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Essential Oils and Their Fractions as Biodiesel Additives: A Review on Quality and Performance Enhancement

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ABSTRACT

Rising global and national energy demands have intensified the pursuit of renewable alternative fuels, with biodiesel emerging as a strategic replacement for fossil-derived diesel. This review critically evaluates the role of essential oil additives in enhancing biodiesel quality and engine performance, with emphasis on their chemical mechanisms of action and practical applicability. The discussion encompasses recent studies on clove, citronella, camphor, and turpentine oils, together with their active fractions: eugenol, limonene, rhodinol, and α-pinene. In Indonesia, biodiesel consumption increased from 9.5 million kiloliters in 2022 to 12.2 million kiloliters in 2023, supported by government policy raising the blending ratio from B20 to B35 in February 2023. The anticipated introduction of B40 by December 2024 is projected to elevate consumption to approximately 15.6 million kiloliters. Reported findings indicate that clove oil can reduce acoustic emissions and carbon residue, citronella oil decreases specific fuel consumption and exhaust gas temperature, and rhodinol lowers particulate matter and moisture content. Alpha-pinene enhances combustion rate and reduces flash point, camphor improves brake thermal efficiency, and limonene shortens ignition delay while increasing cetane number. The incorporation of these essential oil-derived bio-additives into biodiesel blends presents a promising chemical strategy to lessen dependence on fossil fuels and improve energy efficiency. Further research and scalable implementation are essential to support both national energy security and long-term environmental sustainability.

1. INTRODUCTION

Economic expansion and population growth are among the principal drivers of the escalating global demand for energy. With rapid industrial development and accelerating urbanization, global energy consumption is projected to increase by approximately 28% by 2040. This trend exacerbates the risk of an energy crisis, arising from the continual depletion of finite fossil fuel reserves. Consequently, the exploration and development of alternative energy sources have become imperative to address the growing demand for fuels in the face of constrained crude oil supplies.

One promising approach to addressing future energy demands is the utilization of renewable energy sources such as wind, geothermal, hydro, and solar power. Nevertheless, these resources possess inherent limitations, as they are generally unable to produce heat, electricity, and liquid or gaseous fuels simultaneously, forms of energy that are particularly vital for the transportation sector. Moreover, the growing public awareness of environmental preservation has encouraged many nations to pursue the development of more sustainable and environmentally benign energy alternatives [1-3].

In Indonesia, a comparable trend has been observed. Among the various economic sectors, the transportation sector remains one of the largest consumers of fuel. The substantial number of private vehicles, coupled with industrial vehicles that dominate transportation networks, has resulted in a marked increase in fuel demand. This is reflected in the annual growth rate of fuel consumption, which averages approximately 4% per year. Such growth is driven by sustained economic expansion, the rising number of vehicles, and intensified industrial and domestic activities. National biodiesel consumption rose from 9.5 million kiloliters in 2022 to 12.2 million kiloliters in 2023, largely attributable to the government's policy of increasing the biodiesel blend in diesel from B20 to B35 in February 2023. Furthermore, the planned introduction of B40 in December 2024 is projected to raise biodiesel usage to approximately 15.6 million kiloliters [4].

Conversely, domestic diesel production in Indonesia has declined markedly since the year 2000, reaching only around 20 million kiloliters, thereby necessitating imports to address the supply deficit [5]. According to data from BPS, the highest value of oil and gas imports over the past thirteen months was recorded in November 2019, amounting to USD 2.13 billion [6]. This situation underscores the urgent need for more sustainable fuel alternatives, such as biofuels, to replace petroleum-derived fuels [7].

Within the framework of biofuel development in Indonesia, biodiesel has emerged as the principal alternative, owing to its commercial availability and compatibility with conventional diesel engines without the necessity for modification. Biodiesel is a renewable, biodegradable fuel with competitive energy content and the potential to contribute substantially to meeting future global energy demands. Moreover, it generates lower emissions than fossil diesel, thereby offering a more environmentally sustainable option [8]. In Indonesia, biodiesel is predominantly produced from palm oil and used cooking oil, serving primarily as a substitute for petroleum-based diesel fuel [5].

One of the key advantages of biodiesel is its oxygen content, typically ranging from 9% to 12%, which plays a pivotal role in reducing combustion emissions such as carbon monoxide (CO), hydrocarbons (HC), and exhaust gas temperature (EGT). In addition, biodiesel possesses a relatively high cetane number, approximately 58, indicating a shorter ignition delay. A higher cetane number enhances combustion efficiency, resulting in smoother engine performance and improved throttle responsiveness [9]. From both physical and chemical perspectives, biodiesel offers further benefits, as it is free from Sulphur and mineral content, non-toxic, and naturally oxygenated, all of which contribute to lower exhaust emissions. Furthermore, biodiesel exhibits inherent lubricating properties, which aid in prolonging engine component lifespan.

Chemically, biodiesel is composed of fatty acid methyl esters (FAME), synthesized from various vegetable oils (natural triglycerides) through different production pathways, with transesterification being the most widely employed method [10]. In this process, glycerin is generated as a by-product [11]. The transesterification reaction involves triglycerides (acylglycerols) and an alcohol, most commonly methanol, in the presence of a catalyst (Figure 1). This reaction yields biodiesel as the main product, with glycerol as a secondary product.

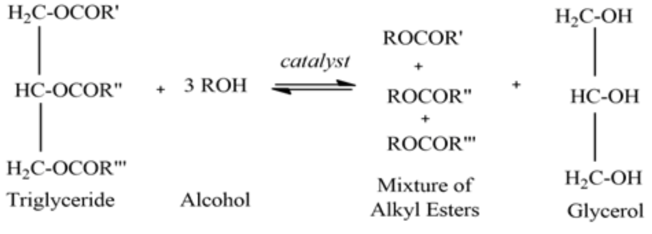

Figure 1. Transesterification of triglycerides to form FAME

In line with Presidential Regulation No. 5 of 2006 on the National Energy Policy and Presidential Instruction No. 1 of 2006 regarding the acceleration of biofuel development and utilization as an alternative energy source, the Government of Indonesia has mandated the phased adoption of biodiesel in industry since 2008, commencing with a 2.5% biodiesel blend. At present, a 40% biodiesel blend (B40) is employed alongside conventional diesel fuel. Nevertheless, the use of biodiesel has been associated with several engine-related issues, including reduced engine power and sediment accumulation within fuel tanks. Such problems stem from the intrinsic chemical properties of biodiesel, which are highly susceptible to degradation. Furthermore, its hygroscopic nature enables it to absorb moisture from the atmosphere, thereby promoting sediment formation that can obstruct fuel lines, particularly at low temperatures. The presence of water in biodiesel also disrupts the combustion process, further diminishing engine performance and, in some cases, leading to engine damage. A further technical challenge in diesel engine applications is the increased emission of nitrogen oxides (NO_x), underscoring the need for continued research and technological innovation to mitigate these limitations [12].

To overcome the limitations of biodiesel, fuel bio-additives derived from Indonesian essential oils present a promising solution. Fuel additives are substances introduced into fuels such as petrol, diesel, or biodiesel to enhance their physicochemical properties, thereby increasing power output and improving overall engine performance. When incorporated into fuel, such additives can reduce harmful emissions, including hydrocarbons (HC), particulate matter, carbon dioxide (CO_2), nitrogen oxides (NO_x), and water content [13].

Essential oils, such as clove, lemongrass, citronella, and eucalyptus, are volatile organic compounds synthesized as secondary metabolites by aromatic plants. Their lipophilic nature, volatility at relatively low temperatures, and distinctive aroma enable diverse applications, including utilization as bio-additives in fuel systems. In such applications, compounds including citronellal, citronellol, and geraniol can attenuate van der Waals dispersion forces between fuel molecules by introducing stronger dipole–dipole interactions, thereby promoting induced dipole interactions between polar and non-polar constituents within the fuel [14, 15]. These molecular-level modifications can lead to measurable enhancements in the physicochemical properties and operational performance of the fuel.

Essential oil-based bio-additives can also improve viscosity, anti-knock characteristics, cetane number, and cold flow performance. Moreover, they enhance thermal stability, promote engine cleanliness, and provide protection against corrosion [16]. To improve fuel efficiency [15], bio-additives are favored for their wholly organic composition, safety, compatibility with diesel fuel, high oxygen content, detergency within the combustion chamber, optimization of engine performance, reduction in diesel consumption, and decreased maintenance requirements. Among the various environmentally friendly options, essential oils represent a particularly promising class of bio-additives.

Indonesian essential oils and their derivatives, such as clove oil, citronella oil, rhodinol, α-pinene, camphor oil, and limonene, possess considerable potential as commercial bio-additives [13]. This potential arises from their comparable physicochemical properties to diesel fuel, the presence of oxygenated compounds, relatively low boiling points, and abundant availability within Indonesia. Additional advantages include high volatility, low density and viscosity, the presence of oxygenated hydrocarbons, favorable solubility in certain fuels, the absence of heavy metals, and their status as renewable resources [17]. Beyond their solubility in diesel fuel, essential oils exhibit low boiling points, enabling them to enhance the combustion process in diesel engines. This is attributed to their molecular structures, which may weaken Van der Waals interactions within diesel fuel and disrupt the carbon chain [15], in addition to containing various oxygenated chemical compounds [18].

A bibliometric analysis of research developments on bio-additives derived from essential oils for biodiesel was conducted using VOS viewer (Figure 2). Bibliographic records were obtained from indexed academic databases, encompassing the period from 2018 to 2023. The results indicate a maturing research field with an increasing diversity of studies addressing fuel performance, emission characteristics, and the application of Indonesian essential oils and their derivatives, such as citronella oil and clove oil. These developments are consistent with international sustainability objectives, particularly in reducing greenhouse gas emissions and advancing the transition towards cleaner transportation energy sources.

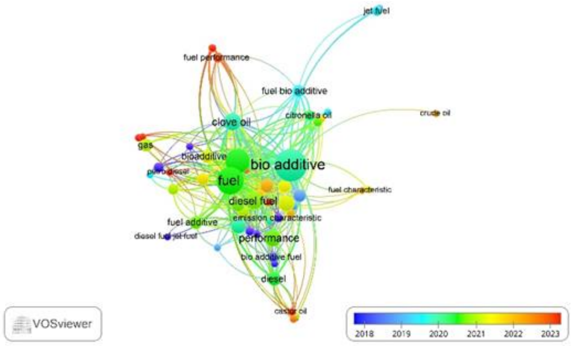

Figure 2. Research mapping of essential oil-derived additives for biodiesel

This article examines the influence of bio-additives obtained from essential oils and their constituent compounds on the quality and performance of fuel oils, with a particular emphasis on biodiesel. It focuses on Indonesian essential oils, including clove oil and its principal component eugenol; citronella oil and its constituents; turpentine oil and α-pinene; and camphor oil.

2. METHODS

The present study employs an integrated methodological approach to examine the driving factors, challenges, and strategies associated with the application of essential oil additives for enhancing biodiesel quality and performance. This approach combines a Systematic Literature Review (SLR) structured in accordance with the PRISMA framework with Pareto analysis. The integration of these methods provides a comprehensive understanding of the critical aspects of essential oil utilization as biodiesel additives, as well as mapping prevailing research trends and identifying gaps within the field. The SLR, guided by PRISMA principles, ensures that the processes of literature retrieval, selection, and appraisal are conducted systematically, transparently, and objectively. In parallel, Pareto analysis is employed to determine and prioritize the most influential factors affecting biodiesel quality and performance upon the incorporation of essential oil-based additives. The insights gained from this review are anticipated to make a substantial contribution to the advancement of cleaner, more efficient, and sustainable biodiesel production through the adoption of bio-derived additives. Nevertheless, this approach is constrained by its dependence on secondary data, the potential for bias within the extant literature, and its inability to fully reflect the dynamic complexity of real-world operational conditions.

2.1 SLR with the PRISMA framework

The SLR method was employed to conduct a comprehensive examination and synthesis of prior studies investigating the effects of essential oil additives in fuels. This approach seeks to elucidate the potential of essential oils as fuel additives through a rigorous process of searching, selecting, and critically evaluating pertinent literature. The review process was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, ensuring that each stage of the review was undertaken in a systematic, transparent, and reproducible manner. In accordance with the PRISMA protocol, the SLR comprised four principal stages [19, 20].

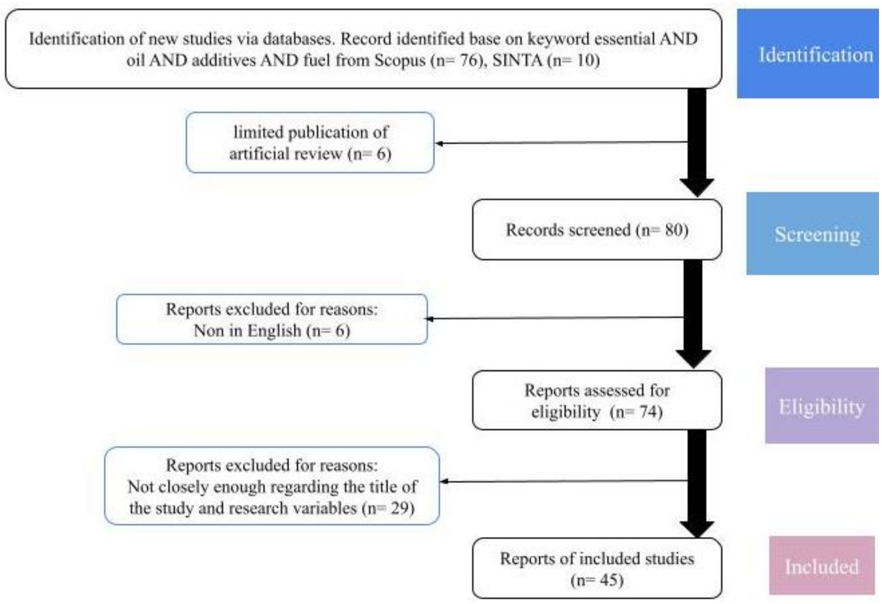

Figure 3. The SLR process using the PRISMA framework

As illustrated in Figure 3, the SLR process, employing the PRISMA framework, outlines the sequential stages of identification, screening, eligibility assessment, and inclusion of the most pertinent references for this study. The SLR methodology offers a structured and dependable approach for exploring existing findings, while PRISMA, as an integral tool within the SLR process, ensures transparency and reproducibility in the literature review, thereby strengthening the credibility and accountability of the research outcomes.

The literature search was conducted using the Scopus and SINTA databases with the keywords "essential AND oil AND additives AND fuel," yielding 86 articles (Scopus: 76; SINTA: 10). After excluding 6 publications consisting of artificial reviews, 80 records were screened. At this stage, 6 articles were excluded for being non-English, leaving 74 reports for eligibility assessment. A further 29 articles were excluded because they were not sufficiently aligned with the research objectives and variables. Finally, 45 studies fulfilled the inclusion criteria and were selected for the review.

Table 1 presents the inclusion and exclusion criteria applied in the SLR based on the PRISMA framework. The inclusion criteria ensured that only peer-reviewed journal articles or conference proceedings, written in English, and directly addressing the application of essential oils or their active constituents as fuel additives with measurable data on fuel properties, combustion characteristics, or engine performance were considered. The exclusion criteria consisted of publications classified as artificial reviews (n = 6), non-English articles (n = 6), and studies not sufficiently aligned with the research objectives or variables (n = 29). Literature that met the inclusion criteria and passed this screening process was further assessed for eligibility with an emphasis on methodological quality, contribution to the topic of essential oil additive utilization, and relevance to biodiesel quality and performance improvement. In total, 45 studies fulfilled all requirements and were selected as primary data sources. The synthesized findings provide deeper insights into the factors driving or hindering the utilization of essential oils as biodiesel additives, while also highlighting the challenges in formulating and applying natural compound-based additives for the development of more sustainable and environmentally friendly biodiesel.

Table 1. Details of the inclusion and exclusion criteria of biodiesel additives articles

No.	Inclusion	Exclusion
1	Peer-reviewed journal articles or conference proceedings	Publications consisting of artificial reviews (n = 6)
2	Written in English	Publications not in English (n = 6)
3	Addressing the application of essential oils or their active constituents as fuel additives	Studies not closely related to the research objectives or variables (n = 29)
4	Reporting measurable data on fuel properties, combustion characteristics, or engine performance	

2.2 Pareto analysis

The literature collection and identification process using the Systematic Literature Review (SLR) method yielded sources that primarily focus on essential oils and their fractions as additives in diesel fuel. Pareto analysis was employed to categorize the advantages of clove, lemongrass, camphor, and turpentine essential oils, along with their corresponding fractions eugenol, limonene, rhodinol, and α-pinene as bio-additives. The Pareto principle, also known as the 80/20 rule, suggests that 80% of outcomes are driven by 20% of the key contributing factors. In this study, the initial step involved grouping the journal articles obtained from the SLR. The grouping was based on the publication year, the country of origin discussing bio-additive research, and the publishers of journals covering bio-additive topics. Each group was assigned a weight according to its level of importance. The weight values were then multiplied by their frequencies to generate a total score, which was subsequently ranked from highest to lowest. From this data, percentages and cumulative percentages were calculated and visualized using a Pareto chart to identify approximately the top 20% of factors contributing to about 80% of the total impact [21-25]. The role of Pareto analysis in this study is to filter and concentrate on the most impactful factors, ensuring that the proposed essential oils and their fractions are selected for their highest efficacy. This study underscores the potential of essential oils and their active fractions as promising bio-additives in diesel fuel.

In this study, the 'importance level' was defined as the degree to which a variable directly influences biodiesel quality and performance. A three-point weighting system was used: high importance = 3, medium = 2, and low = 1. Frequency refers to the number of publications that mentioned a given factor (Table 1). Each frequency value was multiplied by its respective weight to generate a weighted score, which was then used for Pareto ranking and cumulative percentage calculation.

3. RESULTS AND DISCUSSION

3.1 Bibliometric analysis

This study began by identifying data and documents published in the Scopus databases, in accordance with the scope of the research topic, to obtain the most up-to-date information on the quantity and trends of relevant studies at the global level. The next stage involved screening the collected documents to assess their eligibility, allowing for the selection of the most relevant and credible journal articles to serve as the foundation of this scientific review. The publication identification was conducted in December 2024 using the search keywords: "essential" AND "oil" AND "additives" AND "fuel".

As observed in Figure 4, there has been a significant increase in research on the utilization of essential oils and their fractions as additives for diesel fuel, both in publication trends and volume, from 2015 to 2024 at the global level, based on data from the Scopus and SINTA databases. Although the eligibility screening stage showed a gradual decline in the number of publications, a resurgence was noted in line with the improvement in publication quality, particularly in Scopus-indexed Q1 journals. A total of 45 journal articles published between 2019 and 2024 were selected as the most relevant focus for this study. Based on the observed trends and publication volume, it is evident that this research topic is highly relevant and has garnered significant global attention.

This research topic represents an emerging field in the global scientific landscape, attracting growing attention, particularly among researchers in essential oils and their promising fractions as additives for diesel fuel in Indonesia.

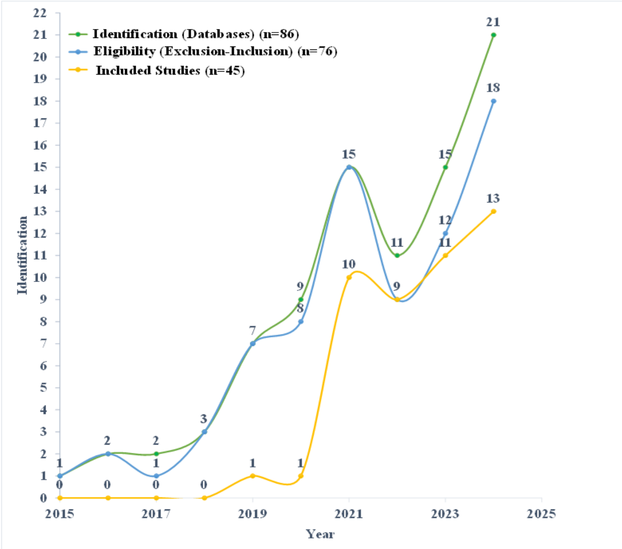

Figure 4. Publication trends and volume in biodiesel additives research (2015-2024)

As observed in Figure 5, research recorded in the Scopus and SINTA databases has been widely distributed with an increasing year-to-year trend from 2019 to 2024. The countries most active in publishing research on fuel additives at the global level are, in order, Indonesia, India, Brazil, China, and Pakistan. Indonesia holds a significant position in research publications and scientific interest related to this topic. This is in line with the abundance of essential oil-producing plantations across various regions of the country, which has driven the rapid growth of the national essential oil industry. Currently, Indonesia ranks among the top five countries in the world in this sector. The advancement of publications in this research area contributes positively to the development of alternative fuels, particularly for diesel engines. These leading countries have the potential to reduce their dependence on fossil fuels, especially in diesel applications. This factor positions them to take the lead in the development of essential oil-based fuel additives, which are derived from horticultural plants.

As shown in Figure 6, among the 45 recorded journal articles, there are 39 different journals, with the majority publishing only 1 article. Several journals, including AIP Conference Proceedings, Frontiers in Energy Research, Designs, and Acta IMEKO, each published 2 articles. Meanwhile, the IOP Conference Series: Earth and Environmental Science contributed 5 articles, and the Fuel journal was the most dominant, publishing 6 articles. This uneven distribution of publications indicates that research on essential oil additives in biodiesel remains concentrated in a limited number of journals, suggesting that this field still offers considerable potential for further exploration and development in the future.

3.2 Essential oil

Essential oils are typically obtained from non-fatty parts of plants, such as flowers, petals, buds, roots, bark, leaves, and stems [26]. Essential oil is a liquid composed of a mixture of volatile, lipophilic compounds with a characteristic aroma, extracted from aromatic plants. Typically, this oil is clear or pale yellow in color, remains liquid at room temperature, has a lower density than water, and possesses a relatively low molecular weight (less than 300). The main component of an essential oil generally determines its biological activity, although minor compounds can also play a significant role in enhancing or modulating its effects [26]. Essential oil is widely used in the production of cosmetics, toiletry products, perfumes, pharmaceutical products, insecticides, detergents, soaps, confectionery food products, soft drinks, alcoholic beverages [27], and as a fuel additive [16].

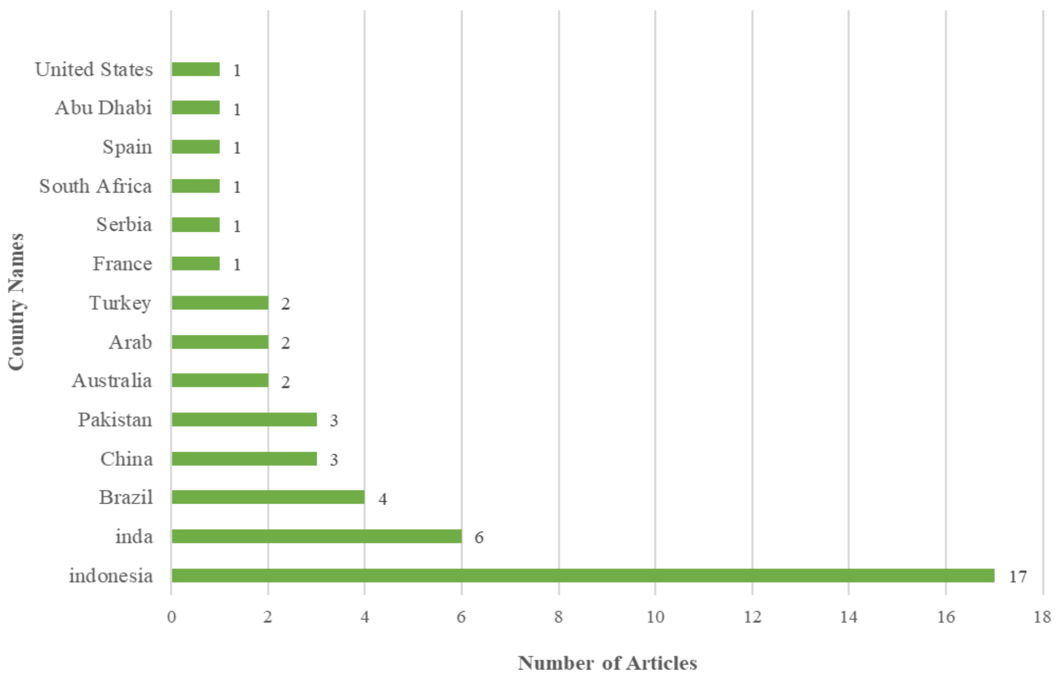

Figure 5. The most active countries in biodiesel additives research

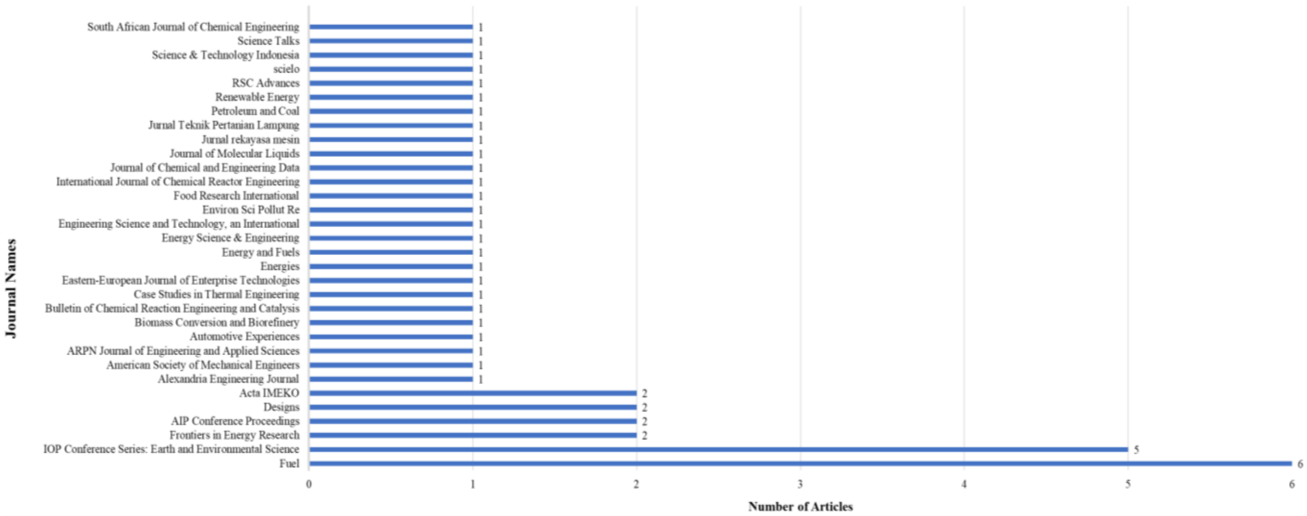

Figure 6. The leading journals in biodiesel additives research

Essential oils and their components have been extensively utilized as fuel additives [13]. Oxygen-rich compounds like eugenol [28], citronellal, and citronellol have demonstrated the ability to lower fuel consumption [15]. Additionally, essential oils derived from alkenes, such as alpha-pinene and limonene, are employed as fuel additives due to their low flash points and ability to decrease viscosity [29]. Recent research indicates that the use of essential oils in fuel can alter its physicochemical characteristics and influence the level of NO_x emissions [12]. Previous studies demonstrated that the addition of pure essential oils as fuel additives effectively reduced hydrocarbon (HC) emissions compared to diesel fuel [30].

3.3 Clove oil

Clove oil is one of the essential oils with promising potential as a bio-additive for fuel. Its high oxygen content promotes more efficient fuel combustion and helps reduce engine noise. When blended with biodiesel, clove oil also contributes to lowering particulate emissions, decreasing metal content in lubricating oil, and minimizing carbon deposits on the piston crown compared to conventional diesel fuel. Additionally, the integration of clove oil into biodiesel blends helps prevent carbon buildup, making it a more environmentally sustainable alternative to petroleum-based diesel [31, 32].

In compression ignition engines, the use of B30 biodiesel leads to higher carbon deposits on the piston crown compared to engines fueled with clove oil. Nevertheless, the cleanliness of the piston in B30-fueled engines is comparable to that of engines using pure diesel or clove oil. Clove oil, functioning as an antioxidant in B30 biodiesel, also contributes to lower engine noise levels due to its high oxygen content, which facilitates more complete combustion. In contrast, engines operating on pure diesel tend to produce higher noise levels than those using B30 or biodiesel containing 3000 ppm of clove oil. Therefore, the addition of clove oil as an antioxidant in biodiesel blends offers a more sustainable alternative for reducing both noise emissions and carbon buildup in diesel engines [32].

Furthermore, the addition of 5% clove oil to biofuels results in increased density, a reduction in viscosity by up to 10%, and a decrease in the flash point by up to 30%. The combustion process is notably more efficient when clove oil is blended with coconut oil (CCO), as compared to when it is combined with kapok oil (KSO) or castor oil (CJO). The higher viscosity of KSO and CJO causes eugenol and terpene compounds in clove oil to become trapped within the fuel droplets. Due to their high volatility, eugenol and terpene quickly evaporate during combustion, triggering secondary atomization and micro-explosions that enhance combustion efficiency [33].

3.3.1 Eugenol-rich fraction

Eugenol, the major compound in clove oil with a concentration of 81.2%, functions as a potent natural antioxidant for biodiesel, particularly for biodiesel derived from waste cooking oil [34]. One of the key factors in maintaining biodiesel quality is its oxidative stability. Biodiesel is highly susceptible to oxidation due to its relatively high viscosity, water content, acidity, and peroxide levels. Environmental factors such as humidity, metal contaminants in the fuel, and exposure to heat and light further accelerate the oxidation process. Oxidation leads to structural changes in biodiesel, primarily through the isomerization of double bonds in free fatty acids, resulting in the formation of saturated compounds. These compounds increase the fuel's density and viscosity, ultimately reducing engine performance and efficiency. To mitigate these effects, antioxidants are commonly used as stabilizing additives in biodiesel. These compounds slow the oxidation process by inhibiting the formation of peroxyl and hydroxyl (OH) radicals. Among various antioxidant types, phenolic compounds are known to be the most effective. The addition of eugenol has been shown to significantly enhance the oxidative stability of biodiesel, with performance levels comparable to those of synthetic antioxidants [28]. In addition, the eugenol compound found in clove oil possesses an asymmetrical carbon chain geometry, which potentially enhances the occurrence of effective collisions between fuel molecules. As a result, fuels containing eugenol exhibit increased combustibility [35].

The use of eugenol-based bio-additive formulations offers a promising approach to address oxidative degradation in engine systems. Eugenol has shown the potential to lower fuel consumption as well as reduce carbon monoxide (CO) and unburned hydrocarbon (HC) emissions. Its high oxygen content contributes to more efficient combustion, thereby enhancing overall engine performance [36]. A study demonstrated that eugenol remains stable within biodiesel even after being stored at 43°C for 150 days. The compound effectively suppressed oxidation, resulting in improved acid values and longer induction periods. Moreover, the research indicated that eugenol is more efficient than TBHQ in enhancing the oxidative stability of commercial biodiesel. It was able to maintain biodiesel quality throughout storage, meeting regulatory requirements. This study, which utilized biodiesel derived from a mixture of soybean oil and animal fat, further supports the potential of eugenol as a natural antioxidant for biodiesel applications [37].

Tests conducted on a 20 kVA generator showed that at loads of 1500 and 3000 watts, the fuel consumption of B20 blended with essential bio-additives comprising turpentine, eugenol, and citronella oil at a ratio of 1:4000 was lower compared to pure B20. However, at maximum speed, fuel consumption remained relatively unchanged. On the other hand, smoke emissions were significantly reduced under high-load conditions when using the B20 blend with essential bio-additives. These findings suggest that incorporating essential oil-based bio-additives can enhance combustion efficiency and reduce exhaust emissions [38].

A study by Souza et al. [39] reinforces the idea that the incorporation of eugenol into soybean biodiesel can improve both its oxidative stability and corrosion resistance. As a natural antioxidant, eugenol functions by donating hydrogen atoms or electrons to free radicals, thereby neutralizing oxidation reactions. Moreover, eugenols can form a protective layer on metal surfaces, mitigating the corrosive properties of biodiesel. The inclusion of eugenol in soybean biodiesel not only enhances its overall quality but also boosts its performance, positioning it as a promising additive for biodiesel production [39].

3.4 Citronella oil

Citronella oil, derived from a renewable and widely available plant, shows significant potential as an alternative fuel for diesel engines. When integrated into diesel fuel, citronella oil helps reduce harmful emissions such as carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), hydrocarbons (HC), and smoke, in comparison to conventional diesel. As such, citronella oil offers a promising, environmentally friendly alternative to fossil fuels that contribute to pollution. Furthermore, the addition of citronella oil to diesel fuel can improve thermal efficiency in engines and lower specific fuel consumption (SFC). The optimal performance is achieved with a blend of 60% diesel, 10% additive (Diethyl Ether), and 40% citronella oil, which not only reduces harmful emissions but also promotes sustainability [40].

The incorporation of natural bio-additives, such as citronella essential oil, into diesel engines has been shown to enhance engine performance while simultaneously reducing fuel consumption [15]. Key constituents such as citronellal (FA) and citronellol-geraniol (FB) in citronella play a significant role in improving fuel efficiency. The concentration of this bio-additive typically ranges from 0.1% to 0.5%, with its addition potentially increasing fuel efficiency by as much as 46%. The extent of this improvement is largely dependent on the concentration of the mixture, with citronellal (FA) being the most influential component. At a concentration of 0.2%, citronellal (FA) notably enhances fuel consumption efficiency, primarily due to its high oxygen content, which supports more efficient combustion within the engine [15].

Citronella oil also functions as a downstream into various commercial products of Z-fract bio-additive [16]. The incorporation of citronella oil bio-additive into the B35 fuel mixture has been shown to reduce carbon monoxide (CO) emissions by 45%, although there is no significant change in hydrocarbon (HC) emissions [10]. Furthermore, the use of citronella extract results in lower exhaust gas temperatures when compared to the use of pure gasoline and synthetic additives [41].

Studies have shown that the inclusion of citronella oil in Homogeneous Charge Compression Ignition (HCCI) engines has a considerable effect on performance. The use of citronella oil in biodiesel blends has been found to improve engine performance by enhancing thermal efficiency and reducing specific fuel consumption. Furthermore, the addition of citronella oil alters combustion characteristics, influencing factors such as pressure and the rate of heat release, while also impacting emissions such as carbon monoxide (CO), nitrogen oxides (NO_x), and unburned hydrocarbons. In addition, incorporating cobalt chromium nanoparticles into citronella biodiesel blends can significantly increase the surface-to-volume ratio, thermal conductivity, and heat transfer rate within the oil layer. Therefore, adding citronella oil to HCCI engines not only optimizes engine performance but also promotes more efficient combustion and reduces harmful exhaust emissions [42].

Research has shown that the addition of citronellal fractions at concentrations of 0.1% and 0.15% led to a reduction in the viscosity of Pertamina-DEX by 2.02% and 2.43%, respectively. This result demonstrates that adding bio-additives to biodiesel can enhance fuel consumption efficiency. The optimal bio-additive concentration was the citronellal fraction (F2) at 0.15%, which resulted in a 20.59% improvement in fuel consumption efficiency [43].

In motorcycle engine testing, the addition of citronella bio-additive has been shown to enhance engine performance significantly. Specifically, it can increase the maximum power output by up to 7.77 horsepower (Hp), representing a 3.11% improvement compared to the baseline pertalite fuel, which yields a maximum power of 7.50 Hp. In addition to power gains, the bio-additive also improves the motorcycle's maximum torque by 8.36 Nm, or 2.03%, when compared to Pertalite's maximum torque of 8.20 Nm. Beyond performance enhancement, the bio-additive mixture also contributes to fuel efficiency, reducing fuel consumption and allowing the motorcycle to cover longer distances. Notably, the S5-3.5% bio-additive mixture results in fuel savings of up to 20.93%, enabling the motorcycle to achieve an impressive fuel efficiency of 69.9 km per liter [44]. This optimized fuel usage and improved engine output highlights the potential of citronella bio-additive as a viable solution for enhancing both performance and fuel economy in motorcycle engines.

3.4.1 Rhodinol-rich fraction

Rhodinol is a compound formed from a combination of citronellol and geraniol. Rhodinol has also been applied as a fuel additive for diesel and B20 (a blend of diesel fuel and biodiesel) in an 80:20% volume ratio, resulting in a 5.14% reduction in fuel consumption. This effect is attributed to rhodinol's ability to enhance oxidation stability, increase calorific value, and decrease the particulate content of pure vegetable oil. Moreover, the structure of essential oils such as rhodinol can weaken Van der Waals bonds in diesel fuel, which in turn optimizes the combustion process and improves the performance of diesel engines [45].

In the B30 biodiesel blend, rhodinol has been shown to effectively reduce both particulate matter and water content. This study highlights that the addition of rhodinol results in a significant decrease in these components, which ultimately contributes to the enhancement of fuel quality [46]. Similarly, in the B35 biodiesel blend, the use of rhodinol as a bio-additive yields substantial improvement. Specifically, the water content is reduced by 18%, or 287.2 ppm, while the levels of particles sized at 4, 6, and 14 microns are effectively lowered [46].

Rusli et al. [47] developed bio-additive formulations composed of a blend of essential oils containing rhodinol. The B30 biodiesel blended with these essential oil-based bio-additive formulations was directly applied to a diesel engine to evaluate its performance and operational stability. Comprehensive analyses were conducted to assess engine revolutions per minute (RPM), fuel consumption, filter pressure differentials, and smoke emissions both before and after the durability test.

The 100-hour durability test demonstrated that the parameters of engine RPM, power output, fuel consumption, filter pressure differential, and smoke emissions remained stable and exhibited no significant deviation from the initial baseline values. Field evaluations further indicated that the incorporation of bio-additives reduced particulate concentrations in the main fuel tank by approximately 60% after four days of operation, accompanied by a corresponding decrease in water content. Moreover, the fuel filters used with bio-additive-treated fuels showed visibly cleaner surfaces compared to those without additive treatment.

3.4.2 Limonene

Limonene exhibits significant potential as a bio-additive due to its favorable physicochemical properties. Permanasari et al. [48] have demonstrated that incorporating 2% of Limonene into B20 biodiesel significantly reduces fuel consumption, highlighting its potential as an effective fuel efficiency enhancer for diesel engines.

During the combustion process, incorporating d-Limonene compounds extracted from citrus oil into diesel-biodiesel blends has been shown to decrease ignition delay by approximately 2 degrees. Additionally, d-Limonene improves the fuel's cetane number, thereby enhancing combustion efficiency [49].

The incorporation of d-Limonene into biodiesel blends has been shown to enhance combustion efficiency by reducing hydrocarbon, carbon monoxide, and particulate emissions in exhaust gases. Even at low concentrations, d-Limonene demonstrates significant effectiveness in improving engine performance within compression ignition systems. Experimental results indicate a reduction in unburned hydrocarbon emissions while simultaneously increasing carbon dioxide emissions. However, its impact on nitrogen oxide emissions remains variable, depending on engine load conditions. These findings suggest that d-Limonene holds substantial potential as a biodiesel additive for optimizing engine performance and refining exhaust gas composition [50].

The addition of limonene to biodiesel has been observed to lower the flash point of the diesel-limonene blend. A progressive decline in flash points occurs as the Limonene concentration increases, reaching up to a 10% volume fraction. Additionally, the thermal behavior of the mixture undergoes notable changes, with the peak TG at 10% Limonene in diesel decreasing by approximately 20°C. These findings suggest that Limonene, functioning as a volatile antioxidant, significantly impacts both the flash point and the thermal characteristics of the biodiesel blend. Furthermore, studies indicate that the selection of antioxidants plays a crucial role in determining the thermal properties of biodiesel mixtures. Thus, careful selection of antioxidants is essential for optimizing the thermal stability and combustion characteristics of biodiesel-based fuels [51].

3.5 Turpentine oil

Turpentine oil is a widely recognized bio-additive and a key industrial product in Indonesia. It is a transparent liquid primarily composed of alpha-pinene ($C_{10}H_{16}$), a highly abundant terpene hydrocarbon, which contributes to its high flammability [52].

The presence of alpha-pinene from turpentine has been shown to improve the combustion properties of castor oil droplets when used as a biodiesel fuel. Specifically, the addition of turpentine reduces viscosity and enhances the evaporation rate, resulting in a shorter ignition delay period and an increase in both flame height and width. Experimental findings suggest that a 15% turpentine blend produces the most favorable outcomes, characterized by accelerated droplet combustion and enhanced combustion efficiency. These findings highlight the potential of turpentine as a combustion-enhancing additive for castor oil-based biodiesel [53]. Experimental findings indicate that the addition of turpentine oil to coconut oil enhances the combustion efficiency of biodiesel by mitigating these limitations [54].

The substantial alpha-pinene content in turpentine oil has been shown to enhance the viscosity and flash point of sunflower oil (CSFO) as a biodiesel feedstock. Experimental results indicate that the addition of turpentine oil enhances combustion behavior by accelerating the combustion rate, lowering the combustion temperature, and narrowing the flame front. Notably, an optimal concentration of 15% turpentine oil results in a significantly faster combustion process and lower operational temperatures. Pure CSFO, in contrast, exhibits a greater maximum flame height due to the micro-explosion phenomenon. Additionally, increasing the proportion of turpentine oil contributes to a reduction in exhaust gas emissions. These findings suggest that turpentine oil plays a crucial role in improving the combustion performance and environmental sustainability of CSFO-based biodiesel [55].

3.5.1 Alpha-pinene-rich fraction

Alpha-pinene is a terpene-derived biofuel that has been extensively investigated to elucidate its thermal degradation characteristics. Experimental findings indicate that alpha-pinene exhibits slightly higher reactivity compared to beta-pinene. For the first time, this research provides activation energy data for alpha-pinene as a plant-based biofuel, underscoring its potential as a viable alternative to conventional fossil fuels. Additionally, the study evaluates gas emissions generated during thermal degradation, offering essential data for numerical simulations of biodiesel combustion. These insights contribute to the broader transition toward sustainable fuel solutions. Furthermore, the findings confirm that α-pinene demonstrates marginally greater reactivity than β-pinene. A comparative analysis with existing literature reveals that the activation energies of these biofuels are similar to those of diesel and sunflower oil-based biofuels. The study also identifies that α-pinene undergoes thermal degradation, leading to the release of camphene and carene, whereas β-pinene primarily undergoes isomerization, yielding α-pinene and carene [28].

Al Zaabi et al. [56] reported that fused-ring cyclic hydrocarbon structures play a significant role in reducing soot emissions, enhancing cetane number, improving structural irregularities in soot, increasing aliphatic and oxygen content, and decreasing the size of primary particles as well as polycyclic aromatic hydrocarbons (PAHs) in soot. Among these hydrocarbons, α-pinene is a notable example. Experimental findings indicate that the addition of α-pinene to diesel fuel effectively reduces soot emissions through a synergistic effect on soot formation, lowering the soot index by 21% and accelerating the oxidation process. Combustion of conventional diesel fuel tends to generate substantial amounts of soot. However, the incorporation of α-pinene mitigates this issue by diluting aromatic and Sulphur-containing components in diesel, thereby modifying its chemical composition. Moreover, α-pinene contributes to increased soot reactivity by reducing the molecular weight and altering the physical properties of the fuel, leading to enhanced evaporation and improved air-fuel mixing. This phenomenon is attributed to the formation of five-membered rings during partial oxidation, which facilitates the development of polycyclic aromatic hydrocarbons and makes soot more susceptible to oxidation. Although α-pinene does not significantly influence the cetane number, a 10% addition of α-pinene to diesel has been shown to reduce the soot index from 63.5 to 61.5 [56].

3.6 Camphor essential oil (CMO)

The addition of camphor essential oil to diesel reduces the activation energy required for O_2-induced soot oxidation, thereby enhancing its oxidative reactivity. This modification decreases the edge length and primary particle diameter of soot while increasing edge tortuosity, crystal lattice disruption, and oxygen functionality. These physicochemical alterations accelerate the soot oxidation process, highlighting camphor oil as a potential additive for diesel. Furthermore, empirical studies suggest that blending diesel with biodiesel or biofuels, including camphor oil, effectively reduces emissions without compromising energy efficiency. This finding underscores the potential of camphor oil as a sustainable alternative to conventional fossil fuels [57].

The integration of camphor essential oil (CMO) as a component in diesel fuel formulations has demonstrated notable effects on the combustion characteristics and overall efficiency of diesel engines. Research findings reveal that the CMO contributes to improved thermal conversion and enhanced brake-specific fuel performance. Furthermore, the chemical constituents of CMO facilitate a reduction in nitrogen oxide (NO_x) emissions, thereby playing a role in decreasing atmospheric pollutants associated with the combustion of conventional fossil fuels [58].

In an engine test utilizing a multi-point fuel injection (MPFI) ignition system with gasoline and a 20% camphor oil mixture (CMO20), the addition of 3% 2-methylfuran (2-MF) to CMO20 resulted in a brake thermal efficiency (BTE) of 27.22%. This value exceeds the BTE of pure gasoline and CMO20 alone, which were recorded at 26.82% and 26.05%, respectively, under an 8-kW load. The incorporation of 2-MF into the CMO20 blend facilitated an advanced ignition timing and a higher combustion rate, thereby increasing cylinder pressure and heat release rate, ultimately enhancing combustion efficiency. Furthermore, the CMO20 blend with 3% 2-MF demonstrated a reduction in carbon monoxide (CO) and hydrocarbon (HC) emissions by approximately 3.75% and 4.76%, respectively, compared to pure gasoline. However, a slight increase in nitrogen oxide (NO_x) emissions was observed, attributed to the elevated combustion temperature [59].

The incorporation of Karanja camphor oil into diesel or camphor oil-based fuel blends has been shown to enhance the thermal efficiency of compression ignition (CI) engines. Specifically, some of its blends exhibit superior thermal efficiency and reduced specific energy consumption compared to conventional diesel. Furthermore, these fuel blends contribute to lower emissions of carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), and particulate smoke, indicating their potential as a more environmentally sustainable alternative to fossil diesel. Additionally, the presence of camphor oil in the fuel mixture influences engine performance by promoting an increased rate of pressure rise, a higher net heat release, and greater cyclic variation as the proportion of camphor oil increases in the blend [60].

A study by Malhotra et al. [61] reported comparable results, demonstrating that the addition of camphor oil to diesel engines enhances thermal efficiency and decreases specific fuel consumption. Furthermore, camphor oil supplementation reduces exhaust emissions while improving the stability and compatibility of fuel blends. These findings underscore the potential of camphor oil as a viable additive for diesel engines. By simultaneously improving engine efficiency and mitigating environmental impact, camphor oil emerges as a promising candidate for advancing sustainable fuel technologies [61].

Beyond enhancing combustion efficiency, camphor oil bio-additive demonstrates significant potential in reducing fuel water content by up to 18% (287.2 ppm). This reduction is attributed to the high oxygenated compound content of camphor oil, which reaches 51.27%. Particulate analysis further indicates that B35 biodiesel blended with camphor oil bio-additive exhibits superior performance in mitigating particulate matter, particularly at sizes of 4, 6, and 14 microns. These findings highlight the dual benefits of camphor oil as both an efficiency-enhancing additive and an effective means of reducing particulate emissions, reinforcing its viability as a sustainable fuel component [62].

The results of the bibliometric analysis identified 46 relevant journals. Subsequently, an assessment was conducted to identify the advantages of essential oils and their fractions as additives for diesel fuel on a global scale, based on previous related research findings.

The data presented in Table 2 pertains to the identification of the potential of essential oils derived from clove, lemongrass, camphor, and turpentine as fuel additives. According to these data, turpentine oil emerges as the primary candidate for use as an essential oil-based additive. Turpentine oil is widely produced in countries such as Indonesia, France, and Spain. As a result, researchers in these countries have employed turpentine as a bio-additive, achieving enhanced engine efficiency and performance, which contributes to cleaner combustion and renewable fuel applications. Additionally, turpentine exhibits good storage stability as a bio-additive. Research findings indicate that the use of turpentine bio-additive can reduce the number of micro-particles in biodiesel [38, 45, 46, 62-66].

The potential of clove essential oil is predominantly found in countries such as Pakistan, Turkey, and Indonesia due to the high consumption of clove as a spice. Based on published data, researchers in these countries have utilized clove essential oil as a bio-additive, demonstrating its ability to extend engine lifespan and improve biodiesel performance. Notably, clove oil as a bio-additive has been shown to reduce the concentration of heavy metals (Pb, Cu, Ni, Cd) in the fuel. Additionally, particulate emissions were reported to be up to 11.61% lower compared to pure diesel fuel [30, 31, 33, 34, 46, 62, 63, 67-71].

Table 2. Comparison of various essential oils on diesel engine performance

Code of Essential Oil	Essential Oil	Bio-Additive Potential	Frequency of Mentions	Percentage of Total Mentions	Location of Study	Reference
CLO	Clove Oil	The addition of clove oil to biodiesel has been proven to offer various benefits to fuel performance and quality. Although thermal efficiency tends to increase, several studies have reported a reduction in braking power and mechanical efficiency of the engine. On the other hand, essential oils act as effective antioxidants, capable of reducing carbon deposits in the engine, as well as lowering engine noise, extending engine lifespan, and enhancing biodiesel performance, making them a practical and environmentally friendly solution for urban transportation sectors. The incorporation of this additive also significantly reduces NO_x emissions and improves the oxidative stability of biodiesel. Furthermore, the use of clove oil in B30 blends has been shown to reduce particulate emissions by up to 11.61% compared to pure diesel, along with a decrease in heavy metal concentrations such as Pb, Cu, Ni, and Cd, indicating reduced engine wear. In terms of physicochemical properties, this additive increases density, reduces viscosity by up to 10%, and lowers the flash point by up to 30%, contributing to more complete combustion. Field tests also demonstrate that the additive does not impair engine performance; on the contrary, it helps maintain it, as evidenced by up to 60% reduction in particles within the main tank, a significant decrease in water content, and cleaner fuel filters. Interestingly, the addition of essential oil at a low concentration (0.5%) already yields a significant positive impact on B30 fuel quality, including enhanced storage stability of biodiesel.	12	36%	Pakistan, Turkey, Indonesia.	[30, 31, 33, 34, 46, 62, 63, 67-71]
CIT	Citronella Oil	The use of Citronella additives in biodiesel provides various positive effects on the combustion process and fuel performance. One of its benefits is the improvement of combustion efficiency, which contributes to a reduction in exhaust gas temperature. The addition of Citronella additives has been proven to reduce water content and enhance fuel stability. As a result, fuel consumption under medium load conditions can be decreased, thereby overall positively influencing the quality and performance of biodiesel.	6	18%	Indonesia, Brazil, India.	[15, 37, 40 - 42, 71]
CHA	Camphor Oil	Camphor oil additive offers several significant benefits to the quality and performance of B35 biodiesel. It effectively reduces water content by nearly 20%, decreases the presence of micro-particles, and prevents filter clogging, thereby enhancing the storage stability of the biodiesel. Additionally, camphor oil improves the physical properties of biodiesel at low temperatures, making it more stable and reliable under various climatic conditions, particularly in cold environments. In terms of engine performance and emissions, the incorporation of camphor oil contributes to the reduction of CO, CO_2, HC, and smoke emissions, while also enhancing the rate of	7	21%	Arab, Abu Dhabi, India, Indonesia, Pakistan, Brazil.	[56, 57, 59, 60, 62, 70, 72]

		pressure rise, net heat release rate, and cycle-to-cycle variation stability during combustion. A notable increase in brake thermal efficiency (BTE) by 27.22% has also been reported, although it is accompanied by a rise in NO_x emissions.				
TUR	Turpentine Oil	Turpentine essential oil additives have demonstrated high effectiveness in various aspects of improving biodiesel quality. The addition of this turpentine essential oil additive has been proven to reduce water content and decrease the number of micro-particles in B35 biodiesel, as well as enhance its storage stability. The use of turpentine essential oil additives in biodiesel blends also improves engine quality over the long term without compromising engine performance. Moreover, the addition of this additive can reduce fuel consumption and smoke emissions, thereby helping to maintain the cleanliness of the combustion system by lowering water and particulate content. As an oxygenated additive, it can enhance combustion efficiency and thermal performance, supporting biodiesel stability across various temperatures while also being environmentally friendly and renewable for automotive and aviation applications. Furthermore, turpentine essential oil additives have the potential to increase combustion reactivity when used in biodiesel. From a thermodynamic perspective, this additive shows promising compatibility in enhancing biodiesel performance. However, regular monitoring is necessary when using turpentine essential oil additives, as they may form complex oxidation products that contribute to secondary emissions.	8	24%	Indonesia, France, Serbia, Spain	[38, 45, 46, 62-66]

Citronella and camphor essential oils hold an equivalent position in terms of potential, based on the identification results. Citronella oil is primarily produced in tropical regions, particularly in Indonesia, Brazil, and India. Studies have shown that citronella essential oil, when used as an additive, can reduce diesel fuel consumption and lower water content. Overall, the use of citronella oil improves biodiesel quality and performance with high efficiency [15, 37, 40-42, 72].

Similarly, camphor essential oil has been investigated as a bio-additive by researchers from the Arab, Abu Dhabi, India, Indonesia, Pakistan, and Brazil. The findings indicate that camphor oil is effective in significantly reducing water content and the number of micro-particles in biodiesel. Emissions of CO, CO_2, HC, and smoke were also considerably reduced [56, 57, 59, 60, 62, 70, 72].

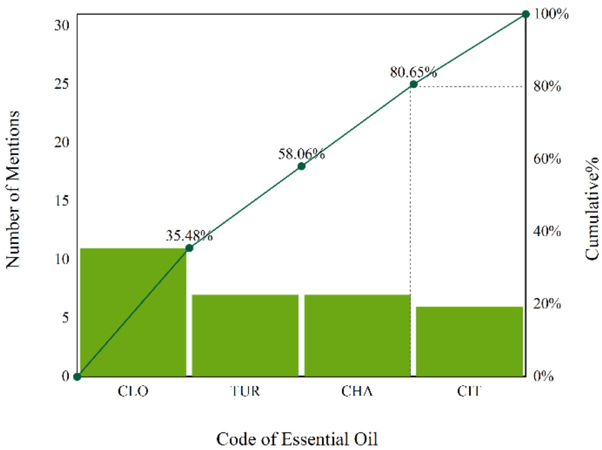

Figure 7. Pareto diagram: Prioritization of essential oils as additives on biodiesel

Based on the Pareto analysis of the identified advantages of essential oils, as illustrated in Figure 7, it was found that turpentine, clove, and camphor essential oils, in that order, possess potential as additive agents for diesel fuel enhancement. Among these, turpentine (TUR), clove (CLO), and citronella (CHA) essential oils are prioritized, contributing up to 80% of the global essential oil-based fuel additives. Therefore, according to the Pareto analysis recommendations, these three essential oils are proposed as key candidates for use as bio-additives. The results of the Pareto analysis can serve as a reference in selecting essential oil feedstocks for large-scale bio-additive production.

The bibliometric analysis yielded 46 relevant journals, followed by the identification of the advantages of essential oil fractions as fuel additives for diesel on a global scale, based on findings from previous related studies.

The data presented in Table 3 identify the potential of essential oil fractions such as eugenol, rhodinol, limonene, and alpha-pinene. According to the data, the limonene fraction clearly stands out as the top priority among essential oil fractions for use as a bio-additive. Through trade routes and international economic relations, the limonene fraction is widely available in countries such as China, Indonesia, Arab, Spain, South Africa, Pakistan, Brazil, Australia, the United States, India, and Serbia. Researchers in these countries have successfully utilized limonene fractions as a bio-additive.

Significantly, the limonene fraction provides greater chemical stability and optimal efficiency when blended with diesel fuel due to its nonpolar nature. From a thermodynamic perspective, limonene demonstrates high compatibility potential for improving biodiesel performance, particularly in combustion efficiency, flow behavior, and energy content, which are governed by molecular interactions [29, 48, 56, 62, 63, 66, 68, 70, 72-86].

Researchers in China, Indonesia, Brazil, and India have conducted studies on the use of eugenol essential oil fractions as fuel additives. The evaluation of eugenol fractions as diesel fuel additives demonstrated notable effects on molecular structure and hydrocarbon stability. These effects are attributed to the polar nature of eugenol, which exhibits high reactivity, making it particularly effective in enhancing Combustion characteristics. Several studies have also reported that eugenol fractions possess anti-corrosive properties on metal surfaces, contributing positively to the durability of engine components and fuel lines [29, 35, 37, 38, 69, 71, 83].

The identification results indicate that α-pinene and rhodinol essential oil fractions exhibit relatively similar characteristics, particularly in terms of the limited number of countries that produce or possess these resources. Countries such as Indonesia, France, China, and Serbia are among those where researchers have utilized α-pinene fractions as fuel additives. As an oxygenated additive, the α-pinene fraction contributes to enhancing combustion efficiency in diesel engine fuel systems. The oxidation behavior of this fraction promotes cleaner combustion processes [63, 65, 67, 85].

Rhodinol essential oil fraction is the only fraction that, to date, has been investigated in countries such as Indonesia, Brazil, and India, which have successfully developed and reported its application as a fuel additive. Additives derived from the rhodinol fraction exhibit the ability to reduce water content, and compared to the previous three fractions, rhodinol is the only one reported to enhance the cetane number of biodiesels [15, 37, 40, 41].

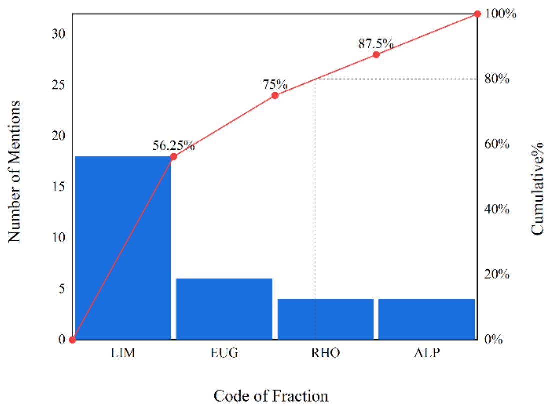

Figure 8. Pareto diagram: Prioritization of fractions as additives on biodiesel

Referring to the Pareto analysis presented in Figure 8, it was sequentially identified that limonene (LIM), eugenol (EUG), alpha-pinene (ALP), and rhodinol (RHO) essential oil fractions contribute the most, accounting for up to 80% of the global application of essential oil-based additives. Based on the recommendations derived from the analysis, three major fractions are prioritized as primary additive candidates. Therefore, the Pareto analysis can serve as a basis for selecting essential oil fractions for large-scale bio-additive production.

The molecular structure of different essential oils strongly influences their effects as biodiesel additives. For instance, monoterpenes such as limonene and α-pinene, which are composed of nonpolar hydrocarbon chains, primarily enhance cetane number and improve ignition quality due to their high volatility and ability to shorten ignition delay. In contrast, phenolic compounds such as eugenol exhibit strong antioxidant properties, owing to the presence of hydroxyl (-OH) groups attached to an aromatic ring. This structural feature enables them to donate hydrogen atoms and inhibit oxidative degradation, thereby improving biodiesel storage stability and reducing deposit formation in engines. Oxygenated fractions like rhodinol also enhance combustion by introducing polarity into the fuel matrix, which promotes better mixing with diesel and reduces particulate emissions.

Despite these promising characteristics, several obstacles remain in the application of essential oil-derived additives. The large-scale availability of bio-based precursors remains restricted, thereby limiting the consistent production of bio-additives. Many candidate compounds, including oxygenated molecules and terpenes, exhibit high volatility, which complicates their formulation and storage. To date, the majority of investigations have been conducted at laboratory or pilot scales, with translation to commercial applications constrained by supply chain limitations, process scalability, and cost efficiency. Moreover, the absence of standardized international protocols for the evaluation and certification of bio-additives poses an additional obstacle. Finally, the stringent requirements of existing fuel quality regulations (e.g., ASTM and EN standards) further exacerbate entry barriers for the commercialization of novel bio-additives.

Addressing these issues requires further research into stabilization techniques, advanced blending strategies, and techno-economic feasibility assessments. Future work should also explore biorefinery approaches that integrate essential oil extraction with other value-added processes, thereby reducing costs and supporting circular bioeconomy principles.

The comparison of the advantages and disadvantages of essential oil-based additives and conventional industrial synthetic additives in terms of cost, environmental sustainability, and performance is presented in Table 4.

Table 3. Comparison of various fractions on diesel engine performance

Code of Fraction	Fraction	Bio-additive Potential	Frequency of Mentions	Percentage of Total Mentions	Location of Study	Reference
EUG	Eugenol	Testing of eugenol essential oil as an additive in diesel engines has shown significant results, particularly in the reduction of NO_x emissions. Furthermore, the development of this additive into an integrated kinetic model enables more accurate and efficient process optimization at the industrial scale. Compared to limonene, eugenol is more effective in reducing CO emissions due to its high oxygen content and low bond energy, which also contributes to improved fuel consumption efficiency. In	7	18%	China, Brazil, Indonesia, India	[29, 35, 37, 38, 69, 71, 83]

		terms of stability, eugenol has proven to be superior to TBHQ in enhancing the oxidative stability of biodiesel, as well as reducing water content and improving oxidative resistance, thereby extending the storage life of biodiesel. Eugenol also protects metal components from corrosion, positively impacting the durability of engine parts and fuel pipelines. Other physical effects include a reduction in viscosity by up to 10%, which enhances fuel flow, and a decrease in flash point by up to 30%, making the fuel more readily combustible. Due to its high viscosity, eugenol becomes trapped in fuel droplets and rapidly evaporates upon heating, causing micro-explosions that facilitate better atomization.				
RHO	Rhodinol	The rhodinol fraction shows significant potential as a bio-additive for biodiesel. Several benefits have been identified, including improved combustion efficiency, reduced water content, lower particulate emissions, and enhanced fuel durability and cetane number. In addition, rhodinol has been found to prevent filter clogging and improve the storage stability of biodiesel. Its application may also reduce fuel consumption and smoke emissions while helping to maintain the cleanliness and safety of the fuel system.	4	11%	Indonesia, Brazil, India, Indonesia	[15, 37, 40, 41]
LIM	Limonene	Limonene essential oil additives provide several key benefits in enhancing biodiesel quality. They lower the flash point and viscosity, improving fuel flow, and help reduce fuel consumption and emissions of CO and HC. Although they may increase NO_x emissions and specific fuel consumption, limonene supports better combustion efficiency and shows good thermodynamic compatibility. It is easily miscible, derived from renewable sources, and is both environmentally friendly and cost-effective. Limonene also enhances hydrocarbon stability and serves as a non-toxic, cheaper alternative to synthetic pour point depressants. Its high reactivity at low temperatures and natural anti-crystallization properties further improve biodiesel performance even at low concentrations as little as 1%.	23	61%	China, Indonesia, Arab, Indonesia, Spain, South Africa, Pakistan, Brazil, Australia, United States, India, Serbia.	[29, 48, 56, 62, 63, 66, 68, 70, 72-86]
ALP	Alpha-pinene	The essential oil α-pinene primarily functions as an oxygenated additive that contributes to improving combustion efficiency in fuel systems. Additionally, this compound enhances thermal performance, thereby supporting the stability of biodiesel under various temperature and pressure conditions. These characteristics make α-pinene an environmentally friendly component suitable for use in modern biodiesel formulations, including applications in the automotive and aviation sectors. This essential oil also shows potential in improving combustion performance, is renewable, and supports efficient chemical conversion processes, ultimately enabling cost optimization to remain commercially competitive. Furthermore, the addition of α-pinene as an additive can accelerate soot oxidation rates, resulting in cleaner combustion while maintaining compatibility with diesel engines due to its minimal impact on the cetane number.	4	11%	Indonesia, France, China, Serbia	[63, 65, 67, 85]

Table 4. The comparison of the advantages and disadvantages of essential oil-based additives and conventional industrial synthetic additives

Criteria	Essential Oil-Based Additives	Synthetic Industrial Additives
Cost	Relatively low can be produced from locally sourced plants (e.g., citronella), does not compete with food crops, and involves simple processing (low-cost use at ~1 ppm) [87].	Variable and potentially high feedstocks, such as nitric acid, are volatile; production costs and corrosion risks contribute to overall operational expenses [88].
Environmental Improvement	Renewable, biodegradable, non-toxic, capable of reducing vehicle smoke emissions, and supports CO_2 reduction and climate change mitigation [15, 87].	Typically, petroleum-derived, less biodegradable, with the potential to increase NO_x emissions if not paired with appropriate mitigation measures [88].
Cetane Number Improvement	Significant improvements reported, e.g., +25.9% in B30 with 1.5% citronella oil [89].	Provides a more moderate increase of approximately +3–8 points at concentrations of 0.05–0.4% m/m (2-EHN) [88].
Thermal Efficiency and Consumption	Several studies report enhanced engine performance, reduced vibration and noise, and increased power and torque [89].	Reduces BSFC by 5.3–7.3% and increases BTE by 3.3–4.7% at concentrations of 1–1.5% (BMF30 blend + 2-EHN) [88].
Emissions (NO_x)	NO_x reduction of up to 21.6% at 2000 rpm with 1.5 % citronella oil in B30 [89].	NO_x reduction of 9.4–17.5% at concentrations of 1–1.5% 2-EHN [88].
Operational Impact / Stability	Minimal corrosion risk, easy to use, biodegradable, and compatible with conventional engines [15, 87].	Risk of corrosion (e.g., seals; up to 12% increase in maintenance costs) and requires strict control of blending processes [88].

4. CONCLUSIONS

The rising demand for fuel in Indonesia, coupled with a decline in domestic diesel production, underscores the urgent need for environmentally sustainable alternatives such as biodiesel. This review highlights that essential oil-derived bio-additives, including clove oil, citronella oil, rhodinol, α-pinene, camphor, and limonene, can significantly enhance biodiesel performance by improving combustion efficiency, reducing exhaust emissions, and lowering maintenance requirements. To fully realize these benefits, policy initiatives that promote the integrated development of Indonesia's domestic essential oil industry and biodiesel sector are recommended, thereby strengthening national energy security, stimulating rural economic development, and supporting long-term environmental sustainability.

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