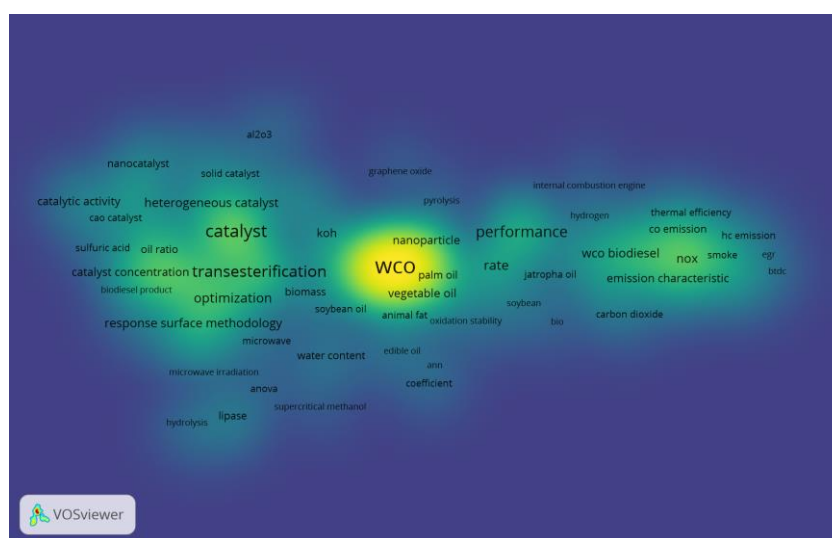


Figure 6. Heatmap of key terms in wco biodiesel research

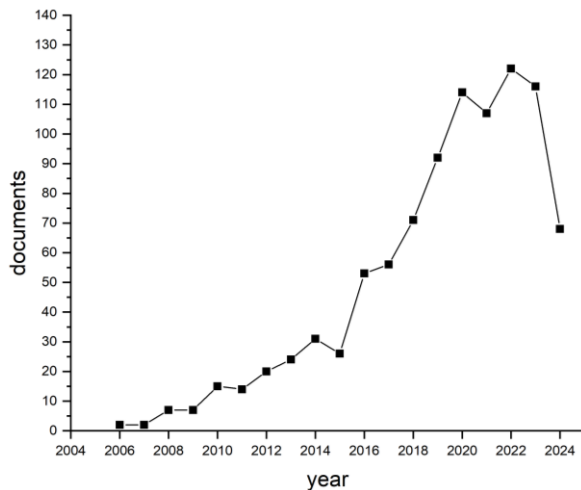


Figure 7. Document publication analysis over two decades

3.3. Research Productivity Analysis: Top Ten Authors in Academic Publications

The bar chart illustrates the number of documents published by ten different authors, showcasing their research productivity (Figure 8). The authors are ranked in decreasing order according to the number of documents they have produced. At the top of the list is Tabatabaei, M, with the highest number of publications at 14 documents, followed closely by Bae, C, with 12 documents. The mid-range contributors include Hwang, J, and Aghbashlo, M, each with 11 documents, while Gad, M.S., Khalid, A., Aboelazayem, O, and Taufiq-Yap, Y.H., each have 10 publications.

In the lower range, Gadalla, M, has published 9 documents, and Saha, B., rounds out the list with 8 documents. The distribution of publications among these authors is relatively close, with the majority having between 8 and 14 documents. This data indicates a highly competitive and active research environment where multiple authors are making significant contributions to their fields. The bar chart effectively highlights the prolific nature of these researchers, providing insights into their impact and influence on academic publishing.

3.4. Global Research Output: Analysis of Document Publications by Country

The bar chart illustrates the number of documents published by researchers from various countries, highlighting significant differences in research output (Figure 9). India leads with approximately 250 documents, indicating a strong

research focus or a larger research community. Malaysia follows with around 140 documents, making it the second-highest contributor, while China ranks third with about 100 documents. Mid-range contributors include Iran with roughly 90 documents, and both Egypt and Saudi Arabia with approximately 70 documents each. The United States has around 60 documents, placing it in the mid-range category.

Lower-range contributors, including Indonesia, Brazil, and South Korea, each have around 50 documents. The chart emphasizes the disparities in research productivity across different countries. India's dominance suggests a significant emphasis on research activities, while Malaysia and China also show robust research outputs. The mid and lower-range contributors, although active in research, produce fewer publications compared to the top three countries. This chart effectively showcases the worldwide distribution of academic contributions and the variable levels of research activity among countries.

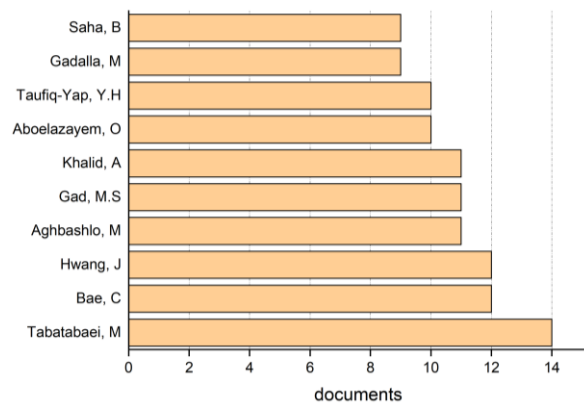


Figure 8. Number of documents published by top authors

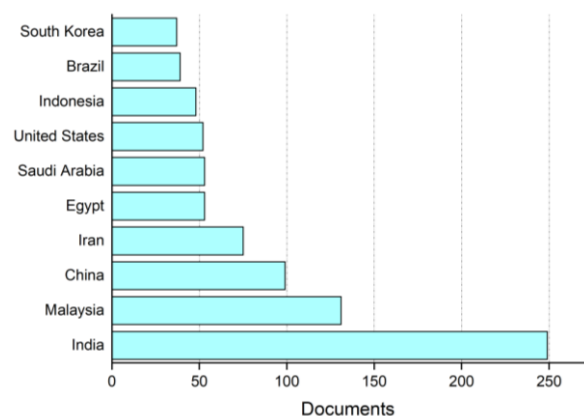


Figure 9. Number of Documents Published by Researchers from Various Countries

3.5. Distribution of Scientific Publications Across Various Disciplines

The pie chart displays the distribution of published documents across various scientific disciplines (Figure 10). The largest segment, representing 22%, is attributed to the category labeled as "others," indicating a diverse range of topics not specifically categorized in the other segments. This is followed by Environmental Science, which constitutes 16% of the total publications, highlighting significant research activity in this field. Engineering and Chemical Engineering each account for 14% and 12% respectively, showcasing their importance in the academic publishing landscape.

Computer Science and Chemistry both contribute 12% of the publications, indicating their vital roles in scientific research. The smaller segments include Materials Science, Physics and Astronomy, each making up 4% of the total, followed by Agricultural and Biological Sciences at 3%. Mathematics and other unspecified disciplines each account for 2%. This distribution underscores the multidisciplinary nature of academic research, with a significant portion dedicated to a variety of fields, reflecting the inclusive nature of scientific inquiry and publication.

3.6. Analysis of Document Type Distribution in Academic Publishing

The pie chart illustrates the distribution of various types of published documents, highlighting the dominance of articles in the academic publishing landscape (Figure 11). A significant 79.90% of the total publications are articles, indicating a strong preference for this format within the research community. Conference papers constitute the second-largest segment, accounting for 14% of the total, underscoring the importance of academic conferences as key venues for disseminating research findings. Reviews make up 3.20% of the publications, reflecting their role in synthesizing existing knowledge. Additionally, book chapters, although representing a smaller portion at 2.40%, still contribute meaningfully to scholarly literature.

Minor contributions come from books and conference reviews, each comprising only 0.10% of the total publications, while errata and retracted documents also account for 0.10% each, indicating minimal occurrences. The overwhelming dominance of articles suggests that they are the preferred medium for presenting research, likely due to their structured format and peer-review process. The significant presence of

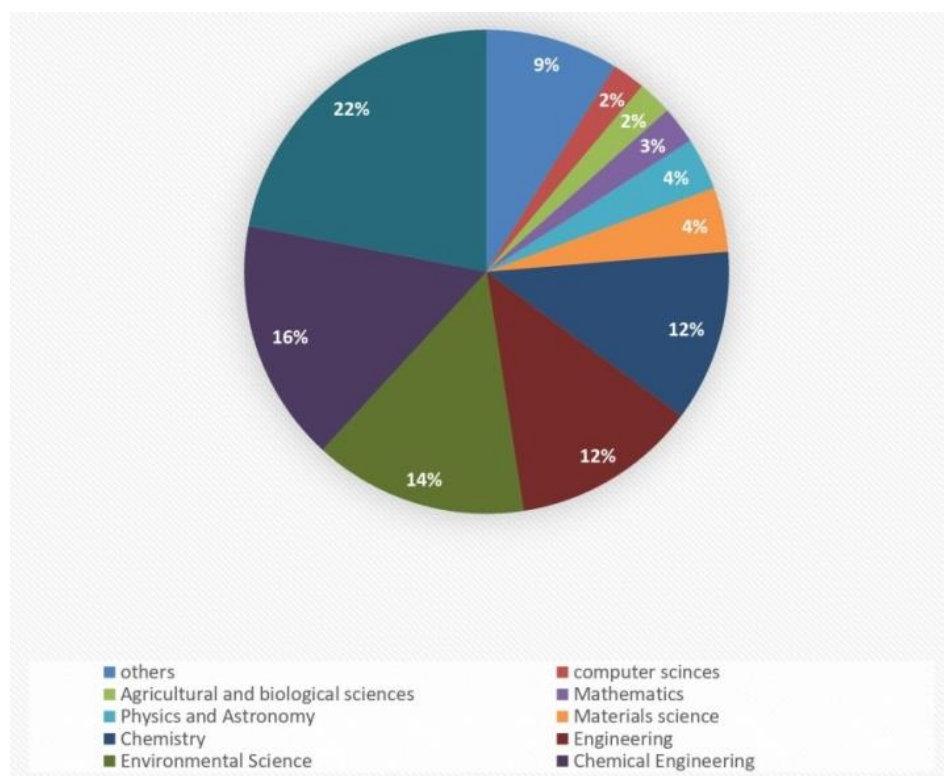


Figure 10. Distribution of published documents across scientific disciplines

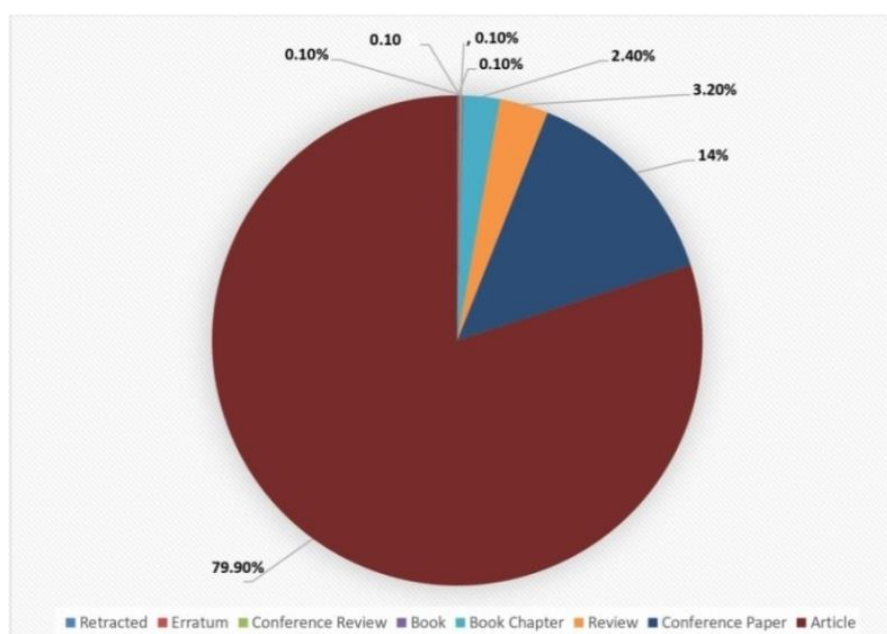


Figure 11. Distribution of Published Document Types

conference papers highlights the ongoing importance of conferences for knowledge exchange. Meanwhile, the modest proportions of reviews and book chapters emphasize their complementary role in the broader academic ecosystem. This chart effectively captures the varied landscape of academic publications, with articles being the predominant form.

4. Biodiesel Production of WCO

4.1. Pre-Treatment

In food preparation, temperatures ranging from 160 °C to 200 °C are used repeatedly and continuously. The oil passes through a process called degradation, which significantly alters the physical and chemical characteristics of the oil. Under normal working circumstances, the three principal degradation reactions are hydrolysis, oxidation, and polymerization. The acid number of WCO is characteristically used to evaluate its quality [35]. By employing sulfuric acid as a catalyst, waste oil with a high acid value (27 mg KOH/g oil) was first esterified with methanol to lower the acid number. Additionally, used frying oil was warmed for 1 hour at 110 °C to eliminate any water traces [36]. Petchsoongsakul [37] reported that the water already present in WCO can hydrolyze triglycerides, producing a high FFA concentration that can be used to make soap (saponification) when combined with an alkaline catalyst.

4.2. Technology Reduction of Water Content

The physicochemical properties of WCOs are influenced by several variables, such as the oil's place of origin, the length and temperature of the cooking process, the kind of food being prepared, the way the oil is stored, and the degree of air exposure [38]. An essential component in the synthesis of biodiesel from waste cooking oil (WCO) has drawbacks, particularly the high levels of water and free fatty acids that impact the yield and quality of the biodiesel produced. Various technologies are employed to decrease the water content in WCO oil using the vacuum drying method [39], utilizing hybridized reactive distillation [37]. The best performance and low cost are obtained from the use of the method (hybridized reactive distillation) [37].

5. Heterogen Catalysed: The Process of Transesterification

An acidic or basic heterogeneous (solid) catalyst can produce high-quality biodiesel while still being environmentally benign. It is inexpensive to produce and readily recovered and repurposed. Additionally, homogeneous catalysts' problems with separation, emulsification, and soap formation are eliminated by solid catalysts [40]. Because it requires less temperature and pressure than a non-catalytic procedure, heterogeneous transesterification is easier to execute. Heterogeneous catalysts further

reduce their detrimental effects on the environment by reducing process waste and effluent [41]. Furthermore, heterogeneous catalysis makes the process of manufacturing biodiesel simpler and reduces production costs, but at the expense of longer reaction periods and bigger catalyst loadings due to the reaction's low catalytic activity [41]. Heterogeneous catalysts provide an option in this case. These catalysts can be derived from biomass and various wastes, including industrial, urban, and agricultural sources, and they may be less corrosive and damaging to the environment. They may also be recovered and used again [42].

There are certain disadvantages to using solid acid catalysts for the manufacture of biodiesel, despite all of its many benefits. Due to the significant leaching of active species into the reaction mixture, which greatly deactivates the catalysts, the catalytic performance of the catalyst in the transesterification process is not good [40]. Gohain [43] sought to improve the conversion of used cooking oil (WCO) into biodiesel. A heterogeneous potassium hydroxide catalyst (KRAC) based on defoliated cake-activated carbon (RAC) from *Rhodotorula mucilaginosa* was created by Gohain [43]. According to Gohain [43] the results, the ideal parameters of a 9:1 methanol/oil ratio, a 3% by weight K-RAC loading at 60°C, and a 3-hour reaction period led to the maximum conversion of fatty acid methyl esters (FAME) of 98.66%.

5.1. Metal-Based Catalyst

The most often used kind of heterogeneous acid catalyst is an acidic metallic solid impregnated in porous materials because of its large surface area, superior thermal stability, and inert nature. To create biodiesel, the transesterification process was examined by Ala'a, et al. [44] stated that the optimal output of biodiesel was 92.3 wt% when the ideal set of process variables was with a time of 4 hours, at a temperature of 80 °C, a molar ratio of 12 (methanol and oil), and a quantity of catalyst of 4% by weight. Gardy, et al. [45] used various ratios of SO₄/Fe-Al-TiO₂ solid acid catalyst to create biodiesel from used cooking oil. After 2.5 hours of reaction at 90°C with 3 weight percent of the magnetic catalyst and a 10:1 molar ratio of methanol to oil, the catalyst produced 96% of the

fatty acid methyl ester (FAME) from WCO, according to the final data. Furthermore, across ten cycles, SO₄/Fe-Al-TiO₂ showed exceptional stability against WCO transesterification and demonstrated efficacy with feedstocks containing up to 20 weight percent free fatty acid (FFA). Copper-doped zinc oxide (CZO) nanocomposite was assessed by Gurunathan [46] as a heterogeneous catalyst for the transesterification of used cooking oil into biodiesel. The greatest biodiesel yield of 97.71% (w/w) was found to be produced under the following conditions: 55 °C temperature, 1:8 (v/v) O/M ratio, 12% (w/w) nanocatalyst concentration, and 50 minutes of reaction time. Ma [47] tried using a modified resin that has been FeCl₃-treated to produce biodiesel from leftover cooking oil. They concluded that a high transesterification rate of around 92% was attained with the following parameters: a 10:1 methanol/oil molar ratio, an 8% catalyst concentration, a reaction temperature of 90 °C, and a reaction duration of 120 min.

Yahya, et al. [48] transesterified spent cooking oil waste into biodiesel using a mesoporous calcium titanate (MCT) catalyst. Calcium was added to titanate to increase its surface area and stability. Consequently, the catalyst possessed a greater surface area and was more stable and basic than the calcium oxide (CaO) catalyst. In an hour at 65 degrees Celsius, a 3:1 methanol to water ratio, 0.2 weight percent MCT catalyst, and a maximum biodiesel yield of 80.0% were achieved. Roy [49] reported on a fascinating investigation into the manufacturing of biodiesel. They released a fascinating study on the production of biodiesel. They released a fascinating study on the production of biodiesel. After conducting the transesterification using BaSnO₃, they found that the following reaction conditions were optimal for obtaining 98% fatty acid methyl ester (FAME) conversion: The catalyst concentration is 2.5 wt%, the catalyst atomic ratio is 1:1, the catalyst activation temperature is 850 °C, the oil-to-methanol molar ratio is 16:1, and the reaction time is 25 minutes. Using KOH/Clinoptilolite as the heterogeneous catalyst in the microreactor, Mohadesi, et al. [50] reported that biodiesel reached its highest purity at a reaction temperature of 65 °C, with a catalyst concentration of 8.1 wt%, an oil-to-methanol volume ratio of 2.25:1, and a residence time of 13.4 minutes. This

process produced biodiesel with a purity of 97.45%.

The greatest catalytic activity was found in the ZnCuO catalyst (without NDG) and ZnCuO/(30%) N-doped graphene (NDG) catalyst. According to Kuniyil [51], they concluded that the maximum yield (97.1%) was obtained with a catalyst loading of 10% weight percent, with a methanol-to-oil molar ratio of 15:1, a reaction time of 8 hours, and a temperature of 180 °C. Oxide-based catalysts have been successfully generated for the biodiesel transesterification reaction by Sulaiman [52]. The best catalyst conditions were found with a charge of 20 weight percent Fe/Ba/Al₂O₃ catalyst calciners at 800 °C, according to their report, for the transesterification process with fixed reaction conditions (65 °C, 1:18 weight percent oil/methanol ratio, 6 weight percent catalyst loading, and 3 hours response time), yielding the maximum biodiesel production of 84.02%. The transesterification reaction can be effectively catalyzed by nanoparticles with a mass ratio of 0.5 for Al₂O₃/Fe₃O₄. An oil conversion rate of up to 99.1% was achieved at a temperature of 99.8 °C, with a methanol-to-oil ratio of 32.1, and a reaction duration of 2.95 hours [53].

5.2. CaO Catalyst

Calcium oxide (CaO) is notable among the heterogeneous catalysts for biodiesel synthesis. It demonstrates high activity in transesterification, even under relatively mild operating conditions [42]. Currently, the commonly used heterogeneous catalyst for the transesterification reaction is CaO [6]. Many solid wastes rich in Ca elements, such as eggshells, crab shells, carbide slag, etc., were used as the sources of CaO to reduce the catalyst cost from raw materials (Figure 12).

Degfie [54] looked into using calcium oxide (CaO) nanocatalysts to turn waste cooking oil (WDO) into biodiesel. The results showed that under optimal experimental circumstances, which comprised 50 °C, a 1:8 WCO oil/methanol ratio, a 1 weight percent catalyst loading rate, and a 90-minute reaction period, the maximum WCO to biodiesel conversion was calculated to be 96%. Mahesh [55] reported achieving a similar result by employing waste cooking oil impregnated with KBr and CaO as a catalyst to produce biodiesel.

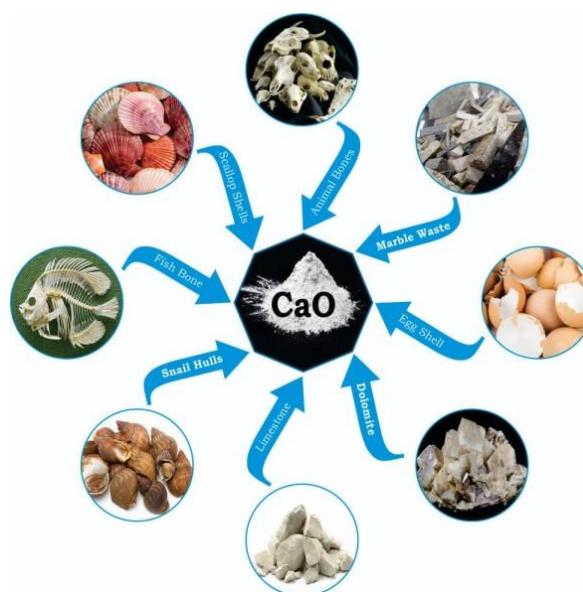


Figure 12. Heterogeneous CaO-based catalyst

The best results were obtained with a catalyst loading of 3% by weight, a methanol-to-oil ratio of 12:1, a reaction temperature of 65 °C, and a reaction period of 1.8 hours. A CaO/MgO nanocomposite was reported to be used as a heterogeneous catalyst by Rabie, *et al.* [56]. At 90 °C and 120 minutes, the maximum biodiesel yield is reached using a 6-weight percent catalyst and a 1:15 oil-to-methanol ratio.

5.3. Biochar Catalyst

Biochar was found to provide superior support for increasing stability, active site concentration, and specific surface area when compared to zeolite [6] (Figure 13). A workable solution to waste management problems and the total cost of producing biodiesel is to use waste biomass as a catalyst source, activated by KOH and H₂SO₄ [1]. Jung [57] concentrated on using chicken manure-derived biochar as a porous medium and catalyst for the production of biodiesel from wasted cooking oil. They stated that the transesterification reaction's temperature was lowered by the chicken dung biochar, resulting in the greatest FAME output (95%) at 350 °C. Moreover, Maneerung [58] asserts that a sustainable way to produce biodiesel is through the transesterification of leftover cooking oil using CaO catalysts derived from chicken manure. The significant amount of calcium compounds in chicken feces readily converts into the active calcium oxide catalyst after being calcined at 850 °C. The results demonstrated that up to 90%



Figure 13. Bio chart catalyst heterogeneous

FAME generation was possible under ideal reaction conditions, which included a 7.5 weight percent catalyst, a 15:1 methanol: oil molar ratio, and 65 °C. Reusable cooking oil waste can be converted into sustainable biodiesel using banana peel charcoal and a magnetic $\text{Fe}_2\text{O}_3/\text{Fe}_2\text{K}_6\text{O}_5$ catalyst. At a methanol to oil ratio of 7:1, a catalyst amount of 4 weight percent, a 3-hour reaction period, and a temperature of 60 °C, a biodiesel yield of 88.83% was achieved [1].

5.4. Eggshells and Bone Catalyst

As per Chung [59], findings, the application of CaO derived from chicken eggshells has a less significant effect than KOH because the calcination process doesn't necessitate an intricate technique or substantial electricity use. Using a Zn-substituted CaO nanocatalyst derived from used eggshells, Borah, *et al.* [60] investigated the transesterification of used cooking oil. The findings showed that a maximum biodiesel conversion of 96.74% was found as a result of the reaction parameters of 20:1 methanol to molar oil ratio, 5 wt% catalyst load, 65 °C reaction temperature, and 4 hours reaction duration. Furthermore, Mansir [61] reported that the designed catalyst successfully achieved a high biodiesel yield of 92.1% at the ideal reaction parameters of 15:1 methanol to molar oil ratio, 3 wt% catalyst loading, 80 °C reaction temperature, and 3 hours reaction time. Additionally, Kamaronzaman [62] reported on the use of chicken eggshell catalysts to produce biodiesel

from leftover cooking oil. A methanol-to-oil molar ratio of 20 to 1, a catalyst dosage of 45.47 g/L or 5 wt%, a catalyst activation temperature and duration of 60 °C, and a catalyst activation period of one hour were the perfect conditions for their inquiry.

In a similar, Kamaronzaman [63] enhanced the catalyst derived from the calcined chicken eggshell by including a particular quantity of nickel. Findings as Displayed. With just a 16 to 1 molar ratio of methanol to oil, 1 weight percent or 9.09 g/L of catalyst, and a reaction temperature of 65 °C for two hours, the output yield of biodiesel can be improved to 100%. The CaO catalyst synthesized from ostrich eggshells has smaller particle sizes, a larger surface area, and more basicity than that of chicken eggshells. The maximum production of biodiesel is 96% at a methanol-to-oil ratio of 12:1, a reaction temperature of 65 °C, a reaction period of two hours at a speed of 250 rpm, and a catalyst weight of 1.5 wt% [64].

5.5. Scallop and Snail Shell Catalyst

Sirisomboonchai [65] evaluated the influence of various factors on the transesterification of waste cooking oil (WCO) and methanol, utilizing calcined scallop shells (CSS) as a catalyst in a closed system for the production of biodiesel fuel (BDF). They contrasted commercial CaO with calcined scallops (CSS) as a heterogeneous solid catalyst for the synthesis of biodiesel. The yield of BDF rose to 86% at 65 °C with CSS when the catalyst was loaded at 5 weight percent (WCO basis) and the reaction was allowed to run for two hours. To produce biodiesel from used frying oil. Naveen [66] created a unique solar parabolic trough collector annex reactor using discarded mussel shells as a calcium oxide catalyst. The highest yield, which was found to be 95.84%, was obtained using the following parameters: a 9:1 ethanol-to-oil ratio, a 180 LPH reagent flow rate, and an agitation speed of 300 rpm. Komintarachat [67] investigated the catalytic increase of calcium oxide from green shells using potassium chloride impregnation in a different work aimed at producing biodiesel from used cooking oil. The maximal yield of FAEE with a catalyst ratio of 4.0% w/w and a molar ratio of 10:1 for EtOH to WCO at 80 °C for three hours is 97% w/w, according to the assigned data. Furthermore,

according to Lin [68], using recycled oyster shells with a methanol-to-oil molar ratio of 9:1, a reaction time of 180 minutes, a reaction temperature of 65 °C, and a catalyst concentration of 6 wt% allowed for the maximum yield of biodiesel to be produced. The yield was stated to be 87.3%. Using a fast homogenizer led to a considerable increase in the rate of biodiesel synthesis with a WCO yield of 88% (30 min) [36]. In contrast to the old agitation strategy, which required 2-3 hours to create equal amounts of biodiesel.

Calcium oxide (CaO) is a heterogeneous catalyst that can be derived from river snail shells [69]. Additionally, CaO is one of the limited number of heterogeneous substances that can be sourced from seaweed. Moreover, Kadir, *et al.* [16] synthesize biodiesel from WCO using a CaO catalyst made from a snail shell. This study's findings showed that an 80% yield of biodiesel derived from WCO was produced using a CaO catalyst made from a snail shell.

5.6. Catalysts of Biomass

Biobased or green catalysts are derived from biomass sources. Natural and biological sources of carbon and calcium have been recognized as potential heterogeneous catalysts for producing biodiesel from vegetable oil [70]. Using this solid waste catalyst in the transesterification process can help decrease the amount of daily waste disposal, processing problems, and biodiesel investment expenses [71]. A solid base catalyst improves separation during the synthesis of biodiesel, reducing expenses and raising recycling efficiency because there is no glycerol byproduct.

It was discovered by Naeem [70] that a one-step heterogeneous activated carbon (AC) catalyst could produce biodiesel. Carbon is abundant in biomass derived from plants. A key factor influencing the degree and yield of biodiesel generation is the kind of catalyst selected for catalysis [24]. Key sources of elements such as calcium and potassium can be employed as active components in creating heterogeneous catalysts for biodiesel synthesis, including bio-based waste products [2].

The yield was 97.8% under the optimal circumstances, which included an hour-long reaction period, a temperature of 45 °C, a 1% by-weight catalyst loading, and an 18:1 methanol to oil molar ratio. Abdullah [72] reported that

leftover cooking oil was converted into biodiesel using a bifunctional nanocatalyst made from palm kernel husk. As a consequence, the production of biodiesel over 4 weight percent was 95.36 1.4%. PKSHAC-K₂CO₃ (20%) CuO (5%) catalyst, 70 °C for two hours, and a methanol to oil molar ratio of 12:1. Rapid pyrolysis of rice straw followed by the sulfonation process produced sulfonated catalyst (RS-SO₃H), as stated by Mohamed [73]. The result in the best-case scenario is this: 10wt% catalyst with methanol and a 20:1 oil molar ratio, heated to 70 degrees Celsius for six hours. The maximum mass production of biodiesel has been increased to 90.37%.

Tan, *et al.* [71] evaluate the feasibility of using leftovers from the combination of fish and chicken bones as an inexpensive option, a recyclable solid catalyst. The optimal working parameters for the transesterification catalyst loading were stated as 1.98% w/v, 1.54 hours reaction duration, and 65 °C reaction temperature, when the alcohol/oil molar ratio was 10:1. In actuality, 89.5% biodiesel was created under the optimum conditions. Another study found that using leftover ostrich bones (*Struthio camelus*) produced a heterogeneous catalyst for sustainable biodiesel synthesis from discarded cooking oil [74]. They concluded that the best biodiesel production of 90,56% was obtained with a reaction period of 4 hours, a methanol/oil ratio of 15/1, a process temperature of 60 °C, and a catalyst loading of 5 wt.%. Catalyst heterogeneous and technology for the production of biodiesel WCO as shown in Table 2.

6. Technology for Biodiesel Production

6.1. Microwave Irradiation

Convection methods with mechanical agitation, process intensification techniques, and catalytic processes, including ultrasonic cavitation, microwave technology, and hybrid technology (a combination of both), have replaced earlier methods for producing biodiesel in recent years. Non-ionizing radiation, such as microwaves, affects molecular motions, including The structure of the molecule remains unchanged during ion migration and dipole rotations [75]. The charged ions oscillate across the solution in the presence of the same electric field, converting kinetic energy into heat energy [76]. Microwave irradiation causes a blend of vegetable oil, methanol, and a catalyst, which includes both

Table 2. Catalyst heterogenous and technology for production of biodiesel WCO

Catalyst	Process	Preparation method			Reaction condition					Yield	Ref
		Temp. calcination (°C)	Time (h)	Methods	Temp. (°C)	Time (h)	Catalyst loading	Methanol to oil molar ratio			
Bones											
Chicken bones	Calcination	900	4	Conventional	65	4	5%	15:1	89,33%	[101]	
Ostrich bones	Calcination	900	4	Conventional	60	4	5%	15:1	90.56%	[74]	
Ostrich bones	Calcination	1000	4	Conventional	65	2	1.5%	12:1	96%	[15]	
Mussel shell	Calcination	900	5	Conventional	80	3	4%	10:1	97%	[67]	
Chicken and fish bones	Calcination	1000	4	Conventional	65	1.54	1.98%	10:1	89.5%	[71]	
Cow horn	Calcination	800	3	Conventional	60	1	3%	6:1	98%	[102]	
CaO											
Eggshell	Calcination	1000	4	Conventional	65	2	1.5%	12:1	94%	[15]	
Eggshell	Calcination	1000	4	Conventional	60	1	5%	20:1	45.52%	[62]	
Egg shell (CaCO ₃)	Calcination	900	5	Conventional	80	3	3%	15:1	92.1%	[61]	
Ostrich-eggshell	Calcination	1000	4	Conventional	65	2	1%	12:1	96%	[64]	
Eggshell and peat Clay (CaO/SiO ₂)	Calcination	900	2	Conventional	60	1.5	10%	14:1	91%	[103]	
CaO/MgO	Calcination	800	3	Conventional	90	2	6%	15:1	96.47%	[56]	
Snail shell+TiO ₂	Calcination	500	6	Conventional	65	3	3%	6:1	95%	[16]	
KOH/Clinoptilolite	Calcination	400	5	microreactor	65	0.21	8.1%	2.25:1	97.45	[50]	
CaO	-	-	-	High-speed homogenizer	50	0.5	1%	10:1	88%	[36]	
Sargassum and river snail shell waste	Calcination and hydrothermal	800	3	Conventional	73	2.6	3%	16:1	99.21%	[6]	
Crab shell and plantain peels	Calcination	900	4	Conventional	60	2.48	5%	13,03:1	93%	[2]	
Metal Catalyst											
CM-SO ₃ H	Hydrothermal	190	24	conventional	110	4	10%	9.35:1	89.6%	[104]	
A-Fe ₂ O ₃	Calcination	900	2	conventional	80	3	6%	12:1	92%	[40]	
Ni-Ca-GBC	Calcination	900	2	Microwave	80	0.5	6%	12:1	94.6%	[105]	
CuO/ZnO	Calcination	500	2	conventional	65	2	5%	9:1	93,5%	[106]	
Ca/Si/Al oxides	impregnation			microwave		0.05	1.5%	6:1	98.7%	[86]	
NaOH/ bentonite	impregnation	400	3		60	4	4%	9:1	91,2%	[107]	
H ₃ PMo ₁₂ O ₄₀ , HPMo	impregnation	300	3	Electrolysis	60	15	0.85%	6:1	90%	[108]	
MgO-ZrO2	Calcination	650	4	Conventional	80	4	4%	2:1	92.3%	[44]	
Coal fly ash	Hydrothermal	600	1.5	Microwave	66.20	0,1	3.99%	9.67:1	94.91%	[82]	
Calcium diglyceroxide	Calcination	900	2	Microwave	62	0.4	1%		94.86 %	[81]	
KOH/ /corncoobs	Activation	600	2	Conventional	45	1	1%	18:1	97.8%	[70]	
Kbr and CaO	Impregnation calcination	900	4	conventional	65	2	3%	12:1	80%	[55]	
KNO ₃	Impregnation calcination	700	4	conventional	65	2	10%	45:1	100%	[109]	
Fe-MMTK10	calcination	500	5	conventional	134.07	6	4.68%	11.77:1	95.26%	[110]	
MTC	Sol gel, calcination	500	5	conventional	65	1	0.2%	3:1	80%	[48]	
La ³⁺ /ZnO-TiO2	Sol-gel	400	2	conventional	35	3	4%	12:1	96.14%	[111]	
Amberlys 15	-	-	-	FIR	110	2	6%	8:1	97.13%	[97]	
Zn/ CaO	calcination	900	0.33	Conventional	65	4	5%	20:1	96.74%	[60]	
ZnAl ₂ O ₄	Impregnation	900	3	Conventional	150	2	10%	40:1	95%	[18]	
20Fe:80Ba/Fe Al ₂ O ₃	Impregnation, calcination	800	5	Conventional	65	3	6%	18:1	84.02%	[52]	
Al ₂ O ₃ /Fe ₂ O ₄	co-precipitation	500		Conventional	99.8	2.95	5%	32.2:1	99.1%	[53]	
RS-SO ₃ H	Pyrolysis	480-510	0.0027	Conventional	70	6	10%	20:1	92.5%	[73]	
MCNT@CdO	Calcination	375	4	Conventional	120	3	0.2g	10:1	92%	[17]	
GO@ZrO2-SrO	co-precipitation	550	3	Conventional	120	1.5	0.5 g	4:1	91%	[112]	
SrSnO ₃	Calcination and hydrothermal	800	4	Conventional	80	0.67	2.9	18.6:1	98.75%	[9]	
CaO/Fe ₂ O ₃	Calcination	450	5	Ultrasound	60	6	6%	11:1	98,7%	[90]	
Biochar											
Coconut chaf	Impregnation	900	4	Magnetic stir	65	2.5	1.5%	12:1	91,05%	[20]	
Carob pod	Calcination	500	4	microwave	65	0.05	1%	10:1	98.20%	[88]	
Vegetable wastes	Calcination	600	5	Magnetic stir	60	2	7%	9:1	94.7%	[3]	
Bagasse	Calcination	600	5	Magnetic stir	66	4	1%	18:1	94.4%	[113]	

Catalyst	Process	Preparation method		Methods	Reaction condition				Yield	Ref
		Temp. calcination (°C)	Time (h)		Temp. (°C)	Time (h)	Catalyst loading	Methanol to oil molar ratio		
Rice straw	Calcination	500	2	Magnetic stir	65	1.5	3.5%	15:1	97.3%	[21]
Empty fruit bunch	Calcination	600	3	Conventional	70	2	5%	12:1	97.1%	[22]
Banana peel biochar-Fe ₂ O ₃ /Fe ₂ K ₆ O ₅	Calcination	700	2	Conventional	60	3	4%	7:1	88%	[1]
Acalypha indica leaves	Calcination	100	0.5	Conventional	63,7	1.16	2,4%	11,8:1	94,74 %	[10]
Radish (Raphanus sativus L.)	Calcination	900	4	Conventional	60	2.5	6%	12:1	98,0%	[114]
Chicken manure biochar	Calcination	350	1	Conventional	340				95,6%	[5]
Other materials										
Cement kiln dust	Calcination	700	4	Conventional	65	6	2%	18:1	98.8%	[115]
Coal fly ash	Calcination	600	1.5	Microwave	66	1	3.99%	9.67:1	94.91%	[82]
Fly ashes	Calcination	120	5	Conventional	60	3	10%	9:1	96%	[116]
Kaolinite (Kaol/K+)	Calcination	300	5	Conventional	70	3	15%	14:1	94.76%	[117]
Zeolite/Chitosan	Calcination	450	4	Conventional	60	3	1%	1:7	93%	[118]
Zeolite (Mg/klinoptilolit)					70	3	4%	16:1	98,7%	[7]
Calcium diglyceroxide (CaDG)	Calcination	900	4	Microwave	62	0.25	1,03%	7,46:1	94,86%	[81]

polar and ionic elements to heat very quickly at the molecular level [75].

Contrary to traditional heating, the bulk reaction mixture is heated primarily by convection, conduction, and radiation from the heating surface [77], [78]. It takes a long time to heat up and generates uneven heating [77]. When compared to the traditional approach, In this process, the reactants are heated by thermal energy through convection, conduction, and radiation from the reactor surface, and the production efficiency of biodiesel can be significantly higher using microwave heating. Microwaves have frequencies and wavelengths that fall between 300MHz and 300GHz and 1mm and 1m, respectively [79]. Materials can either emit, reflect, or absorb microwave radiation. Using a dielectric heating mechanism, solids, and liquids must be able to absorb electromagnetic energy and transform it into heat for microwave heating to work [76]. Process microwave irradiation aids in increasing the effectiveness of heat transmission, leading to quicker chemical reactions. The dielectric characteristics of the material being employed determine the heat transmission efficiency [80]. Microwave irradiation demonstrated the importance of rapid mixing of the heterogeneous phase and efficient heating of the reaction mixture, boosting the velocity of the transesterification reaction in comparison to the traditional water bath heating approach [81]. Using microwaves could decrease

the need for methyl acetate and significantly shorten the times required for esterification and transesterification reactions [82], increase biodiesel yields, create more cost-effective processes, and shorter separation and purification times [76]. For the reaction with a thermal effect and methanol evaporation due to the strong microwave interaction of the material Xiang [84], a microreactor was used to reduce the residence time to about 1 minute. Based on the optimization's findings, it is possible to obtain less-than-ideal circumstances and reach a biodiesel purity of up to 99% [83].

The use of microwave heating has been widely applied in the production of biodiesel from waste cooking oil (WCO) employing various types of heterogeneous catalysts derived from various types of shells, such as snail shell [84], metal oxides [85], Ca/Si/Al composite [86], steel slags [87], carob pod [88]. Calophyllum inophyllum oil and waste cooking oil (WCO) are combined to create biodiesel using the alkaline transesterification process using microwave radiation. The production of biodiesel was 97.40% efficient. Additionally, the reaction time was dramatically shortened to 15.9 minutes when this approach was used in the transesterification process [80].

Furthermore, microwave irradiation accomplished the reaction speed, activation energy, and advantages of microwave technology over conventional methods in just four hours [89].

The kinetics of the enzymatic reaction have been successfully enhanced by process intensification techniques such as the use of ultrasound, microwaves, and supercritical fluids. Among other things, microwave technology has demonstrated encouraging results in accelerating reaction rates and raising production yields [89]. As a result of combining microwave and continuous flow actuation techniques, continuous flow microwave reactors is a synthetic platform approach. The reactants in these reactors are fed through a flow cell that is positioned inside the microwave cavity to produce energy [78]. Compared to conventional heating methods, MW may hasten and complete the chemical reaction quickly, produce a high-purity product with less energy input, and provide a greener, more pleasant, secure, and cleaner environment for the chemical process. The MW intensification technique relies on high localized heating caused by MW radiation's interaction with polar molecules without causing the molecules' structure to change [81].

6.2. Ultrasonic Assisted

Besides the catalyst development, the mixing system also plays an important factor in heterogeneous catalyst systems. The non-homogeneity can be observed at high catalyst loading. Ultrasonic-assisted systems have been employed to intensify mixing to enhance the productivity of the immiscibility reactant system [90]. Alkali-catalyzed transesterification is used commercially to make biodiesel, typically in mechanically agitated reactors. The transesterification reaction can be accelerated by a variety of techniques, including microwave, infrared, and ultrasonic irradiation [91]. Additionally, a focusing collector can be used to increase the amount of energy that is provided by solar radiation. A form of intensification that produces a considerably quicker heating process is the parabolic trough collector [66]. The two basic methods for producing cavitation are hydrodynamic cavitation (by varying the flow restrictions like orifice and venturi) and acoustic cavitation (bypassing the US at a frequency >16 kHz). Two immiscible phases can be emulsified with the use of acoustic cavitation, which increases production and quickly creates vast surface areas for the reaction. Additionally, a

cavitation reactor aids in improving esterification by accelerating phase mixing and removing mass transfer resistances [92].

The use of energy that amplifies mass and heat transfer in reactions is thought to make ultrasound a more effective alternative reaction system to improve biodiesel synthesis. At a response time of 60 minutes, the ultrasonic technique yields more biodiesel than the infrared technique [93]. Sonication is the state-of-the-art method used to speed up reactions by increasing the contact between the reactants on a compact scale. Sonication uses a low ultrasonic frequency irradiator to induce cavitation bubbles in the reaction mixture. The cavitation bubble that is created has extremely high interior pressures and temperatures, which aids in accelerating the reaction. This method significantly reduces the conversion time and encourages the synthesis of biodiesel in large quantities [94]. The ultrasound-assisted technique produces microscopic bubbles within the solvent through repeated cycles of expansion and compression. These bubbles gradually enlarge, storing energy until they ultimately implode a process referred to as acoustic cavitation [8].

6.3. Radiation Infrared

Infrared methods are more effective at producing biodiesel because of their enhanced rate of mass transfer between the immiscible reactants, enhanced chemical reactions, and reduced reaction time and energy consumption [93]. Infrared energy within the range of 0.001–1.7 eV is capable of penetrating the reactant mass to greater depths than electromagnetic radiation and is absorbed more intensely than microwaves [93]. The infrared radiation technique resulted in lower time and energy consumption compared to the conventional method used for biodiesel production [95], [96].

Many researchers have extensively employed infrared radiation in the production of biodiesel from various types of feedstock, such as goat tallow [96], *Sterculia foetida* oil [93], *Reutealis trisperma* [95], waste mustard oil [97], rice bran oil [98], oiled mustard and sunflower [99] and *Ceiba pentandra* [100]. In approximately 0.5 hours, a high yield of biodiesel (97.13% FAME content) was produced from WMO using energy-efficient far-infrared radiation (FIR) [93]. Kusumo, et al.

[93] found that, at the same reaction time (60 minutes), the ultrasonic technique produced a higher biodiesel yield (99.41%) compared to the infrared technique (98.55%). Unfortunately, only a limited number of researchers have utilised infrared radiation in the production of biodiesel from WCO employing WCO-based catalysts.

7. Conclusion and Recommendations

This study provides a comprehensive overview of global research developments in biodiesel production from waste cooking oil (WCO) using heterogeneous catalysts, employing both bibliometric analysis and literature review. The findings indicate that heterogeneous catalysts such as CaO, biochar, and metal or biomass-based materials play a crucial role in enhancing the efficiency and sustainability of the transesterification process. Furthermore, the bibliometric approach has successfully identified the most productive countries, institutions, and authors, as well as key research themes over the past two decades. The results indicate that publication trends experienced a substantial increase between 2014 and 2021, followed by a decline after 2022, which may be attributed to research saturation or changes in funding priorities. From the bibliometric analysis, it can be concluded that India and Malaysia are the countries that have made the most substantial contributions to research in this field. The study confirms that, the most prolific researcher in this field was Tabatabaei et al., with 14 publications, followed by Bae et al., who produced 12 publications. Moreover, it was found that the use of Sargassum and river snail shell catalysts at a 3% concentration in biodiesel production yielded a biodiesel efficiency exceeding 99.21%. Nevertheless, future research opportunities remain extensive, particularly in the development of environmentally friendly catalysts, the improvement of biodiesel oxidation stability, and the integration of biodiesel production technologies with other renewable energy sources such as bioethanol and biogas. In conclusion, this study not only contributes to the mapping of WCO biodiesel research but also offers strategic direction for advancing sustainable, waste-based energy solutions, thereby supporting global efforts to reduce dependence on fossil fuels.

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Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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