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MIXTURES OF ESSENTIAL OILS AND ALCOHOLS WITH DIESEL OIL USE AND IMPACT ON ENGINE PERFORMANCE AND POLLUTANT EMISSIONS. A REVIEW

Recent discoveries in the field of using blends of essential oil, alcohol and diesel in diesel engines open new perspectives for optimizing performance and reducing pollutant emissions. This work focuses on evaluating the combined effects of these blends on engine performance parameters and pollutant emission profiles, providing insight into the benefits and challenges associated with their use. The review of the literature and empirical data highlights the promising potential of steam extraction of biofuels, as well as the efficiency and cost-effectiveness of transesterification of oils in the production of biofuels. Also, mixing distilled alcohol with essential oil and diesel fuel is revealed as a viable strategy for improving the combustion characteristics and performance of the diesel engine. The results indicate a number of significant improvements in engine performance, including reduced specific fuel consumption, increased power and torque, as well as improved thermal efficiency and reduced smoke emissions. However, it is important to note that certain mixtures may lead to a slight increase in nitrogen oxide (NO_x) emissions, which requires further research to optimize the composition of the mixtures and minimize the environmental impact. Overall, this study highlights the promising potential of using blends of essential oil, alcohol and diesel in diesel engines, highlighting the importance of continued research in the field to develop sustainable and energy efficient solutions for road transport.

Keywords*:* essential oils, alcohols, diesel engine, engine performance, pollutant emissions.

INTRODUCTION

In the past three decades, road transport has undergone a significant transformation marked by a continual rise in the number of motor vehicles and an expansion of the road network (Mo, Wang, Zhang, & Zhuang, 2017), (Hassan, Amlan, Alias, Ab-Kadir, & Sukor, 2022; Mulholland & Feyen, 2021; Pažout, Brughmans, & de Soto, 2023; Schubert, Sys, Vanelslander, & Roumboutsos, 2022; Wu, Yu, & Zhang, 2023). This expansion has been accompanied by advances in vehicle technology and road safety, including the introduction of driver assistance systems and stricter safety regulations. However, the rapid growth in road traffic has also brought about environmental challenges, such as greenhouse gas emissions, noise pollution, and air pollution (Tasma, D. et al., 2011).

Looking ahead, the replacement of diesel fuel has become a pressing concern due to the adverse environmental impacts associated with fossil fuels and their limited resources. Substantial progress has been made in developing alternative fuels and enhancing electric and hybrid vehicle technologies. Nevertheless, challenges persist, particularly concerning the cost, availability, and infrastructure necessary for the widespread adoption of these technologies. Internal combustion engines, still widely used in vehicles today, present their own set of challenges. They emit greenhouse gases and pollutants affecting both human health and the environment. The ongoing energy crisis has made researchers turn their attention even more to oils as a potential source of renewable fuel. Oils derived from renewable sources, offer an alternative to finite fossil fuels. This paper delves into the utilization of pure essential oils or blends with diesel oil at varying proportions in diesel engine to investigate performance characteristics and pollutant emissions. Technologies of biofuels production are also revised. Biofuels, including essential oils, can be directly used in engines with minimal or no major modifications, contingent on the method of introduction into the fuel system (Chivu et al., 2023). The utilization of blends comprising alcohols, essential oils, and diesel fuel in engines stands as a promising avenue in contemporary research on alternative fuels. The study and development of these biofuel mixtures involve intricate analyses of their chemical properties, combustion efficiency, emission characteristics, and overall environmental footprint, further enriching the academic discourse on alternative energy sources.

In general, biofuels can be used directly in an engine without making constructive changes, or major constructive changes, this depends a lot on the method by which the biofuel is introduced into the fuel system.

PURPOSE AND OBJECTIVES OF THE STUDY

This study focuses on the overall objective of synthesizing existing literature and empirical data to provide an assessment of the use of essential oil and alcohol blends in diesel fuel, with an emphasis on their collective impact on both engine performance parameters and pollutant emission profiles. By elucidating the precise objectives of the study, including identifying key research questions and delineating methodological approaches, this study aims to provide a roadmap for further analysis and discussion. In addition, it highlights the importance of the study in the wider context of alternative fuel use and its potential implications for mitigating environmental impact and increasing engine efficiency without major modifications. By exploring these aspects, the aim is not only to understand the phenomenon in detail, but also to outline a robust framework to guide future research and technological development in the field of alternative fuel use and engine performance.

BIOFUEL PRODUCTION

Distillation (Mangalagiu, I., 2011), an essential separation technique in chemical engineering, involves the thermal separation of a liquid mixture into its constituent components by exploiting differences in their respective boiling points. This process entails subjecting the mixture to heat, causing it to vaporize; subsequently, the resulting vapours are then collected and condensed back into a liquid state for further processing (Figure 2).

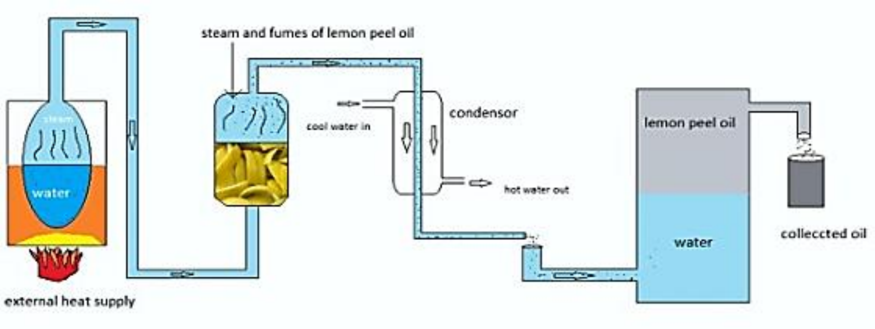

Figure 2– Distillation of lemon oil (Dhana Raju et al., 2022a).

Distillation constitutes a pivotal method in chemical engineering for the separation of liquid mixtures based on the disparities in their boiling points. In this process, components with lower boiling temperature volatilize more rapidly and are collected in advance, whereas those with higher boiling points remain in their liquid state and are subsequently gathered. Within the realm of biofuel production, particularly in the context of bioethanol extraction, distillation assumes a critical role in securing high-purity final products. Leveraging subtle differentials in boiling points among mixture constituents, distillation facilitates their efficacious segregation. Bioethanol, a prominent biofuel variant, is typically derived through fermentation processes, with distillation serving as the pivotal phase that transmutes it from a composite mixture into pristine ethanol fuel, primed for utilization in internal combustion engines. The utilization of distillation in bioethanol production offers salient advantages. Firstly, it embodies an environmentally benign approach, purging deleterious substances and contaminants from the mixture, thereby rendering the resultant biofuel cleaner and more ecologically sustainable. Moreover, distillation engenders the production of a high-calibre end product characterized by diminished impurity levels and consistent physicochemical attributes, rendering it apt for integration into contemporary engine systems. Nonetheless, ongoing research endeavours in the realm of distillation are directed toward enhancing process efficiency and curbing production outlays. Novel methodologies and technological innovations are continually being pioneered to render distillation more sustainable and cost-effective, thereby fostering the viability and accessibility of biofuels as a substitute for conventional fossil fuels. Consequently, distillation remains poised at the vanguard of innovation within the biofuel domain, charting a trajectory toward a cleaner and more sustainable energy landscape.

Bioethanol (Inderwildi & King, 2009) is a renewable fuel obtained by fermenting plant biomass. The bioethanol distillation process involves the following steps:

Fermentation (Partovinia, Salimi koochi, Talaeian, & Rasooly Garmaroody, 2022; Shen & Li, 2023; Šokarda Slavić et al., 2023) initiates this intricate journey, wherein plant biomass or starchy grains undergo a transformative process catalysed by microorganisms like yeast. This biological alchemy converts sugars into ethyl alcohol (ethanol), laying the foundation for subsequent stages;

Primary Distillation: Post-fermentation, the resultant mixture undergoes primary distillation, a fundamental step aimed at purging impurities such as water and non-alcoholic substances. Carried out within a still or a distillation column, this process yields a dilute ethyl alcohol solution;

Alcohol Concentration: The diluted ethyl alcohol solution then undergoes secondary distillation, a meticulous process where alcohol is concentrated. This phase entails the strategic evaporation of alcohol at precise temperatures, effectively separating water and other impurities and resulting in a higher alcohol concentration;

Dehydration (Zhu et al., 2016), (Silva et al., 2021) the final leg of this intricate journey involves dehydration, a critical step in obtaining pure bioethanol. This phase employs specific drying agents, including zeolites or reverse osmosis membranes, to meticulously eliminate any remaining traces of water and impurities;

Bioethanol utilization: Bioethanol obtained through this rigorous distillation process emerges as a versatile and eco-friendly resource. Its application as a motor vehicle fuel source serves a dual purpose: reducing greenhouse gas emissions while contributing to sustainable energy practices. The distillation process, with its ability to yield high-quality and pure bioethanol, paves the way for diverse applications, from automotive technology to renewable energy initiatives. In essence, the synergy between fermentation and distillation not only exemplifies the complexity of bioethanol production but also underscores the paramount importance of these processes. Through their integration, the scientific community continues to enhance the efficiency and sustainability of bioethanol production, offering a viable solution in the quest for cleaner energy alternatives.

Transesterification, as referenced in (Otera, 1993), involves the conversion of an ester into either another ester or an alcohol through its reaction with alcohol. Conversely, esterification, as explicated in (Araújo, Cardoso, Souza, Cardoso, & Pasa, 2021; Cannilla, Bonura, Costa, & Frusteri, 2018; Foukis et al., 2017; Rajabi & Luque, 2020; Wang et al., 2018; Zhang et al., 2023) entails the chemical reaction between an organic acid and an alcohol, resulting in the formation of an ester and water. Typically, acids or bases serve as catalysts in these reactions. In the esterification process, the hydroxyl groups (-OH) present in both the organic acid and alcohol are eliminated, leading to the formation of an ester bond (-COO-) between the respective acid and alcohol residues. This exothermic reaction is reversible through hydrolysis. The versatility of esterification is evident in its application across diverse domains, including the production of aromatic esters, essential oils, and plasticizers. Furthermore, esterification plays a crucial role in the production of biodiesel, as delineated in (Alfredo Quevedo-Amador, Elizabeth Reynel-Avila, Ileana Mendoza-Castillo, Badawi, & Bonilla-Petriciolet, 2022; Kingkam et al., 2022; Lee et al., 2022; Mahesha et al., 2022; Shrivastava et al., 2023). Biodiesel, a renewable biofuel, is generated through the transesterification of vegetable oils or animal fats. This involves combining the oil or fat with an alcohol (typically methanol) and a catalyst (e.g., sodium hydroxide) to yield fatty acid methyl esters and glycerol. The transesterification process replaces glycerol molecules with methanol in the fatty acids. Importantly, biodiesel derived from transesterification serves as a sustainable alternative to fossil fuels and can be seamlessly integrated into diesel engines without substantial modifications. Beyond the realm of biodiesel production, transesterification finds application in diverse sectors such as cosmetics production (Park & Kim, 2020) and other chemical synthesis processes. It is notably employed in organic synthesis within chemistry laboratories. In summary, both transesterification and esterification processes are integral to numerous industrial processes, contributing significantly to the synthesis of various products with applications ranging from biofuels to cosmetic formulations.

BLENDING BIOFUEL WITH REGULAR FUEL

This study delineates a strategy employed in the advancement of fuel properties through the blending of biofuels, as documented in references (Hoang et al., 2023; Martos, Doustdar, Zeraati-Rezaei, Herreros, & Tsolakis, 2023; Nagappan & Babu, 2023; Tsanaktsidis, Favvas, Tzilantonis, & Scaltsoyiannes, 2014) within the context of scientific discourse. The practice of blending, exemplified by the amalgamation of biodiesel with ethanol to formulate ethanol-diesel (Kharkwal, Kesharvani, Verma, Dwivedi, & Jain, 2023), represents an innovative approach aimed at enhancing the characteristics of extant fuels. This blending process is instrumental in ameliorating fuel quality by mitigating the flash point, enhancing fluidity at lower temperatures, and diminishing greenhouse gas emissions. The resultant ethanol-diesel blends exhibit the potential for seamless integration into existing diesel engines, obviating the necessity for substantial engine modifications. It is imperative to note, however, that ethanol, being an alcohol, is conventionally suited for utilization in spark ignition engines. Additionally, the strategic blending of ethanol with gasoline, as manifested in ethanol-gasoline formulations such as E10, E15, E85, etc. stands as another noteworthy practice. These blends, encompassing ethanol concentrations ranging from 10% to 85% serve the dual purpose of diminishing reliance on fossil fuels and mitigating environmental impact. Beyond the realm of blending established biofuels, ongoing research endeavours are focused on the development of novel renewable fuels, including those derived from algae or genetically modified bacteria-produced oils. The text underscores the emergence of essential oils as a subject of research interest, wherein their admixture with diesel, as expounded in references (Gad, He, El-Shafay, & El-Seesy, 2021; Gowthaman & Thangavel, 2022; R. Kumar, Kumar, Kumar, & Goga, 2023a; Sekar, Venkadesan, & Panithasan, 2022; Singh, Singh, & Kumar, 2020; Y. , Earnest, Raghavan, George Roy, & Koshy, 2022) manifests combustion behaviour akin to traditional diesel. The performance characteristics of such blends are contingent upon the specific composition, thereby offering a versatile approach to tailoring fuel properties, concomitant with a reduction in polluting emissions.

ANALYSIS OF LITERATURE DATA AND FORMULATION OF THE PROBLEM

This section initiates a methodical literature review relevant to the integration of essential oil and alcohol blends with diesel oil, scrutinizing their diverse effects on metrics related to engine performance and emissions of pollutants. Employing a rigorous synthesis of both empirical observations and theoretical frameworks, this chapter aspires to elucidate the fundamental mechanisms governing the interplay between these alternative fuel compositions and internal combustion engine configurations. Through the amalgamation of a comprehensive survey of existing research, this chapter establishes the foundational framework for subsequent analyses and deliberations, delineating the breadth and significance of the surveyed literature while identifying critical gaps in knowledge and articulating pertinent avenues for further investigation.

The impact of the mixtures on the performance and combustion characteristics

The paper (R. Kumar, Kumar, Kumar, & Goga, 2023b) investigates the performance characteristics of a compression ignition (C.I.) engine fuelled with distinct blends of eucalyptus biodiesel and conventional diesel fuel. The study focuses on the brake-specific fuel consumption (BSFC) and brake thermal efficiency (BTE) parameters across a range of loads (20 W to 100 W) for samples denoted as A and B. The results elucidate the variation in BSFC and BTE with respect to load for different biodiesel blends (Eu10-10% eucalyptus oil, 90% diesel to Eu100- 100% eucalyptus oil). The findings suggest a discernible impact of load on fuel consumption across all biodiesel blends, with a consistent increase in BSFC as load decreases. Notably, the BSFC for Eu100A (100% eucalyptus oil sample A) and Eu100B (100% eucalyptus oil sample B) exhibits a reduction of 8.18% and 4.05%, respectively, compared to diesel fuel at full load conditions. This implies a favourable performance of Eu100A and Eu100B in terms of fuel efficiency. Furthermore, this research reveals an inverse relationship between BTE and BSFC, indicating that the brake thermal efficiency of the C.I. engine is influenced by the fuel consumption rate. The BTE for Eu10-10% eucalyptus oil, 90% diesel, Eu30-30% eucalyptus oil, 70% diesel, Eu50-50% eucalyptus oil, 50% diesel, and Eu70-70% eucalyptus oil, 30% diesel in both samples (A and B) is observed to be lower than diesel fuel, suggesting a potential trade-off between fuel efficiency and biodiesel content. However, Eu100A and Eu100B exhibit higher BTE compared to diesel fuel, with an impressive 9.63% and 4.88% increase at full load conditions. This notable improvement in BTE is attributed to the effective vaporization and blend preparation of eucalyptus oil, resulting in an enhanced heat release rate. The comparison between sample A and sample B suggests that, in terms of engine performance, sample A, particularly Eu100A, outperforms sample B. The study contributes valuable insights into the impact of biodiesel blends on the fuel consumption and efficiency of C.I. engines, emphasizing the potential benefits of higher biodiesel content, specifically in the case of Eu100A and Eu100B. Other studies on the use of eucalyptus oil as fuel have shown similar trends in terms of engine performance (Liazid, Naima, Tazerout, Tarabet, & Bousbaa, 2019), (Suryawanshi & Ladekar, 2017), (Naima et al., 2022), (Kommana, Naik Banoth, & Radha Kadavakollu, 2015). Another research (Devan & Mahalakshmi, 2009a) investigates the performance characteristics of a methyl ester (Me) and eucalyptus oil (Eu) blend in comparison to other biodiesel blends and standard diesel fuel. The study focuses on BSEC, BTE, cylinder pressure variations, and heat release rates across different load conditions. The Me50–Eu50 blend stands out by exhibiting lower BSEC compared to other blends and methyl ester. This is attributed to improved combustion and increased energy content, as evidenced in Figure 3. The enhanced BTE observed in the Me50–Eu50 blend, as depicted in Figure 3, is associated with reduced viscosity leading to improved atomization, fuel vaporization, and combustion. The blend's closer ignition delay time to diesel contributes to faster burning of eucalyptus oil, further enhancing thermal efficiency, a phenomenon elucidated in subsequent heat release curves. As the concentration of eucalyptus oil increases in the mixture, the ignition delay increases and the release of heat is greater (Devan & Mahalakshmi, 2009b). The efficiency of Me50–Eu50 at full load is reported as 31.42%. Examining cylinder pressure variations, the high eucalyptus oil blends generate higher cylinder pressure compared to standard diesel, owing to the lower cetane number of eucalyptus in the blend. The addition of an ignition improver (methyl ester of paradise oil) decreases peak pressure and ignition delay, aligning the cylinder pressure trend of the 50% blend closer to that of standard diesel fuel. Analysing the heat release rates, Figure 3 reveals that the Me50–Eu50 blend closely resembles the heat release pattern of standard diesel, while other blends deviate more significantly. The concentration of eucalyptus oil in the blend correlates with an increased ignition delay and higher heat release, attributed to the lower cetane number of high eucalyptus oil blends. Notably, cylinder peak pressure shows a nuanced response to the proportion of eucalyptus oil at different loads, with a slight increase at medium and high loads and a slight decrease at low load. The deviation in heat release patterns and the observed trends in cylinder pressure underscore the intricate interplay of eucalyptus oil concentration, combustion characteristics, and load conditions.

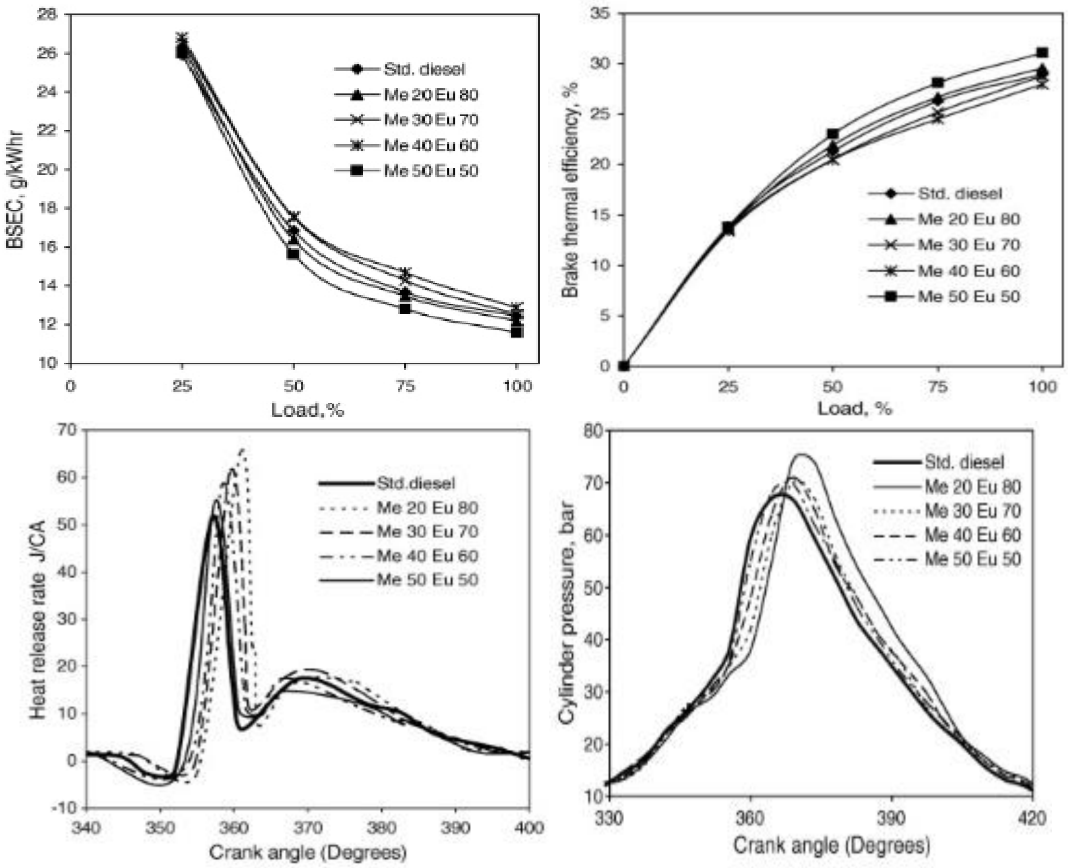

Figure 3 – Engine performance with fuel mixtures (Devan & Mahalakshmi, 2009a).

Senthur et al. (Senthur, Ravikumar, & John, 2014) conducted a rigorous investigation aimed at assessing the viability of eucalyptus biodiesel as a prospective alternative fuel in diesel engines. Employing the transesterification process, the researchers derived biodiesel from eucalyptus oil, subsequently subjecting the resultant blend, in conjunction with diesel, to empirical scrutiny utilizing a single-cylinder direct injection diesel engine. The empirical findings indicated that, across all load conditions, BSFC and BTE of the eucalyptus biodiesel blend surpassed those of conventional diesel. It is noteworthy, however, that despite the heightened BSFC and marginally reduced BTE, the physicochemical attributes of eucalyptus biodiesel closely paralleled those of diesel, affirming its amenability as a plausible alternative fuel. The discerned increase in BSFC with escalating biodiesel content within the fuel blend was attributed to a concomitant reduction in the heating value of the amalgamated fuel. Furthermore, the observed minor reduction in BTE for biodiesel blends compared to diesel was predominantly ascribed to the lower calorific value inherent in the composite mixture. This comprehensive evaluation underscores the utility of eucalyptus biodiesel as a viable alternative fuel, substantiated by its congruence with diesel in physicochemical properties, despite the nuanced variations in BSFC and BTE.

The essential oil from the orange peel was studied by M. A. Asokan et al (Asokan et al., 2021). They investigated BTE and BSFC of blends comprising Orange Peel Oil (OPO) and diesel across various brake power levels. The study reveals that, particularly at full load, the BTE of OPO/diesel blends aligns with that of diesel oil, a phenomenon attributed to enhanced atomization and mixing within the combustion chamber. The reported BTE values for B20 (20% OPO + 80% Diesel oil), B30 (30% OPO + 70% Diesel oil), B40 (40% OPO + 60% Diesel oil), B100 (100% OPO), and D100 (100% Diesel oil) are 34.77%, 34.98%, 32.48%, 28.63%, and 36.68%, respectively. Notably, BTE for B20 and B30 closely approximates that of diesel oil, exhibiting a marginal reduction of 5.2% and 4.6%, respectively, which may be ascribed to the improved combustion of OPO. Moreover, the presence of substantial oxygen content in OPO is posited as a contributing factor that enhances the combustion process. Conversely, B100 demonstrates a lower BTE compared to diesel, attributed to the lower heating value of OPO. The observed proximity of B20 and B30 to diesel, despite a slight reduction in BTE, underscores their promise as viable blends. The combustion efficiency gains attributed to the improved burning of OPO and the oxygen content in OPO are pivotal in mitigating the BTE reduction relative to diesel. The investigation extends to the BSFC, where it is discerned that, across all loads, BSFC for OPO blends exceeds that of diesel due to the lower calorific value and higher density of OPO. At full load, the reported BSFC values for B20, B30, B40, B100, and D100 are 0.25, 0.25, 0.27, 0.31, and 0.24 kg/kWh, respectively. Remarkably, B20 and B30 exhibit lower BSFC compared to other OPO blends, albeit slightly higher than diesel. However, B40 and B100 manifest higher BSFC values than diesel oil, primarily attributed to the elevated viscosity and density of biodiesel. Another research about OPO for diesel engine was made by A. M. Kumar et al (A. M. Kumar, Kannan, & Nataraj, 2020) scientific investigation depicted in the article delves into the alterations in BTE and BSFC concerning Brake Power (BP) for various fuels, including diesel, Orange Peel Oil Methyl Ester (OOME), and nanoemulsions of OOME with titanium dioxide at concentrations of 50% (OOME-T50) and 100% (OOME-T100). The comprehensive portrayal in Figure 4 elucidates a noteworthy augmentation in BTE with increasing BP across all tested fuels. Notably, the BTE for conventional diesel consistently surpasses that of all experimental fuels across different BP levels. The peak BTE values were observed at 31.5% for diesel, 26.5% for pure OOME, 28.1% for OOME-T50, and 29.5% for OOME-T100 at the maximum BP. Remarkably, both nanoemulsions, OOME-T50 and OOME-T100, exhibit higher BTE in comparison to pure OOME across all BP levels. The heightened BTE in nanoemulsion fuels is attributed to the occurrence of microdetonation because of oxygen in the fuel blends and the catalytic by-products of titanium dioxide, contributing to enhanced combustion. The presence of nanoparticles within the emulsion offers a large surface-to-volume ratio, facilitating rapid vaporization and improved atomization of the fuel. Additionally, oxygen molecules in the nanoemulsion of orange peel oil biodiesel promote swift evaporation and thorough mixing with air, enriching the combustion process and resulting in higher thermal efficiency. The BSFC results, as illustrated in Figure 4, reveal that at maximum BP, diesel exhibits the lowest BSFC at 0.237 kg/kWh, whereas pure OOME records a higher value at 0.256 kg/kWh. The rationale behind the increased BSFC for OOME is attributed to its lower calorific value compared to diesel. Notably, nanoemulsion fuels, particularly OOME-T50 and OOME-T100, demonstrate lower BSFC compared to pure OOME, suggesting an improvement in fuel efficiency. The presence of oxygen molecules in the nanoemulsion fuels is identified as a contributing factor, reducing droplet size during secondary atomization and increasing the rate of fuel evaporation. Citrus peel oil has been investigated as a fuel by other researchers.

V. Dhana Rajuet al (Dhana Raju et al., 2022b) used mixtures of essential oils from LPO (lemon peel oil) in different proportions to which he also added DEE (diethyl ether). They report that the variation of brake thermal efficiency (BTE) with engine load is presented, highlighting that BTE is improved by 3.7% for the LPO20 DEE10 blend (20% LPO, 70% diesel, and 10% diethyl ether) compared to LPO20 (20% LPO and 70% diesel oil) at full load. Although lemon peel oil has a slightly lower energy content than diesel oil, it exhibits superior BTE due to the enhanced combustion phenomenon, influenced by its reduced viscosity and lower boiling point.

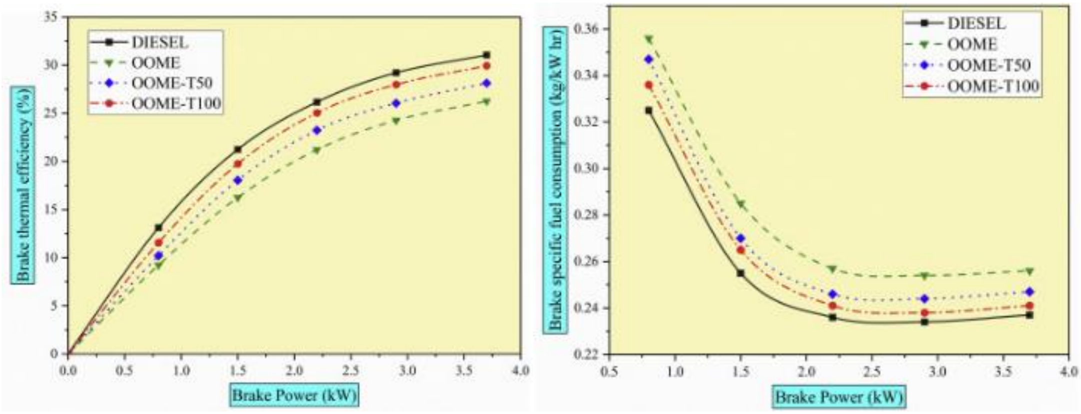

Figure 4 – Engine performance with nano-emulsion biodiesel(A. M. Kumar et al., 2020).

The BSFC values at maximum load for diesel, LPO10 (10% LPO and 90% diesel), LPO20 (20% LPO and 80% diesel), LPO30 (30% LPO oil and 70% diesel), LPO20 DEE5 (20% LPO, 75% diesel, and 5% diethyl ether), and LPO20 DEE10 are, respectively, 0.24 kg/kWh, 0.28 kg/kWh, 0.27 kg/kWh, 0.29 kg/kWh, 0.26 kg/kWh, and 0.25 kg/kWh. The addition of 10% DEE led to a reduction in BSFC at maximum load compared to the other blends. Additionally, the net energy of lemon peel oil is competitive with diesel, and its inherent O_2 content supports the enhanced ignition process. BSEC, an effective parameter in the comparative assessment of fuel utilization, decreases with the increase in indicated mean effective pressure (IMEP). The BSEC values at maximum load for diesel, LPO10, LPO20, LPO30, LPO20 DEE5, and LPO20 DEE10 are, respectively, 10.2 MJ/kWh, 11.88 MJ/kWh, 11.44 MJ/kWh, 12.26 MJ/kWh, 10.88 MJ/kWh, and 10.49 MJ/kWh. Although the lower heating value of lemon peel oil indicates a slight increase in BSEC compared to diesel, the addition of 10% DEE resulted in a reduction in BSEC at maximum load. The cylinder pressure significantly increases for the investigated fuels, and the addition of LPO to diesel markedly raises the cylinder pressure and ignition delay period. This is due to the reduced viscosity of lemon peel oil, which supports fuel evaporation and atomization, leading to improved combustion. The cylinder pressure values for diesel, LPO10, LPO20, LPO30, LPO20 DEE5, and LPO20 DEE10 are, respectively, 68.5, 66.6, 66.8, 65, 67.4, and 67.9 bar at maximum load, with higher pressures observed for diesel and LPO20 DEE10. The total heat release rate (HRR) is significantly affected by the fuel's energy content and ignition nature. The authors reported a similar trend in HRR for all fuel blends, with LPO20 DEE10 highlighting a higher HRR at maximum load. The HRR values for diesel, LPO10, LPO20, LPO30, LPO20 DEE5, and LPO20 DEE10 are, respectively, 75.51 J/°CA, 71.31 J/°CA, 72.68 J/°CA, 70.84 J/°CA, 73.05 J/°CA, and 74.84 J/°CA. These findings underscore the positive contribution of adding citrus peel oil and DEE to the combustion dynamics and engine efficiency, opening significant prospects for the use of these blends in the context of alternative fuels.

The use of diesel in combination with alcohols, known as "diesel-alcohol," is a growing strategy to optimize engine performance and reduce environmental impact. This blend may include alcohols such as ethanol or methanol, adding a renewable and more environmentally friendly component to traditional diesel fuel. Diesel-alcohol has the potential to improve combustion characteristics, reducing particulate and greenhouse gas emissions. It can also contribute to diversifying energy sources and reducing dependence on fossil fuels in the transportation sector. However, ongoing research is needed to assess the efficiency, safety, and long-term impact of this technology in the context of evolving energy sustainability. W. Zhao et al (Zhao, Yan, Gao, Lee, & Li, 2022), investigated the in-cylinder pressure and HRR for various types of fuels tested at different engine loads, focusing on blends of diesel with higher percent of alcohols. They report that both peak in-cylinder pressure and HRR increase with higher engine loads, attributed to increased fuel injection for greater power output, leading to more heat released during the combustion process and resulting in higher peak in-cylinder pressure and HRR values. It is noteworthy that diesel/higher alcohol blends exhibit delayed combustion phases compared to diesel, as evidenced by the in-cylinder pressure and HRR curves shifting towards larger crank angles. The investigated alcohols have lower cetane numbers, higher self-ignition temperatures, and greater latent heat of vaporization compared to diesel. These properties contribute to a weaker ignition property and longer ignition delays, despite the higher oxygen content of the blends. These fuel characteristics result in delayed combustion phases for diesel/higher alcohol blends under the test conditions. Blends with different alcohols exhibit varied combustion phases due to differing ignition delays. All diesel/alcohol blends show longer ignition delays compared to diesel. At higher engine loads, the elevated in-cylinder temperatures lead to shorter ignition delays for all tested fuels, and the differences in ignition delays among the fuels decrease. Overall, the study highlights the specific contributions of alcohols and engine load to combustion dynamics, opening interesting perspectives for the use of these blends as alternative fuels.

The impact of mixtures on pollutant emissions

Investigating the pollutant emissions of fuels is crucial in the context of global concerns regarding the environment and air quality. Fuels used in internal combustion engines are a significant source of pollutant emissions, such as CO, NO_x, HC, and fine particles. These substances can have a substantial impact on air quality, negatively affecting human health and ecosystems. Greenhouse gas emissions from burning fossil fuels are a major factor in climate change. Investigating pollutant emissions helps deepen the understanding of the impact of different types of fuels on global warming and climate change. Research on pollutant emissions encourages the development of cleaner and more sustainable fuels. Identifying and promoting alternatives to fossil fuels, such as biofuels or renewable energy sources, is essential for reducing carbon footprint and minimizing the negative impact on the environment. The findings of research on pollutant emissions contribute to the development of regulations and emission standards for industry and transportation. These regulations promote innovation and encourage the adoption of cleaner technologies. Chemicals emitted into the atmosphere can have harmful effects on human health, causing respiratory, cardiovascular, and other health issues. Investigating pollutant emissions provides vital information for assessing risks and developing strategies to protect public health. In the context of increasing social awareness and a focus on corporate responsibility, companies are increasingly concerned about the ecological impact of their activities. Studies on pollutant emissions enable them to adjust their practices to minimize their environmental impact.

The HSU (Hartridge Smoke Unit) is a measurement unit used to quantify the density of smoke emitted from an engine. In the context mentioned, a lower value of HSU indicates that the smoke is cleaner or more transparent. The decrease in HSU values is attributed to the use of oxygenated blends in the fuel. Oxygenated blends refer to fuel mixtures that contain a certain percentage of oxygen-containing compounds, such as ethanol or other biofuels. These blends are known for their potential to improve combustion efficiency and reduce emissions. The reduction in smoke emission (R. Kumar et al., 2023b), as indicated by the decrease in HSU values, highlights the positive impact of oxygenated blends on the environmental performance of the engine. Specifically, the researchers report a significant reduction in smoke emission of about 66% and 64.4% for Eu10A and Eu10B blends, respectively, under higher load conditions. This substantial decrease in smoke emission underscores the effectiveness of incorporating oxygenated blends into the fuel composition.

PK Devan et al (Devan & Mahalakshmi, 2009a) present the experimental data clearly and provide relevant interpretations of the results. A notable aspect of the study is the investigation of NO_x emissions (Figure 5) in the case of Me–Eu (methyl ester-eucalyptus oil) blends. The authors report an increase in NO_x emissions, possibly due to the presence of oxygen in both components of the blends. This observation aligns with previous research indicating that oxygenated blends can lead to an increase in NO_x emissions. The authors explain this trend by complete combustion, resulting in higher combustion temperatures that favour NO_x formation. Additionally, the decrease in cetane number at higher proportions of eucalyptus contributes to increased NO_x emissions, as a lower cetane number leads to ignition delay and rapid heat release at the beginning of combustion. Interestingly, NO_x emissions for blends with higher eucalyptus percentages are higher than those for standard diesel, especially for the Me20–Eu80 blend, where emissions are 8% higher. However, it is observed that for the Me50–Eu50 blend, the increase is smaller, approximately 2.7%. Regarding HC emissions (Figure 5), an increase is highlighted at lower loads for blends with a higher eucalyptus content, but this level is lower than that of diesel. At higher loads, standard diesel exhibits the highest HC emissions, while Me–Eu blends, especially Me50–Eu50, show a significant reduction of 34%. CO emissions (Figure 5) show an interesting trend, with significant decreases at higher loads for Me–Eu blends compared to standard diesel. This reduction is explained by the oxygen enrichment resulting from the addition of eucalyptus oil and biodiesel, promoting further oxidation of CO during the engine exhaust process. There is a 37% reduction in CO emissions for the Me50–Eu50 blend. The significant reduction in smoke emissions is a positive outcome of the oxygenated blends. Smoke is primarily produced in the diffusive combustion phase, and the oxygenated fuel blends contribute to the improvement of diffusive combustion for the Me50–Eu50 blend, resulting in a reduction of approximately 49% in smoke emissions (Figure 5) at full load.

The study (Senthur et al., 2014) indicates a significant reduction in CO emissions for biodiesel blends compared to diesel fuel. This decrease is attributed to more efficient and complete combustion facilitated by the increased number of oxygen atoms in biodiesel. Researchers emphasize CO emissions in engines, attributing them to incomplete combustion caused by a lack of oxygen atoms or insufficient time for effective burning. The study reveals a significant decrease in HC emissions in eucalyptus oil blends with diesel compared to pure diesel fuel. Remarkably, the E30 blend (30% eucalyptus oil and 70% diesel) records the lowest HC emissions, showing a 32.5% reduction compared to the E20 blend (20% eucalyptus oil and 80% diesel). The efficient and complete combustion in biodiesel fuel blends is credited for the decrease in HC emissions. Variations in NO_x emissions for diesel and eucalyptus oil blends are explored, indicating an increase in NO_x emissions with higher engine loads. The higher combustion temperature and increased oxygen concentration in eucalyptus oil contribute to higher NO_x emissions compared to diesel at all engine loads. This observation aligns with the understanding that NO_x formation is influenced by the combustion temperature and oxygen availability.

This research (Asokan et al., 2021) investigates the emissions of CO in Orange Peel Oil (OPO) and its blends with diesel under different loads. At full load, it is evident that CO emissions for OPO and its blends are lower than those for pure diesel. This reduction is attributed to the effective combustion of OPO blends compared to diesel. Specifically, at full load, the CO percentages for B20 20% OPO + 80% Diesel, B30 30% OPO + 70% Diesel, B40 40% OPO + 60% Diesel, B100 100% OPO, and D100 100% Diesel are recorded as 0.085%, 0.131%, 0.118%, 0.12%, and 0.165%, respectively. Notably, there is a significant reduction in CO emissions for B20 compared to other fuel blends and diesel. Furthermore, HC emissions at full load are generally higher for all tested fuels, but B20 and B100 exhibit lower HC emissions than diesel. The study reveals a substantial 30.66% reduction in HC emissions for B20 compared to pure diesel (D100). This reduction is attributed to the higher percentage of oxygen content in biodiesel, which enhances combustion efficiency. The article also touches upon the impact of oxygen content and combustion temperature on NO_x emissions, referencing previous studies. Orange peel oil, despite having a lower heating value and a cetane number similar to diesel, exhibits a higher ignition delay, leading to increased NO_x in the exhaust.

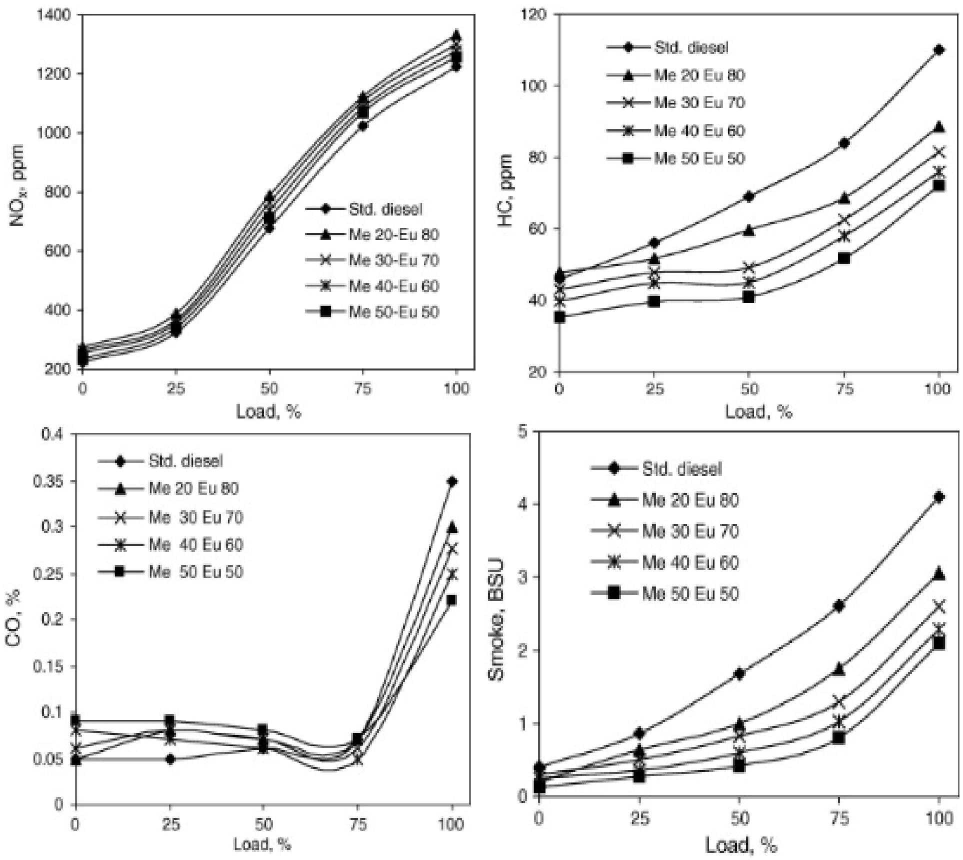

Figure 5 – Engine emissions for paradise oil methyl ester and eucalyptus oil blends (Devan & Mahalakshmi, 2009a).

The pollutant results of orange peel oil blends (A. M. Kumar et al., 2020) indicate a significant reduction in CO emissions (Figure 6) for OPO blends and nanoemulsions compared to diesel. This reduction is attributed to more efficient and complete combustion and richer oxygen conditions in the fuel blends, especially in the case of pure OPO. At maximum load, CO emissions for mineral diesel are higher than for all other tested fuels due to insufficient oxygen and the formation of a fuel-rich mixture inside the combustion chamber. Pure OPO blends show a notable reduction in CO emissions, and this reduction is further emphasized in the case of nanoemulsions, thanks to the presence of TiO_2 acting as an oxidation catalyst, providing more oxygen for combustion. HC emissions (Figure 6) generally increase with engine power, as more fuel is supplied to maintain a constant engine speed. However, OPO blends and nanoemulsions exhibit lower HC emissions compared to diesel, with an additional decrease in HC emissions observed for nanoemulsions. NO_x emissions (Figure 6) are influenced by the maximum cycle temperature and oxygen content. The study indicates an increase in NO_x emissions with increased engine power, with pure OPO blends showing higher NO_x emissions than other fuel types. Nevertheless, nanoemulsions with TiO_2 have a reduced effect on NO_x emissions, as the nanoparticles act as NO_x reducing agents, converting nitrogen oxides into nitrogen and oxygen. Smoke emissions Figure 6 are significantly reduced for OPO blends and nanoemulsions compared to diesel. This reduction is attributed to rapid evaporation and the formation of an improved air-fuel mixture, generated by microscopic explosions and secondary atomization of the fuel within the cylinder.

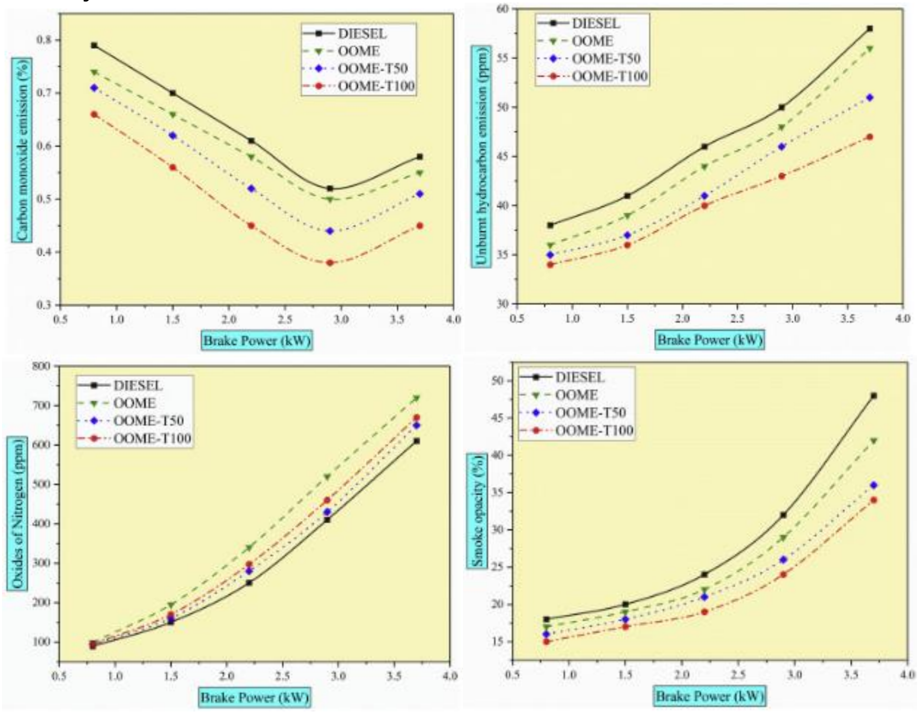

Figure 6 – Pollutant emissions of engine with nanoemulsion biodiesel (A. M. Kumar et al., 2020).

In another study (Dhana Raju et al., 2022b) LPO10, LPO20, LPO30, LPO20 DEE5, and LPO20 DEE10 biodiesel blends exhibit CO values of 0.048%, 0.058%, 0.059%, 0.062%, 0.053%, and 0.049%, respectively. Notably, LPO20 DEE10 demonstrates a 16.94% reduction in CO emissions compared to LPO20 at full load, attributed to its low viscosity and fine atomization promoting better ignition. HC emissions, indicative of partial or incomplete combustion, vary with engine load. LPO10, LPO20, LPO30, LPO20 DEE5, and LPO20 DEE10 biodiesel blends exhibit respective values of 30 ppm, 42 ppm, 41 ppm, 44 ppm, 36 ppm, and 31 ppm for carbon monoxide. LPO20 DEE10 consistently shows reduced hydrocarbon emissions at all load conditions, with a significant 24.4% reduction compared to LPO20 at peak load, attributed to the addition of oxygenated fuel. NO_x emissions, released due to increased oxygen availability and high cylinder temperature, are slightly lower for the LPO20 DEE10 blend compared to others. At peak load, LPO10, LPO20, LPO30, LPO20 DEE5, and LPO20 DEE10 biodiesel blends exhibit NOx values of 1618 ppm, 1930 ppm, 1967 ppm, 1878 ppm, 1812 ppm, and 1735 ppm. LPO20 DEE10 shows an 11.8% reduction in NO_x emissions compared to LPO20. Smoke opacity, representing the concentration of smoke and combustion efficiency, is influenced by the combustion process. LPO10, LPO20, LPO30, LPO20 DEE5, and LPO20 DEE10 biodiesel blends exhibit smoke values of 71%, 65%, 64%, 69%, 61%, and 56%, respectively, at maximum load. LPO20 DEE10 demonstrates a lower smoke opacity, with reductions of 21.1% and 12.5% compared to diesel and LPO20 at full load. The study suggests that higher oxygen availability in DEE contributes to improved ignition and reduced fuel-rich zones which lead to lower smoke opacity. Another study (Chen et al., 2022) shows that when alcohol fuel is added to diesel the results indicate an increase in CO emissions with the rise in engine load, attributed to a decrease in the air-fuel ratio at high loads, but also a significant reduction in these emissions through the addition of alcohols, especially methanol. The introduction of Al_2O_3 nanoparticles to diesel and ethanol blends demonstrates a substantial decrease in CO emissions, suggesting a catalytic effect of the nanoparticles. HC emissions increase with the engine load, and alcohol blends exhibit higher emissions, explained by the formation of a lean air-fuel mixture. The addition of Al_2O_3 nanoparticles reduces HC emissions, and this effect is more pronounced at higher nanoparticle concentrations, attributed to the catalytic effect and facilitation of complete combustion. NO_x emissions increase with the engine load, and alcohol blends show a slight reduction at low loads but an increase at high loads, suggesting a decrease in the cooling effect of alcohols in high-temperature environments. The addition of Al_2O_3 nanoparticles increases NO_x emissions, with a more significant increase at high nanoparticle concentrations, highlighting a combined effect of catalysis and oxygen absorption capacity.

According to other research (Datta & Mandal, 2016), NO_x emissions with higher engine loads for diesel, ethanol-blended diesel (DE), and methanol-blended diesel (DM) fuels. Interestingly, the addition of ethanol and methanol results in a reduction of NO_x emissions, with a more pronounced effect observed with ethanol blends. The lower air-fuel ratio and reduced combustion temperature with alcohol blending contribute to this decrease, emphasizing the potential of alcohol-diesel blends in mitigating NO_x emissions. Furthermore, the investigation examines specific CO_2 emissions, representing the amount of CO_2 formed during fuel combustion to produce unit power. It is noted that, despite the opposing influences of the low carbon-to-hydrogen ratio in alcohols and the oxygen content promoting better combustion, there is no significant variation in CO_2 emissions with alcohol blending. Smoke opacity, indicating dry soot emissions and a primary contributor to particulate matter formation, is studied. The results reveal that the use of pure diesel leads to the highest smoke and PM emissions, followed by lower emissions with DE5 and DM5 blends. Notably, the lowest emissions are observed with DE15 and DM15 blends. The reduction in smoke and PM emissions is attributed to improved combustion, decreased fuel-rich zones, and enhanced oxygen delivery in the alcohol-diesel blends.

LONG TERM USE OF BIOFUELS IN THE COMPRESSION IGNITION ENGINE

The long-term use of biofuels in diesel engines raises many questions and challenges, which require a detailed analysis and a deep understanding of the technical, economic and ecological implications. In this chapter, we propose to examine several aspects, exploring the advantages and limitations of the long-term use of biofuels in the diesel engine context, as well as their prospects for long-term sustainability and energy efficiency. The specialized literature illustrates a wide range of relevant research for the integration of biofuels in the context of compression ignition engines. These investigations raise crucial issues that must be considered when evaluating the long-term use of biofuels in these engines. Through the specialized literature, not only the potential advantages of biofuels are highlighted, but also the limits and challenges associated with their integration into diesel technology.

The oxygenated biofuels obtain in the experimental tests mentioned above better characteristics in terms of engine performance and pollutant emissions compared to classic fuel, but when it comes to their use in long term tests (Patil, Singh, & Kumar, 2024) show that they can cause certain problems in what concerns carbon deposits on the metal surfaces of the engine. The authors performed long tests on engines both from the small sector (small automobile engines) and tests with large engines from the field of agriculture in different regimes according to the Figure 6.

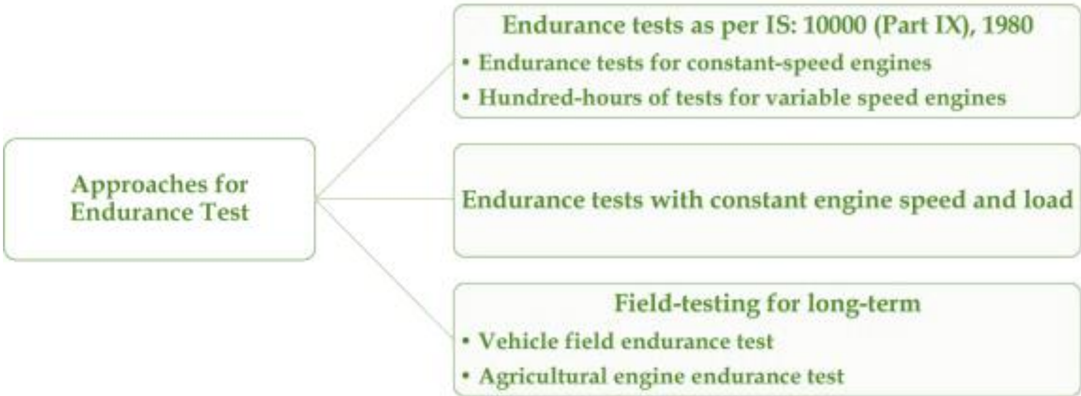

Figure 6 – Endurance test example, adapted from (Patil et al., 2024)

Engines operating long-term with vegetable oil register significant carbon deposits in the combustion chamber compared to conventional diesel as reported in (Bari, Yu, & Lim, 2002) In another study (Hoang & Pham, 2019), the authors tested another type of biofuel in the long term. They noticed significant carbon deposits after approximately 300 hours of operation. Carbon deposits are the result of a complex process that takes place at temperatures exceeding 350°C, based on two predominant mechanisms: the decomposition of hydrocarbons with the formation of solid carbon and the condensation of hydrocarbons into more complex aromatic molecules (Hoang & Pham, 2019).

Mixing biofuels with diesel fuel is also studied from the point of view of long-term deposits. In the studies (Agarwal & Agarwal, 2021b; Agarwal & Dhar, 2009, 2012; Reddy & Nanthagopal, 2021; Terry, McCormick, & Natarajan, 2006) the authors investigated this and concluded that carbon deposits are slightly increased in the combustion chamber when the engine is fuelled with a mixture of biofuel and diesel, in addition, when fuel mixtures are used, traces of erosion were also observed in the upper part of the piston. These deposits over time affect the performance of the engine leading to additional costs. Numerous studies reveal that carbon deposits in diesel engines on the injector nozzle significantly affect the engine's performance characteristics and polluting emissions (Birgel et al., 2012; Liaquat et al., 2013; Urzędowska & Stępień, 2016; Yüksek, Kaleli, Özener, & Özoğuz, n.d.). However, some tests have shown that certain combinations of biofuel and diesel lead to the formation of deposits in a smaller amount (Agarwal & Agarwal, 2021a; Kumar Patidar & Raheman, 2020; Suthisripok & Semsamran, 2018).

Certain advantages of the use of biofuels from the point of view of the lubrication of the high pressure pump components are also reported. In the studies (Agarwal & Agarwal, 2021a; Chourasia, Patel, Lakdawala, & Patel, 2018; Kumar Patidar & Raheman, 2020; Pehan, Jerman, Kegl, & Kegl, 2009) it was reported the lower wear of the pump and injectors when using biofuels.

DISCUSSIONS

The blending of diesel fuel with essential oils represents a burgeoning area of research aimed at enhancing the performance of internal combustion engines while mitigating their environmental footprint.

Implications for Engine Performance: One of the primary discussions centres around the impact of essential oil blends on engine performance metrics. Additionally, the combustion characteristics of diesel fuel may be altered by the inclusion of essential oils, potentially resulting in enhanced combustion efficiency and power output. However, variations in the chemical composition of different essential oils may yield divergent effects on engine performance, necessitating thorough investigation and optimization.

Effects on Emissions: Another key aspect of the discussion pertains to the influence of essential oil blends on pollutant emissions from diesel engines. While diesel combustion typically generates pollutants such as nitrogen oxides (NO_x) and particulate matter (PM), the introduction of essential oils may alter combustion kinetics and emissions profiles. Some studies suggest that certain essential oils possess antioxidant, which could potentially mitigate the formation of harmful pollutants. However, the complex interactions between essential oil components and combustion processes warrant comprehensive emissions testing to assess their net environmental impact. An important thing is the fact that the research results are influenced by many factors, from the region where the biofuel comes from to the type of engine in which it is introduced. A disadvantage of essential oil is its degradation over time, especially if it comes into contact with oxygen and ultraviolet light. The advantage of these biofuels lies in the fact that the plants from which they come absorb throughout their life a part of the carbon dioxide removed when the fuel is burned.

However, some studies show that the long-term use of certain biofuels can affect the operation of the engine due to the deposits inside the engine, leading to a decrease in performance and an increase in pollutant emissions, reaching the complete destruction of the engine.

CONCLUSION

This study endeavours to evaluate the use of essential oil and alcohol blends in diesel fuel, focusing on their combined effects on engine performance metrics and pollutant emission profiles. Through a synthesis of existing literature and empirical data, the study aims to elucidate key research inquiries and methodological approaches, thereby providing a foundation for further analysis and discourse. Furthermore, it underscores the broader significance of investigating alternative fuel sources within the context of environmental sustainability and engine optimization, aiming to offer insights into potential strategies for reducing environmental impact and enhancing engine efficiency without significant alterations. The following conclusions emerge from the analysis conducted in this present review:

- steam distillation is proving to be a promising next step for the extraction of biofuels, offering both favourable economic prospects and high yield. Detailed analysis of the literature and empirical data highlights the potential of these techniques to contribute to the sustainable development of biofuel industries. Efficiency and cost-effectiveness are supported by its advantages in the purification and concentration of biofuels from varied feedstock. However, to maximize the benefits, it is essential to continue research to create technological processes and reduce the impact on the environment. In light of these findings, steam distillation remains a promising solution for obtaining biofuels, with significant implications towards sustainability and energy efficiency.
- the transesterification of oils to obtain biofuels intended for diesel engines stands out as an efficient and promising method from a technical and economic point of view. Detailed analysis of the literature and empirical data reveals the potential of this technique to significantly contribute to the reduction of greenhouse gas emissions and other pollutants associated with the use of fossil fuels. In addition, transesterified biofuels have demonstrated the ability to improve engine performance and extend engine

life. However, to fully exploit the benefits of this technology, continuous research is needed to optimize the processes and raw materials used.

- blending distillate alcohol with essential oil, transesterified vegetable oil and diesel fuel turns out to be a promising strategy for improving the combustion characteristics and performance of diesel engines. In addition, this mixture can be considered an economical solution, with significant impacts on the operating and maintenance costs of diesel vehicles.
- in some cases, a decrease in BSFC of up to 5% is observed, indicating a better use of the energy provided by the mixture. At the same time, engine power and torque can increase by up to 4%, reflecting improved mechanical performance. Also, the BTE and the amount of heat released in the cylinder can show an increase of about 6%, which suggests a greater efficiency in the conversion of chemical energy into mechanical energy. In-cylinder pressure may also increase for some fuel blends, indicating more complete combustion and more efficient use of the mixture by the engine.
- hydrocarbon (HC) emissions are reduced by up to 7%, reflecting more complete combustion and better utilization of the fuel mixture. Smoke emissions are also reduced by around 12%, indicating cleaner burning and lower particulate emissions. Although CO may decrease in some situations compared to the reference fuel, with values up to 4% lower, it is important to note that NO_x emissions may increase slightly, up to 6%. This increase can be attributed to the higher temperatures and oxygen content of certain biofuels, which can promote the formation of NO_x during the combustion process. Overall, the use of ternary fuel blends shows significant benefits in reducing pollutant emissions, with the exception of a slight increase in nitrogen oxide emissions, which underlines the importance of continuing research to optimize the blend and minimize environmental impact.
- from the research found in the literature, we conclude that performance parameters and pollutant emissions can be influenced by certain carbon deposits in the engine, this fact leads to additional research for the optimization of biofuel mixtures in compression ignition engines.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data will be made available on request.

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