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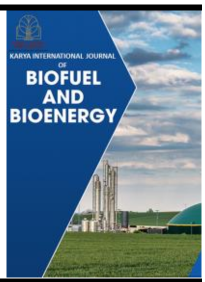

Recent Advances in Sustainable Biodiesel Production from Meliaceae Plants

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ABSTRACT

This review explores the potential of *Meliaceae* plants as a sustainable feedstock for biodiesel production. The study systematically analyzes research from 2010 to 2025, focusing on advancements in biodiesel production technologies and the environmental benefits of utilizing *Meliaceae* oils. The article also highlights the use of innovative catalysts, such as mixed-phase $BaTiO_3/Ba_2TiO_4$ nanoparticles and magnetic spinel catalysts, and advanced techniques like membrane reactors and two-stage transesterification to optimize biodiesel yield and quality. Several *Meliaceae* species, including neem, *Aglaia korthalsii, Swietenia macrophylla*, and *Toona ciliata*, have shown promise as biodiesel feedstocks. The environmental and sustainability aspects of plant-based biodiesel are emphasized, with a focus on reduced greenhouse gas emissions, resource efficiency, and minimized competition with food crops. A bibliometric analysis using VOSviewer and Scopus reveals collaboration patterns and trends in Meliaceae-based biodiesel research. The review concludes by highlighting future research directions and addressing current limitations, providing valuable insights for advancing sustainable biofuel production from Meliaceae plants.

1. Introduction

The increasing demand for sustainable energy solutions has placed biofuel at the forefront of renewable energy research [1,2]. Biodiesel, a biodegradable and environmentally friendly alternative to conventional fossil fuels, is produced through the transesterification of oils or fats with alcohol [3]. It offers significant environmental benefits, such as reduced greenhouse gas emissions, lower particulate matter, and improved biodegradability [4,5]. However, challenges such as feedstock availability, production costs, and competition with food resources necessitate the exploration of alternative, sustainable feedstocks [6].

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The Meliaceae family, comprising 575 species and 51 genera, thrives in tropical and subtropical regions globally and represents a potential source of non-edible oils for biodiesel production [7]. This family includes several species known for their medicinal [8-10], industrial [11], and ecological significance, such as Azadirachta indica (Neem), Swietenia macrophylla (Mahogany), and Toona ciliata [12]. The utilization of oils from Meliaceae plants aligns with the principles of green chemistry, as it minimizes reliance on edible crops and promotes the use of renewable and underutilized resources [13].

Recent advancements in biodiesel production technologies have highlighted the potential of Meliaceae plants as viable feedstocks. Innovative catalysts, such as Mixed-phase Barium Titanium Oxide ($BaTiO_3$/$Ba2TiO_4$) nanoparticles [14], magnetic spinel catalysts [15], and waste-derived materials, have enhanced conversion efficiencies and reduced environmental impacts [16]. Additionally, the development of advanced techniques, including membrane reactors [17] and two-stage transesterification [18], has addressed challenges associated with high free fatty acid content and scalability. These advancements underscore the need for a systematic review to consolidate existing knowledge and identify research gaps.

This review aims to provide a comprehensive overview of recent advancements in biodiesel production from Meliaceae plants. By systematically analyzing studies published over the last decade, this work seeks to:

a) Explore the potential of various Meliaceae species as biodiesel feedstocks.
b) Assess the environmental and sustainability aspects of biodiesel production from Meliaceae plants.
c) Conduct a bibliometric analysis to identify trends, collaborations, and influential contributions to the field.

By integrating systematic and bibliometric methodologies, this review intends to advance the understanding of sustainable biodiesel production from Meliaceae plants and provide insights for future research and practical applications.

2. Methodology

The current research was performed systematically, adhering to certain guidelines put forth by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement; the protocol used by previous studies [19,20].

2.1 Data and Literature Sources

The search strategy used a combination of electronic databases, including Science Direct, Scopus, and Google Scholar, to find relevant scholarly literature from academic journals, conference proceedings, and grey literature sources, such as technical reports, dissertations, and preprints.

The search strings used were ("plant oils" OR "seed oils" OR "essential oils") AND ("biodiesel" OR "biofuel") AND ("Meliaceae" OR "Mahogany") for Google Scholar and Science Direct, and ("biofuel" OR "Oil") AND ("Meliaceae" OR "Mahogany") for Scopus.

The retrieved articles were then assessed using Rayyan, a collaborative research platform specifically designed for systematic and literature reviews. Rayyan facilitated deduplication, the inclusion and exclusion of search results. This strategy aimed to capture studies published from 2010 to 2025 that focused on recent advances in sustainable biodiesel production from Meliaceae plant family.

The bibliometric analysis was conducted using VOSviewer in conjunction with the Scopus database. VOSviewer, a powerful tool for bibliometric analysis, allows researchers to visualize and explore connections within scientific literature. Its integration with Scopus, a vast database encompassing numerous disciplines and regions, provides researchers with access to a wealth of knowledge.

2.2 Study Selection

Articles were initially screened by title and abstract and classified as "included" or "excluded" based on four inclusion criteria as adopted by a study [19]. These are publication date, research focus, data reporting and language.

2.3 Overview of the Data Collection

The initial literature search yielded 1,423 articles, which was then reduced to 1,349 after removing duplicates. A preliminary screening for eligibility further narrowed down the pool to 257 articles. Ultimately, only 10 articles met the inclusion criteria and were included in the study (Figure 1).

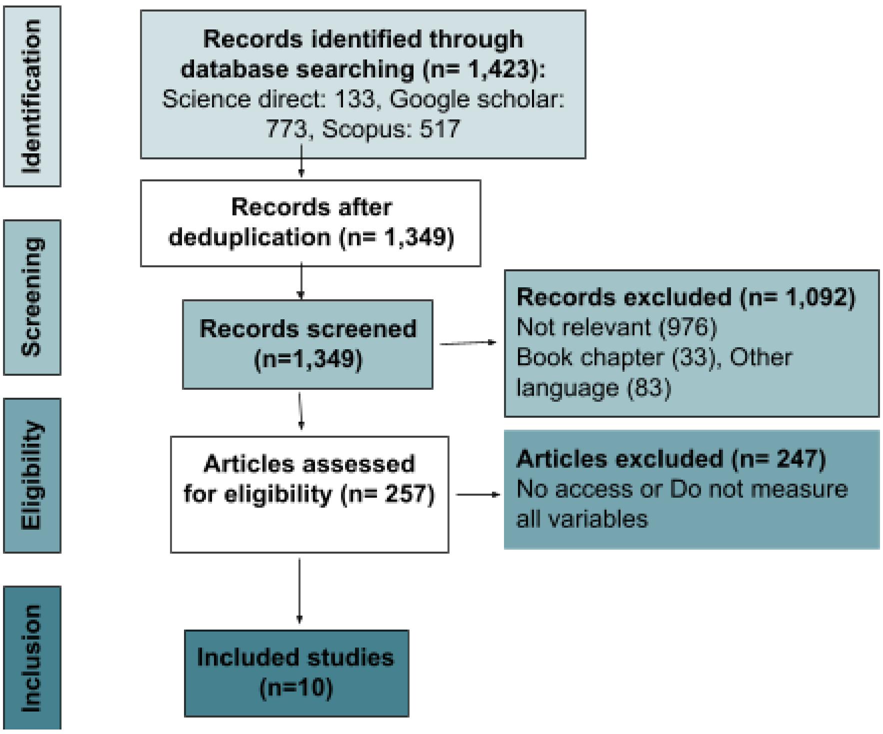

Fig. 1. PRISMA Diagram

Table 1 provides a summary of all the reviewed studies, including the country where the study was conducted, the objective of the study, the research method used and conclusion among others.

Table 1
Summary of reviewed articles

Entries	References	Country	Plant	Objective	Research Method	Contribution	Limitations	Conclusion
1	[21]	Malaysia	*Aglaia Korthalsii*	To study the potential of *Aglaia korthalsii* seed oil as a feedstock for biodiesel production using waste marine barnacle as a solid catalyst.	Transesterification using a solid base catalyst (barnacle, a source of CaO)	Demonstrated the successful conversion of *A. korthalsii* oil into biodiesel with high conversion using a waste material as a catalyst, which can be reused.	The study was limited to laboratory-scale experiments and did not include engine testing or a full life cycle assessment.	*A. korthalsii* seed oil and waste marine barnacles are promising resources for sustainable biodiesel production.
2	[22]	Philippines	*Swietenia macrophylla*	To determine the potential of *Swietenia macrophylla* (mahogany) seeds for bio-oil and biodiesel production	Extraction of oil from mahogany seeds, followed by transesterification using potassium hydroxide and methanol.	Showed that mahogany seeds can yield a high amount of bio-oil, which can be converted into biodiesel with high heating value.	The study was limited to laboratory-scale experiments and did not include engine testing or a full life cycle assessment.	Mahogany seeds are a potential source of high-energy biodiesel.
3	[23]	India	*Swietenia mahagoni*	To investigate the potential of *Swietenia mahagoni* seed oil as a feedstock for biodiesel production.	Acid-catalyzed esterification followed by base-catalyzed transesterification.	Acid-catalyzed esterification followed by base-catalyzed transesterification	The study was limited to laboratory-scale experiments and did not include engine testing or a full life cycle assessment.	*S. mahagoni* seed oil is a promising new source for biodiesel production.
4	[24]	Brazil	*Terminalia catappa L. and Carapa guianensis*	To evaluate the potential of *Terminalia catappa* L. (TC) and *Carapa guianensis* (CG) oils for biofuel production.	Transesterification and thermal cracking.	The biodiesel and bio-oil produced from TC and CG oils had acceptable physical-chemical properties for use in diesel engines	The bio-oils were not completely deoxygenated, which may affect their long-term stability	TC and CG oils are potential sources for biodiesel and bio-oil production
5	[25]	India	*Neem*	To review the potential of neem oil as a feedstock for biodiesel production in India.	Review of existing literature and research on neem oil and biodiesel production.	Neem oil is a potential feedstock for biodiesel production in India, and its use can help	The high free fatty acid content of neem oil can pose challenges for biodiesel	Neem oil is a promising alternative feedstock for biodiesel production

						to diversify the country's energy sources	production.	in India, but further research is needed to optimize the production process.
6	[26]	China and Nigeria	*Neem*	To examine the impact of neem biodiesel (NB) blends with pure diesel on the physical and chemical properties of particulate matter (PM) from diesel engines	Combustion of NB blends in a diesel engine and analysis of the emitted PM using physical and chemical techniques.	NB blends, particularly B20, can significantly reduce PM emissions from diesel engines and improve PM properties	The study was limited to a single-cylinder diesel engine and did not include a full life cycle assessment.	NB has the potential to be an alternative fuel for diesel engines, but NOx mitigation strategies are needed.
7	[27]	Iran	*Neem*	To optimize the catalytic performance of bimetallic spinel magnetic catalysts in the esterification/transesterification reaction of neem synthetic oil for biodiesel production.	Esterification/trancesterification of neem oil using bimetallic spinel magnetic catalysts, optimized using response surface methodology (RSM)	The catalyst showed the highest catalytic activity and reusability, achieving a biodiesel production of 99.29% under optimal conditions.	The study was limited to laboratory-scale experiments and did not include engine testing or a full life cycle assessment.	Bimetallic spinel magnetic catalysts, are promising for biodiesel production from neem oil.
8	[28]	Pakistan and Saudi Arabia	*Toona ciliata*	To synthesize biodiesel from *Toona ciliata* seed oil using a membrane reactor and barium oxide nano catalyst.	Transesterification of *T. ciliata* seed oil using a membrane reactor and barium oxide nano catalyst	Achieved a high biodiesel yield (94%) using a membrane reactor and a green synthesized barium oxide nano catalyst. The produced biodiesel met international standards.	The study was limited to laboratory-scale experiments and did not include engine testing or a full life cycle assessment.	Membrane technology and barium oxide nano catalyst are promising for sustainable biodiesel production from *T. ciliata* seed oil.
9	[29]	India	*Amari (Amoora Wallichii King)*	To investigate biodiesel production from Amari (*Amoora Wallichii* King) tree seed oil (ATSO).	Two-stage acid-base transesterification	Achieved a high biodiesel yield (88.5%) from ATSO using a two-stage process. The biodiesel properties were similar to other Amoora and Pithraj	The water and sulphur contents of the biodiesel slightly deviated from the standards.	Amari tree seed oil is a potential feedstock for biodiesel production

						tree seed biodiesels and met most ASTM and EN standards.		
10	[30]	Nigeria	*Neem and Camelina sativa*	To study the emission characteristics and performance of neem seed and *Camelina sativa* based biodiesel in a diesel engine.	Engine testing of diesel blends with neem and Camelina sativa oil methyl esters.	The biodiesel blends reduced CO, HC, and CO_2 emissions compared to diesel fuel, but NOx emissions were higher	The study was limited to a 1.9 Multijet diesel engine and did not include a full life cycle assessment.	Camelina sativa-based biodiesel (CB10) showed the best overall performance and emission characteristics and can be used as a diesel fuel replacement

3. Results and Discussion

3.1 Overview of Potential Meliaceae Species Studied for Biofuel Production

3.1.1 Aglaia korthalsii

Aglaia korthalsii is a lesser-known plant species native to Malaysia, with its seeds being investigated as a novel feedstock for biodiesel production. As reported by previous study [21], the seeds of this plant, collected from Kelantan, Malaysia, were found to have an oil content of 16.2 ± 0.18 wt.%. This oil content was determined using the Soxhlet extraction method with n-hexane as the solvent.

The fatty acid profile of the A. korthalsii seed oil was analyzed and found to be dominated by unsaturated fatty acids, with oleic acid being the most abundant, followed by palmitic acid. The high proportion of unsaturated fatty acids is beneficial for biodiesel properties, particularly cold flow properties, as it lowers the cloud and pour points.

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3.1.2 Swietenia macrophylla

Swietenia macrophylla, characterized by its impressive size, it can reach heights of 30 - 40 meters and boasts a broad, spreading crown. The tree produces clusters of small, fragrant flowers that display a greenish-white color [31,32]. Its seeds are rich in oil that can be converted into bio-oil and biodiesel. The resulting biodiesel derived from this plant oil exhibits fuel properties comparable to traditional diesel, including suitable viscosity and flash point, alkanes, esters, aromatics, hydroxyl, and carbonyl; compounds that are similar to the other biodiesel profile [22].

A previous study [22] investigated the potential of Swietenia macrophylla (Figure 2) seeds as a biodiesel source. The researchers extracted oil from the seeds and used a transesterification process with potassium hydroxide and methanol to produce biodiesel. Response surface methodology was employed to optimize biodiesel production by considering factors like reaction time, catalyst loading, and methanol amount.

Fig. 2. Swietenia macrophylla

The seeds had a moisture content of 10.6% and yielded 48.44% bio-oil with a density of 0.86 g/cm³ and a pH of 6.25. The final biodiesel yield was 36.10% of the extracted oil. FTIR analysis showed the presence of alkanes, esters, aromatics, hydroxyl, and carbonyl groups in the biodiesel. The biodiesel's high heating value was 39.87 MJ/kg, similar to commercial heavy fuel.

3.1.3 Swietenia mahagoni

The potential of Swietenia mahagoni (mahogany) seed oil as a sustainable feedstock for biodiesel production was explored in a study [23]. The S. mahagoni seeds were found to have a substantial oil yield of 58.1%, with a fatty acid profile suitable for biodiesel conversion, containing major components like linoleic, oleic, stearic, linolenic, and palmitic acids. Due to the slightly high free fatty acid (FFA) content (1.39%) in the oil, a two-step process was employed. Initially, acid-catalyzed esterification was used to reduce FFA content, followed by base-catalyzed transesterification to convert the oil to biodiesel. The resulting biodiesel met both ASTM and EN specifications, with its physico-chemical properties, including iodine value, oxidative stability, viscosity, density, cloud point, pour point, and flash point, all within acceptable ranges. The researchers concluded that S. mahagoni seed oil could serve as a potential feedstock for biodiesel production. The oil's high yield, favorable fatty acid composition, and the biodiesel's compliance with international standards support its viability as a sustainable and renewable energy source.

3.1.4 Terminalia catappa L. and Carapa guianensis

Terminalia catappa L. (almond tree) and Carapa guianensis (crabwood) have been studied for biofuel production as Iha *et al.,* [24] explored the potential of Terminalia catappa L. (TC) and Carapa guianensis (CG) as biofuel feedstocks due to their abundance in Brazil and potential to provide a non-food, non-deforestation oil source. They found that the oil content of TC kernels was 50%, higher than many commercial oil sources, while the oil content of CG seeds was not determined but estimated to be up to 45% based on previous literature. Fatty acid analysis showed that both oils had a similar saturated content (around 30%). However, CG oil was mainly monounsaturated, while TC oil had an almost equal mix of mono- and di-unsaturated chains. Due to the high acid content of the oils, biodiesel was produced using a two-step process. The resulting biodiesel had physical and chemical properties suitable for diesel engines. Bio-oil was also produced via thermal cracking, and its physical and chemical properties were analyzed. The bio-oils showed potential as renewable fuels for diesel engines with further processing, including complete deoxygenation.

The study concluded that both TC and CG oils could be used to produce biodiesel and bio-oil, offering promise as alternative, sustainable biofuel sources. Future studies should focus on complete deoxygenation of the bio-oil and further improvement of biofuel properties.

3.1.5 Neem (Azadirachta indica)

A widely known medicinal plant, neem has garnered attention for its oil's suitability in biodiesel production. Extensive research has demonstrated neem oil's potential to reduce emissions while achieving high biodiesel yields. Its abundant availability in countries like India, Nigeria, and China positions it as a significant contributor to sustainable biofuel initiatives.

A study [25] conducted a review on Neem oil, derived from neem seeds, and they concluded that the feedstock is a promising option due to its abundance and the versatility which thrives in diverse environments and has various uses. Neem oil extraction is typically done through cold pressing to maintain oil quality.

A study [30] explored the use of Neem seed and Camelina Sativa oils as potential sources of biodiesel, assessing the emissions and engine performance of the derived biodiesel and its blends with conventional diesel fuel. The biodiesel, NOME (Neem oil methyl ester) and COME (Camelina Sativa oil methyl ester), were produced via transesterification and blended with conventional diesel at 5% and 10% concentrations (NB5, NB10, CB5, CB10). A 1.9 Multijet diesel engine was used to test the performance and emissions of the various fuel blends at different speeds and loads. The emissions measured included hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), and nitrogen oxides (NO_x).

The results indicated that the biodiesel blends had a slightly higher brake specific fuel consumption (BSFC) and slightly lower brake power (BP) than conventional diesel fuel. However, the biodiesel blends significantly reduced CO, HC, and CO_2 emissions, while NOx emissions were slightly higher compared to conventional diesel. Hence Camelina Sativa biodiesel (CB10) demonstrated the best performance, with lower emissions and comparable engine performance to diesel fuel. The study concludes that both Neem and Camelina Sativa-based biodiesels show promise as sustainable and environmentally friendly alternatives to conventional diesel, with Camelina Sativa biodiesel being particularly promising.

This study [26] investigated the potential of neem oil biodiesel (NB) as an alternative fuel for diesel engines by examining its effects on particulate matter (PM) emissions. Researchers tested pure diesel and NB blends (B5, B10, B15, B20) in a single-cylinder, 4-stroke diesel engine. PM was captured directly from the engine at two standard engine speeds and analyzed using physical microscopy and chemical analyses.

Results showed that compared to pure diesel, the B20 blend significantly reduced CO emissions and PM size and opacity at both low and high engine speeds. The carbon content and total carbon concentration of PM were also lower for B20 than for pure diesel. However, NO_x emissions increased with the use of NB blends. The study concludes that neem oil biodiesel, particularly the B20 blend, shows promise as an alternative fuel for diesel engines due to its positive impact on PM emissions.

This study conducted by previous researcher [27] that explored the potential of using bimetallic spinel magnetic catalysts ($CoZnFe_2O_4$, $NiZnFe_2O_4$, and $CuZnFe_2O_4$) to produce biodiesel from neem oil through esterification/transesterification reactions. The study concludes that bimetallic spinel magnetic catalysts, particularly $CoZnFe_2O_4$, are efficient and recyclable catalysts for biodiesel production from neem oil. The use of neem oil and magnetic catalysts provides a sustainable and environmentally friendly approach to biodiesel production.

3.1.6 Toona ciliata

Toona ciliata, or red cedar, is a tree species native to South Asia. The research by previous study [28] explores the use of membrane technology and green synthesized barium oxide nanoparticles to produce biodiesel from Toona ciliata seed oil.

The oil was extracted using a Soxhlet apparatus, and barium oxide nanoparticles were synthesized using Toona ciliata leaf extract. This process eliminates the need for hazardous chemicals and leverages plant-based reducing agents, thereby minimizing environmental impact as supported by a study [33]. Biodiesel was produced via a single-step transesterification reaction in a membrane reactor, and the synthesized barium oxide nanoparticles were used as a catalyst.

The optimal conditions for biodiesel production (90°C, 150 minutes, a 9:1 methanol-to-oil molar ratio, and a 0.39 wt% catalyst amount) resulted in a biodiesel yield of 94%. The barium oxide nanocatalyst could be reused multiple times.

The study concludes that membrane technology offers a feasible and efficient method for biodiesel production from Toona ciliata seed oil, using green synthesized barium oxide nanoparticles as a catalyst. The produced biodiesel is of high quality and meets international standards.

3.1.7 Amari (Amoora Wallichii King)

Amari tree is recognized for its oil-rich seeds. Research into this plant has revealed its capacity to produce biodiesel with properties similar to other high-performing biofuels. A previous study [29] explored the potential of Amari tree seed oil (ATSO) for biodiesel production. The study was motivated by the need for sustainable energy sources, and ATSO was chosen due to its abundance and non-edible nature. The researchers extracted oil from Amari seeds and characterized its fatty acid composition. The high free fatty acid content necessitated a two-stage acid-base transesterification process, which is well-established for biodiesel production from high free fatty acid (FFA) feedstocks [34,35]. Experiments were conducted to optimize reaction parameters, and the produced biodiesel's properties were analyzed and compared to international standards. Findings included a 42.85% oil content in Amari seeds, a fatty acid profile predominantly linoleic and oleic acids, and a maximum yield of 96% and 88.5% in the acid and base transesterification stages, respectively. The biodiesel properties mostly complied with international standards. The study concluded that Amari tree seed oil is a viable feedstock for biodiesel production in India.

These plants present significant promise as biodiesel feedstocks, each contributing unique advantages to sustainable energy development. While further research is necessary to address scalability and environmental considerations, they highlight the potential for integrating plant-based biodiesel into global energy strategies.

3.2 Catalysis and Biofuel Production

Catalysis plays a pivotal role in advancing sustainable biodiesel production from Meliaceae plants by improving reaction efficiency, enhancing biodiesel yield, and reducing waste [36]. Recent studies underscore the utilization of innovative catalysts and techniques for the transesterification of various Meliaceae plant oils. For instance, Aglaia korthalsii seed oil has been successfully converted to biodiesel using waste marine barnacle-derived calcium oxide (CaO) as a solid base catalyst, demonstrating high conversion rates and catalyst reusability [16]. Similarly, Swietenia mahagoni seed oil underwent acid-catalyzed esterification followed by base-catalyzed transesterification to produce biodiesel meeting ASTM and EN standards [18]. These studies highlight the potential of underutilized Meliaceae plant oils as biodiesel feedstocks.

Neem (Azadirachta indica), a prominent Meliaceae plant, has garnered significant attention due to its high oil content and renewable availability. Studies in India reviewed the potential of neem oil for biodiesel production, emphasizing its role in diversifying energy resources, despite challenges posed by high free fatty acid content [20]. Advanced catalytic systems, such as bimetallic spinel magnetic catalysts, have optimized neem oil transesterification, achieving a biodiesel yield of 99.29% under optimal conditions [22]. Additionally, neem biodiesel blends, particularly B20, have demonstrated reduced particulate matter emissions in diesel engines, though strategies for mitigating NO_x emissions are needed [21].

The integration of nanotechnology further enhances catalytic efficiency in biodiesel production [37]. For example, Toona ciliata seed oil was converted into high-quality biodiesel with a 94% yield using a membrane reactor coupled with green-synthesized barium oxide nanocatalysts [23]. This approach aligns with green chemistry principles and demonstrates the feasibility of membrane technology in biodiesel production [17,38,39]. These advancements emphasize the critical role of innovative catalytic methods and Meliaceae plant oils in sustainable biofuel production, laying a foundation for further research into scaling up these processes while addressing associated challenges such as lifecycle assessments and engine testing.

3.3 Environmental and Sustainability Aspects of Plant-Based Biodiesel

The production of biodiesel from plant-based feedstocks offers a sustainable alternative to fossil fuels [40], which is known for damaging the environment. Environmental pollution causes some health problems [41]. Production and utilization of biofuel aligns with global efforts to reduce greenhouse gas (GHG) emissions and mitigate climate change [42,43]. Biodiesel derived from renewable resources, such as neem and Toona ciliata, exhibits a lower carbon footprint due to the carbon-neutral cycle of plant growth and combustion [44]. Using waste materials, such as marine barnacles in Aglaia korthalsii biodiesel production, and underutilized plants like Camelina sativa, supports resource efficiency and waste reduction [45-47]. Additionally, the cultivation of and utilization of non-edible plants in biofuel production ensures minimal competition with food crops, promoting sustainable land use and biodiversity [48,49].

By leveraging locally available feedstocks, plant-based biodiesel enhances energy independence while providing socioeconomic benefits through job creation in rural areas. However, challenges like scalability and lifecycle impacts must be addressed to maximize environmental benefits and align with sustainable development goals.

3.4 Bibliometric Analysis

A comprehensive bibliometric analysis was conducted to explore the global landscape of research on the sustainable production of biodiesel from Meliaceae plants. For this purpose, VOSviewer software was employed to visualize and analyze the collaborative networks, trends, and geospatial distribution of related publications [50,51].

This bibliometric network visualization, generated using VOSviewer, illustrates the international collaboration patterns between countries in a specific research domain. The size of the nodes represents the volume of research output from each country, while the connecting lines and their thickness indicate the extent of collaborative linkages. Distinct colors denote clusters of closely linked countries, reflecting regional or thematic research networks.

The visualization shows the United States as the central hub with the largest node, signifying its leading role in research output and extensive international collaborations, especially with countries such as the United Kingdom, India, Brazil, and Nigeria (Figure 3). This is consistent with findings from bibliometric studies highlighting the dominance of developed nations, particularly the United States, in driving global research and fostering international partnerships [52,53].

India and Brazil are also prominent in the network, forming significant clusters. India's collaboration with countries like Malaysia and Japan indicates its active engagement in regional partnerships. Similarly, Brazil’s strong ties to Mexico and other Latin American countries underline regional cooperation. Research suggests that emerging economies often focus on collaborative networks within their regions, driven by shared interests and geographical proximity [54].

European countries, including France, Germany, and Italy, are tightly clustered, reflecting the strong intra-regional collaboration fostered by frameworks like the European Union's Horizon programs [55,56]. These nations also have notable connections with African countries such as Nigeria and Cameroon, highlighting the increasing focus on transcontinental research initiatives addressing global challenges.

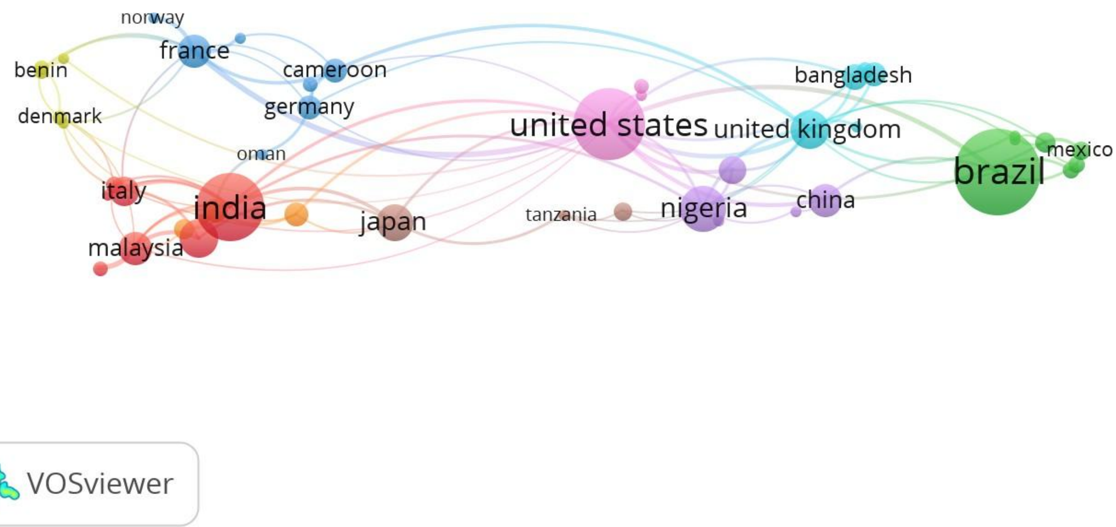

Fig. 3. Countries research linkage

Smaller nodes representing countries like Denmark, Oman, and Tanzania indicate lower research output and less collaboration intensity, aligning with studies showing disparities in research capacity and funding between developed and developing nations [57]. Hence, this bibliometric map emphasizes the critical role of international collaboration in advancing research, particularly among developed nations and emerging economies. Efforts to support equitable partnerships and capacity-building in less represented regions are essential to foster inclusive scientific progress.

These findings suggest that research on Meliaceae-based biodiesel production is not only concentrated in specific regions but also spans across diverse geographical locations (Figure 4). The application of VOSviewer allows for a clearer understanding of the interconnectedness and collaborative efforts among these countries, providing valuable insights into the global efforts toward advancing sustainable biodiesel production technologies.

Fig. 4. Global representation of commitment

3.4.1 Co-Authorship network

The bibliometric analysis of the co-authorship network in the context of biodiesel production from Meliaceae plants reveals two distinct clusters, represented by red and green, which reflect groups of authors primarily collaborating within their own networks (Figure 5). One cluster likely focuses on the chemical and biochemical processes involved in biodiesel production, such as transesterification and catalysis, while the other emphasizes the development of plant-based feedstocks and sustainability aspects. Central figures, such as "Yamada, Takeshi" and "Tanaka, Reiko," have made significant contributions either to exploring Meliaceae plants, such as Azadirachta indica and Mahogany species, as biodiesel feedstock, or to advancing sustainable production methods. Their high connectivity suggests their work is pivotal in driving collaborations and serves as essential references for the review. The dense intra-cluster connections indicate well-coordinated efforts within research teams, with the green cluster potentially specializing in sustainability topics like lifecycle assessment and environmental impact, while the red cluster may focus on improving biodiesel production efficiency and technology. This aligns with bibliometric studies highlighting the value of tightly knit collaborative networks in producing impactful and specialized research outcomes [58,59].

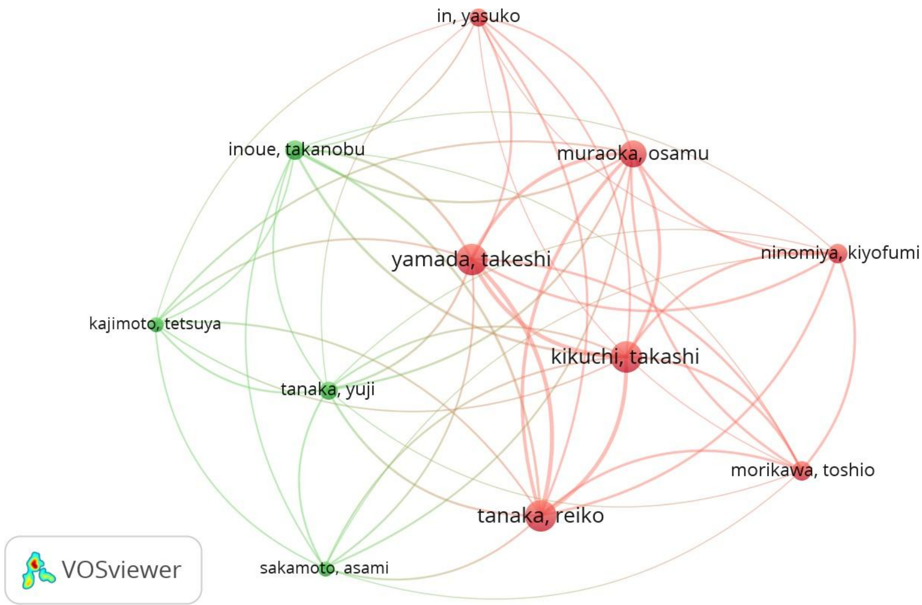

Fig. 5. Co-authorship collaboration

The limited inter-cluster links highlight opportunities for greater integration of expertise from different subdomains, such as combining sustainability analysis with advanced processing techniques. Bridging the gaps between plant-based resource development and biodiesel

processing innovation could enrich Meliaceae-based biodiesel research, with the network suggesting potential for enhancing knowledge exchange through collaboration among less central authors, particularly in underexplored areas like lifecycle optimization and scaling up production. Identifying key authors and research groups specializing in green chemistry, renewable energy, and plant resource management offers valuable insights for advancing sustainable biodiesel production from Meliaceae plants [60].

3.5 Biodiesel from Meliaceae Plants: Future Outlook

To further enhance the economic viability and scalability of biodiesel sources from Meliaceae plants, future research should prioritize scaling up production processes from laboratory to industrial levels which is inline with [61]. This will allow for the evaluation of economic feasibility and optimization of operating conditions for commercial biodiesel production [62]. Additionally, comprehensive engine testing under various load conditions should be conducted to understand the long-term performance and emission characteristics of the biodiesel; like the one conducted by previous study [63].

To ensure sustainability, a detailed Life Cycle Assessment (LCA) should be conducted to quantify the environmental impacts of biodiesel production as conducted on mixed vegetable and cooking oil [64-67]. Research should also continue on novel catalysts, particularly green and reusable options, to enhance reaction efficiency and minimize production costs. Furthermore, genetic engineering and selective breeding could be employed to improve the oil yield and quality of Meliaceae species, making them more competitive as biodiesel feedstocks.

Integrating biodiesel production with the principles of circular economy by leveraging waste materials as catalysts or co-products can also reduce waste and improve sustainability. Finally, investigating the performance of biodiesel blends with other biofuels or conventional fuels can provide insights into their practical applications and mitigate challenges such as cold flow properties and NOx emissions.

3.6 Drawbacks of Meliaceae Biodiesel

Despite the promising advancements, several limitations hinder the widespread adoption of biodiesel from Meliaceae plants. The seasonal nature and geographic limitations of these plants may restrict consistent biodiesel production, necessitating strategies for feedstock storage and alternative plant sources as some research focuses on drought resistant plants for biodiesel production [68]. Additionally, high Free Fatty Acid content in some Meliaceae oils poses challenges for biodiesel production, requiring additional pretreatment steps. Incomplete deoxygenation of some bio-oils may impact long-term storage and stability. That is why previous studies [69,70] focused on finding a solution to likely limitation. Furthermore, the studies reviewed have relied on small-scale engines, which do not represent the performance of biodiesel in commercial engines under diverse conditions. The use of certain catalysts may raise environmental concerns [71], and few studies have conducted a comprehensive LCA to assess the net environmental benefits of biodiesel production from these plants. On the other hand, heterogeneous solid catalysts are less active for biodiesel production due to deactivation effects, lower reactivity under moderate conditions, and issues with porosity, surface area, and material stability [72].

3.7 Summary and Conclusion

This review paper explores the potential of Meliaceae plants as a sustainable feedstock for biodiesel production. By examining various Meliaceae species and their oil yields, fatty acid profiles, and biodiesel conversion processes, the study highlights the promising future of these non-edible oil sources in meeting the growing demand for renewable energy. The utilization of innovative catalysts and advanced techniques, coupled with the environmental and sustainability benefits of plant-based biodiesel, further strengthens the argument for Meliaceae-based biofuels. Additionally, a bibliometric analysis reveals trends and collaborations in this research area, providing valuable insights for future studies.

The exploration of Meliaceae plants as biodiesel feedstocks offers a sustainable and environmentally friendly alternative to fossil fuels. Advancements in catalyst technology and biodiesel production processes have shown promising results in converting Meliaceae oils into high-quality biodiesel that meets international standards. The abundance of these non-edible oil sources, coupled with their lower carbon footprint and reduced competition with food crops, makes them a compelling option for sustainable biofuel production. However, further research is needed to address challenges related to scalability, feedstock availability, and engine performance to fully realize the potential of Meliaceae-based biodiesel as a mainstream renewable energy solution.

Declaration of Competing Interest

The authors affirm that they have no potential conflicts of interest, whether financial or personal, that could be interpreted as influencing the work presented in this paper.

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