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Review Article

The use of turpentine as additive for diesel oil. A review

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ABSTRACT

This paper reviews research on the effects of substituting diesel oil with mixtures containing turpentine on the performance and emissions of internal combustion engines. Studies have shown that turpentine-diesel blends offer several potential benefits when used as fuel. In some cases, significant reductions of up to 10% in fuel consumption have been observed. Overall, pollutant emissions decreased, with reduction in smoke opacity exceeding 40%, as reported in some studies. Certain blends exhibited increased engine performance, potentially due to improved fuel atomization from the lower viscosity of the mixture. Additionally, studies have documented thermal efficiency gains exceeding 3% in specific cases. However, the effectiveness of these blends is highly dependent on several factors, including the source of the turpentine (its geographic origin can significantly impact its properties and suitability for blending); the injection pressure (which is crucial for maximizing the benefits of the blend) and the proportion of the turpentine in the mixture (which significantly influences the observed effects).

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INTRODUCTION

In the face of continued global energy demand and growing concerns about climate change, finding innovative and sustainable solutions for energy production is vital. In this context, exploring alternative sources and sustainable fuels is a crucial direction for contemporary scientific research [1-18]. One such emerging fuel that has attracted significant attention from the scientific community is turpentine oil. Turpentine oil ($C_{10}H_{16}$) is gaining interest as a potential fuel source. By researching and developing this type of fuel, scientists and engineers are working collectively to optimize energy production while considering its impact on the planet and future generations [19-21]. Turpentine, derived from conifer resin, is traditionally used in the pharmaceutical industry due to its antimicrobial and anti-inflammatory properties. Recently, the fuel industry has shifted its focus to this substance. The use of turpentine as a substitute for diesel oil has become a rapidly expanding area of research given its potential to enhance engine performance and efficiency [22]. The chemical characteristics of turpentine, detailed in Table 1, including its complex composition of hydrocarbons and aromatic compounds, play crucial role in the combustion

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process. These properties influence the chemical reactions during combustion, directly affecting engine efficiency and emissions. Furthermore, turpentine has significant energy potential, as it can provide a substantial amount of energy during combustion, contributing to increased engine efficiency and reduced greenhouse gas emissions. Turpentine is notable for its ability to blend uniformly with diesel, forming a stable and homogeneous mixture. This uniformity is essential for ensuring even and efficient combustion in the engine, minimizing carbon deposits, and improving engine durability. Therefore, exploring the potential of turpentine as an energy source is a promising area of scientific research. Analysing its chemical and energy properties, along with developing suitable technologies for its use in conventional engines, could pave the way for sustainable and efficient alternatives in the fuel industry. In turn, this could contribute to reducing the environmental impact and promoting a cleaner energy future.

Over the last three decades, countries worldwide have focused on promoting the use of renewable energy sources. The use of crops or residues as an efficient, low-cost, locally available, and sustainable source of energy has seen significant growth, offering advantages to both farmers and governments, while positively impacting the environment. Through transesterification (the displacement of alcohol from an ester by another alcohol), vegetable oil can be chemically modified to reduce its viscosity and improve its physical properties, such as the cetane number [23-24]. Studies have shown that methyl ester produce lower smoke levels and higher thermal efficiencies compared to unmodified vegetable oils. The published research provides valuable information on the technical procedures for transforming vegetable oils into high-quality fuels for diesel engines via the transesterification process. These insights are foundational for the research and continuous development of alternative fuels, aiming toward a more sustainable world [25-31]. Transesterification, a well-studied and documented chemical process involves the reaction of vegetable oils with alcohols, such as methanol or ethanol, to produce methyl or ethyl esters, known as biodiesel. Biodiesel obtained through transesterification possesses optimized physical and chemical properties for use in diesel engines, ensuring efficient combustion and reduced emissions [32]. The literature describes various transesterification processes and presents several types of catalysts and reaction conditions used to optimize the process [33, 34]. Additionally, specialized studies offer insights into technical aspects such as phase equilibrium and product separation, which are crucial for the mass production of biodiesel. Researchers have also addressed issues related to raw materials, analysing diverse sources of vegetable oils used in the transesterification process. This includes evaluating the advantages and disadvantages associated with oils derived from different plants and their impact on the quality and durability of the produced biodiesel [35].

Table 1. Physico-chemical properties of turpentine oil [71]

Properties	Turpentine oil	Diesel
Formula	C_{10}-H_{16}	C_{12}-H_{23}
Molecular weight (g/mol)	136	167
Boiling point (°C)	150–180	180–340
Specific gravity	0.86-0.9	0.83
Kinematic viscosity @ 40°C (cSt)	1.3	2.5
Latent heat of vaporization (kJ/kg)	305	230
Flash Point (°C)	38	74
Auto-ignition temperature (°C)	220-255	254-285
Calorific value (kJ/kg)	44 400	42 500
Cetane index	20–25	40–55
Density (kg/m^3)	860-900	830

In general, it is not common to obtain turpentine from vegetable oils because they require specific process for extracting and distilling pine resin. Vegetable oils and turpentine are two substances with distinct composition and properties. However, research and technologies continue to evolve, and innovative methods for producing turpentine from vegetable sources might emerge in the future. Currently, turpentine is primarily derived from pine resin and other coniferous resins.

The main chemical compounds in pine turpentine oil are terpenoids and terpenes. The structure of this oil varies significantly depending on the type of pine from which it is extracted, the time of harvesting, and geographical location. Turpentine is a semi-fluid substance consisting of resins dissolved in volatile oil, which can be broken down by distillation into different fractions [12]. These fractions include a volatile oil called turpentine oil or spirit and a non-volatile component known as rosin. The two main types of oils obtained from plants are triglyceride oil, extracted from plant seeds, and turpentine oil, which can be obtained from any part of the plant. Plants such as eucalyptus and pine are recognized for the significant amounts of turpentine oil they produce [36]. In general, there are five types of turpentine oils according to the production method [37]. One of the most traditional resin collection techniques is bark chipping. This ancient technique involves removing the bark of the tree to a certain width. Open cups were clamped to the trees to collect the resin produced from the chiselled portion. This is a repetitive process at regular interval of three to four weeks [38]. Another technique used to avoid the limitations of the traditional bark-cutting method is the drilling method. This method involves drilling holes applying chemicals such as ethephon and installing containers for collection. A crucial aspect of this technique is that it prevents early solidification of the resin, which extends the flow period. Additionally, the drilling method is more economical than the bark-cutting method, because it requires significantly less physical labour. The oleoresins obtained by the above-mentioned procedures are subsequently directed to a steam distillation unit, where they are processed to produce turpentine oil [39]. Turpentine can be easily mixed with diesel oil at any ratio and can be used in diesel engines owing to its properties [40].

This study has the potential to contribute to the field of using turpentine as a diesel additive. Analysing and synthesizing available data on engine performance and pollutant emissions will provide a comprehensive perspective on the benefits and challenges associated with adopting this alternative. Additionally, current research gasp will be identified, and directions for further investigation to optimize the use of turpentine as an additive will be suggested. This review will not only enrich current knowledge in the field but also provide essential information for industry decision-makers and researchers involved in the development and implementing sustainable solutions in the fuel industry [41].

OBJECTIVES

Numerous studies have explored the prospect of integrating diesel with various renewable fuels, among them, turpentine is a notable candidate. This review delves into the feasibility, implications, and potential benefits of incorporating turpentine, a renewable resource derived from pine trees, into diesel oil blends [42-46].

The primary objective of this study was to conduct a comprehensive review of existing research findings on the use of turpentine as an additive for diesel oil in internal combustion engines. This review aims to provide an understanding of the behaviour of turpentine-diesel blends in diesel engine systems. Key aspects of interest include their impact on engine performance metrics, thermal efficiency characteristics, and emission profiles. This review spans over a decade of literature to identify potential research gaps.

Cost of Biofuel

The production cost of biofuels compared to diesel is a topic of significant interest and debate in the energy sector. Biofuels, derived from organic materials such as crops, algae [47, 48], and waste [49, 50], represent a renewable alternative to fossil fuels such as diesel. However, their production processes often involve complex extraction, conversion, and refinement steps, which can contribute to higher production costs compared to traditional petroleum-based diesel [51].

Several factors influence the production cost of biofuels, including the feedstock used, technology used for conversion, and scale of production. For instance, biofuels derived from food crops such as corn or soybeans may compete with food markets, leading to fluctuations in feedstock prices and affecting overall production costs [52]. On the other hand, advanced biofuels produced from non-food sources such as algae or agricultural residues, may offer more sustainable alternatives but could involve higher processing costs due to less mature technologies and economies of scale. In contrast, diesel production primarily involves extraction and refining processes applied to crude oil, which has well-established infrastructure and economies of scale. However, the cost of diesel production is subject to fluctuations in crude oil prices and geopolitical factors, making it vulnerable to market volatility.

In recent years, advancements in biofuel production technologies, coupled with increasing environmental concerns and policy incentives, have aim to reduce the production costs of biofuels and enhance their competitiveness with diesel oils. These efforts include improving feedstock yields, optimizing conversion processes, and scaling up production facilities to achieve economies of scale [53]. Although the cost of biofuels production may still be higher than that of diesel in certain contexts, broader societal benefits, such as reduced greenhouse gas emissions and enhanced energy security, often justify investments in biofuel production and use. Additionally, ongoing research and development efforts continue to drive innovations in biofuel production, aiming to further narrow the cost gap between biofuels and diesel, and promote their widespread adoption in the global energy mix [54].

Several studies have indicated that the stability of biofuels is susceptible to various influencing factors. Compared to conventional fuels, biofuels are more sensitive to external influences, such as light and temperature [55], resulting in greater oxidation [56, 57]. Consequently, proper handling and storage are essential to prevent deterioration [58, 59]. Moreover, biofuels tend to absorb moisture from the environment, a property known as hygroscopicity [60], which can negatively impact their properties and long-term usability.

Importance of Atomization

Fuel atomization in a combustion chamber is an essential aspect for the combustion process in many applications, such as thermal power plants, internal combustion engines, and industrial furnaces [61]. Atomization converts liquid or solid fuel into fine droplets or small particles, which increases the surface area of the fuel exposed to the oxidizing medium (usually air). This allows for more efficient mixing of the fuel and oxidizer, resulting in more complete and efficient combustion [62]. With more efficient combustion, more energy is released from the fuel, which improves system efficiency. Effective fuel atomization contributes to more controlled and complete combustion, which can reduce the emissions of pollutants, such as carbon monoxide such as carbon monoxide, hydrocarbons, and particulate matter. This is crucial for meeting environmental emission regulations and reducing the impacts on air quality and human health. Atomization of biofuels is particularly important in the energy industry and various applications. It offers benefits similar to those of traditional fuels, with specific consideration related to the nature of biofuels [63]. A previous study used a dispersion analysis system to study the details of the dispersion process of a biodiesel ethanol blend. This mixed fuel is characterised by smaller droplet size and faster evaporation (due to the higher volatility of ethanol) compared to biodiesel dispersion without additives [64]. In another study, a high-speed camera was used to analyse the atomization characteristics of several types of fuels, including diesel, biodiesel, and biodiesel blended with ethanol (at a concentration of 50% by volume). This study investigated the influence of fuel properties and injection pressure on fuel dispersion and mixing with air. The most efficient spray, with the highest dispersion angle, was observed with diesel blended with ethanol at a concentration of 50% by volume and injection pressure of 50 MPa. This type of fuel is the preferred choice for modern internal combustion engines because it improves the mixing of the fuel with air [65]. The cavitation phenomenon is noted in studies that emphasises the efficiency of spraying and burning. The droplet cavitation characteristics are influenced by how the injections are performed and the shape of the nozzle. Typically, cavitation occurs near the bottom wall of the nozzle when the injection pressure is high [66]. It is possible to improve the atomization process of biodiesel can be improved by lowering its viscosity and surface tension using alcohol additives [67].

Effects of Turpentine-Diesel Mixtures on Engine Performance

This section provides an overview of several research endeavours involving experiments with biofuel blends (such as turpentine) mixed with diesel and other biofuels. Most of these investigations were conducted on engines using traditional fuel-injection systems. Given the limited exploration of biofuels in engine combustion, researchers have chosen this approach, primarily to maintain engine functionality.

In [68], researchers investigated engine performance with blends of jatropha oil and mineral turpentine mixed with diesel. The results indicated that the BSFC of the JMT50 blend was comparable to that of diesel oil. However, jatropha oil has a lower heating value than diesel oil, this results in a lower heating value of the blend and, consequently, a higher BSFC. The BTE of the blends of jatropha oil and mineral turpentine was lower than that of the diesel oil.

Nevertheless, the JMT50 blend exhibited a thermal efficiency remarkably close to that of diesel oil at 75% and full engine load. The presence of oxygen in fuel enhances combustion characteristics, but the high viscosity and poor volatility of vegetable oils contribute to their reduced combustion features. Therefore, the thermal efficiency was lower for higher blend concentrations than for diesel oil. The cylinder pressure, measured at the maximum load, shows that the blends of jatropha biodiesel and mineral turpentine are closer to neat diesel owing to better atomization and mixing. In a CIE, the pressure increase depends on the burning level in the early phases, which is influenced by the quantity of fuel involved in the uncontrolled burning. With the increase in mineral turpentine in jatropha biodiesel, it was observed that the crank angle of the decisive HHR became more progressive. These findings suggest that blends of jatropha oil and mineral turpentine with diesel oil can provide satisfactory results under specific engine operating conditions. However, challenges related to heating values and thermal efficiency remain. The study highlights the importance of optimizing the blend composition to maximize engine performance and efficiency in the context of using these alternative energy sources.

Researchers experimented to evaluate the potential of a blend of jatropha biodiesel and turpentine oil in a single-cylinder four-stroke engine [69]. They used five blends with compositions varying between 10% and 50% turpentine oil, and the remainder jatropha biodiesel. The engine was set at a constant speed of 1500RPM and the mixtures were injected at a pressure of 200 bar. Researchers measured exhaust gas temperature, fuel consumption, exhaust emissions, cylinder pressure, and HRR. The results showed that, compared to that of diesel oil, the BSFC increased with the use of jatropha-turpentine blends. This increase in the BSFC is attributed to the inferior lower heating value of jatropha oil. Higher concentrations of jatropha oil in the mixture reduce the heating value of the blend, leading to higher fuel consumption. Additionally, the higher density and viscosity of the blend contributed to increased fuel consumption. The presence of oxygen in the fuel improved combustion quality, but the higher viscosity and reduced volatility of plant oils resulted in poor atomization and combustion properties. Notably, for higher wood turpentine concentrations, the BTE decreased compared that with of diesel oil. The EGT of jatropha and jatropha-mineral turpentine blends was comparable to that of diesel at all loads. The study observed that the EGT increased with higher engine loads in all the cases. Specifically, the JWT10 blend exhibited the highest EGT value of 422°C, whereas the temperature for D100 was 410°C. As reported by Anand Prem B. [70], the properties of turpentine oil fuel blends are comparable to those of conventional diesel oils. Fuel blends with turpentine oil can produce braking power like diesel oil, while blends with 30% turpentine oil can produce higher braking power and net HHR than conventional diesel like the results reported in [71]. In [72], a cylinder pressure measurement was performed, and the authors found that the biofuel blends had a higher cylinder pressure than the standard blend. A higher HRR was also observed. It seems that the dual-fuel mixtures had a slightly longer ID (approximately 0-2 degrees), allowing more time for air-fuel mixing. This resulted in an increase in the HRR during the combustion process. In one experiment [73], turpentine oil was tested in a single-cylinder diesel engine operating in DF mode, with a direct injection at a pressure of 190 bar, and the injection timing was set at 26 degrees before TDC. The engine was operated at a constant speed of 1500 RPM, and turpentine was introduced into the combustion chamber by fumigation [74, 75]. To allow this process, some constructive changes were made to the engine. Performance parameters such as BSFC, BTE, cylinder pressure, and ID were measured. According to the authors, BSFC was lower up to 75% engine load and BTE was better than the reference fuel (diesel oil) up to the same load. However, the brake thermal efficiency decreased after 75% of the engine load, due to the detonation phenomenon. In addition, the volumetric efficiency was lower than that of the reference fuel because turpentine was injected into the intake manifold, which is very volatile and, through evaporation, consumes some heat from the cylinder. Consequently, the volumetric efficiency decreased with increasing load and with the amount of turpentine introduced into the intake. In addition, ID was considerably longer when turpentine fuel was used because the injection of the pilot fuel (diesel oil) takes place in an environment where the temperature and oxygen concentration are lower than in the case of DBL operation. Evaporation of turpentine oil inside the cylinder leads to lower oxygen concentration and temperature of the mixture at the time of injection. As the engine load increases, due to a higher amount of octane fuel (turpentine) introduced into the intake, knocking occurs. Therefore, the performance of the DF engine starts to degrade when the load exceeds 75%.

In another study mixtures of turpentine and *Chlorella Vulgaris* were made [76]. Particular attention was paid to the main engine, which was a four-cylinder, naturally aspirated, direct-injection diesel engine, and the revs were constant during the tests. The researchers created several fuel blends but found that the best-performing blend was C50T50. The authors reported an HRR for the C50T50 blend higher than conventional fuel. By measuring the pressure in the cylinder, it was found that the C50T50 mixture reaches the highest pressure (about 70 bar) at full engine load, while the pressure in the combustion chamber with conventional fuel reaches about 40 bar. The ID is the time between the start of fuel injection and the first ignition points, expressed in degrees of crank angle. According to the classical theory of ignition developed by Karthikeyan [77], auto-ignition describes the initial period when chemical reactions play a key role before ignition. The authors found that the ID of the C50T50 mixture is significantly lower than that of diesel oil.

In the research [78], renewable energy sources such as bio-vegetable oil and pine oil were tested in a diesel engine. To optimize the use of these fuels, researchers have tried to improve the properties of the raw material obtained from pine oleoresins, as it has a lower viscosity and boiling temperature. These improvements allowed for a more efficient combustion and lower emissions. The experimental study conducted with the 50Diesel:50Biodiesel oil mixture in a diesel engine showed that the engine thermal efficiency and the maximum HHR are higher than those of traditional diesel. Additionally, the BSFC is lower when using a mixture of 50% pine oil and 50% diesel oil.

In [79] the authors mixed pine oil with diesel oil to form four blends of different concentrations, namely 0%, 20%, 40%, and 50% by volume, denoted P0, P20, P40, and P50. To maintain constant performance, the EGR ratio was set at 24.6%, based on the authors' previous results that showed this to be a tipping point before a dramatic increase in soot emissions [80]. The engine speed was maintained at 1800 RPM and the 4-cylinder test engine was equipped with a common rail fuel injection system with a maximum operating pressure of 160 MPa. The engine inlet pressure was controlled at 0.15 MPa (relative pressure) and the inlet temperature was maintained at 30±2°C. During the experiments, four different injection pressures (100 MPa, 120 MPa, 140 MPa, and 160 MPa) were tested for each fuel mixture. The engine load was maintained at 40% load for all four fuel blends, and engine performance was evaluated for each blend. The authors also investigated the atomization characteristic of fuel blends under different injection pressures, reporting that fuel blends with pine oil exhibited better atomization than diesel oil. Increasing the injection pressure led to better spray penetration and improved atomization, promoting fuel-air mixing, reducing the ID period, and anticipating the ignition start point, which led to increased peak burn rate values, HHR, cylinder pressure, and BSFC. The authors found that, at a fixed injection pressure, the cetane number of the fuel mixture decreases once pine oil is added to the diesel oil, extending the ID period. The higher the pine oil concentration, the greater the spray penetration and spray cone angle, indicating relatively good atomization. The peaks of in-cylinder pressure and HHR values first increase and then decrease with increasing pine oil concentration, leading to an initial increase in BSFC. Therefore, biofuel mixed with diesel oil behaves differently in terms of engine performance depending on certain parameters such as the injection pressure and the concentration of biofuel in the diesel oil.

By using the transesterification process [81] CPME was obtained from Ceiba pentandra seed oil. As the percentage of CPMEP increased, the flash point and viscosity increased, and the heating value decreased compared to the mixture of pine oil with diesel oil. As the percentage of CPMEP blends increased, the BSFC increased slightly and so did the ID, resulting in a reduction in brake thermal efficiency. The brake thermal efficiency with pure pine oil was 4.76%, and the peak cylinder pressure, HHR, cumulative HHR and ID increased, while the BSFC decreased in comparison with diesel oil.

Effects of Mixtures on Pollutant Emissions

Blends of turpentine and diesel oil represent a solution to mitigate harmful emissions in the transportation sector, given the specific properties of turpentine, such as volatility and its ability to enhance the combustion characteristics of the blend. However, despite their potential, the precise effects of these blends on particulate matter emissions, nitrogen oxides, and greenhouse gases require

Table 2. Summary table

Ref	Method Used	Results	Limitation	Practical Implication	Conclusion
[71]	• Experimental tests with diesel and turpentine blends. • Measurement of fuel consumption and pollutant emissions. • Use of AVL analyzers for pollutant concentration determination.	• Turpentine blends had a slightly positive effect on torque and power. • Turpentine improved efficiency and fossil GHG emissions but increased NO_x emissions. • Turpentine had mixed effects on unburned hydrocarbons and smoke emissions. • Turpentine showed potential as a fuel blend with diesel.	• Limited impact on engine performance, mixed effects on emissions. • Turpentine's NO_x emissions increased due to improved engine performance.	• Turpentine blends can reduce fossil fuel consumption and CO_2 emissions. • Minimal engine modifications are necesary for up to 30% turpentine incorporation. • Potential for increased torque, power, and efficiency in driving conditions. • Turpentine from sustainable pine forest management can be economically competitive. • Advanced after-treatment is needed to assess the impact on turpentine viability.	• Turpentine blends had a slight impact on engine performance parameters. • Turpentine improved torque and power but had mixed effects on emissions. • NO_x emissions increased due to the improvement in engine performance. • Smoke emissions decreased with the incorporation of turpentine in the fuel.
[81]	• Experimental investigation of performance, emission, and combustion characteristics of biofuels. • Transesterification process to produce CPME from ceiba pentandra seed oil.	• Pine oil and CPME blends increased BSFC and decreased brake thermal efficiency. • NO_x emissions decreased, while smoke emissions increased for CPME and CPMEP blends. • Pine oil increased brake thermal efficiency and reduced BSFC. • CPMEP blends showed increased ignition delay and slightly reduced combustion duration. • Up to B50 blends have the potential for future energy needs.	• No specific limitations were mentioned in the research paper.	• CPME and CPMEP blends show potential for future energy needs. • Pine oil can be used directly in a diesel engine. • Experimental fuels up to B50 blends are promising for energy.	• CPME and CPMEP blends affect fuel consumption, emissions, and combustion characteristics. • Pine oil can be used directly in a diesel engine. • B50 blends show potential for future energy needs.
[80]	• Experimental investigation on pilot injection timing and mass. • Combustion simulation using n-heptane-n-butanol-PAH-toluene mixing mechanism.	• Pilot injection timing affects heat release rate, emissions, and combustion. • Blending n-butanol in diesel improves soot emissions. • Increasing the n-butanol ratio reduces NO_x and soot emissions. • Advanced pilot injection timing reduces NOx and soot emissions.	• No specific limitations were mentioned in the research paper.	• Investigates pilot injection effects on combustion and emissions in diesel engines. • Shows how n-butanol-diesel blends impact soot emissions and combustion characteristics. • Highlights the potential of n-butanol as a green substitute fuel.	• Advancing pilot injection timing reduces the heat release rate for pre-injection fuel. • Increasing pilot injection fuel mass affects the peak heat release rate. • Blending n-butanol in diesel improves soot emissions. • Addition of n-butanol delays ignition time in n-butanol-diesel oil blends.

Table 2. Summary table (continued)

Ref	Method Used	Results	Limitation	Practical Implication	Conclusion
[79]	• Investigated spray characteristics, combustion, and emissions of pine oil-diesel blends. • Conducted experiments on a four-cylinder diesel engine under medium EGR. • Analyzed spray morphology, penetration, cone angle, and combustion characteristics. • Tested pure diesel and three blends of pine oil and diesel oil.	• Injection pressure affects spray characteristics, combustion, and emissions of blended fuels. • Pine oil ratio influences atomization, heat release, and emissions of blended fuels. • Increasing pine oil reduces soot emissions and total PM mass concentration. • Injection pressure decreases CA50 values and shortens ignition delay periods.	• Limited research on pine-oil diesel blends' emission characteristics. • Few studies on spray characteristics of pine-oil diesel blends.	• Pine oil-diesel blends can reduce emissions and improve combustion efficiency. • Increasing injection pressure can lower PM emissions in diesel engines. • Blending pine oil enhances atomization and fuel evaporation processes. • Injection pressure affects soot emissions differently in pure diesel and blends.	• Injection pressure increases spray penetration, combustion peak values, and emissions. • Pine oil ratio affects atomization, in-cylinder pressure, emissions, and soot concentration. • Increasing injection pressure or pine oil amount reduces total PM.
[78]	• Experimental setup with Kirloskar diesel engine and water-cooled dynamometer. • Addition of ignition promoters IAN and DTBP to improve ignition. • Performance evaluation of 50D:50B, 50D:50B-IAN, and 50D:50B-DTBP.	• Pine oil-diesel blend with DTBP reduced NO_x emission by 19.2%. • 50D:50B-DTBP showed 6.2% increased BTE compared to 50D:50B. • Ignition promoters IAN and DTBP improved ignition and reduced NO_x emission. • Engine performance parameters and emissions were analyzed and compared.	• Lower cetane number affects diesel engine performance. • Alcohol-based fuels require ignition assistance due to lower cetane number.	• Pine oil-diesel blends can enhance engine performance and reduce emissions. • The addition of ignition promoters like IAN and DTBP can reduce NO_x emissions. • DTBP is more effective in reducing NO_X emissions than IAN.	• Pine oil in diesel engines showed improved performance and reduced emissions. • Ignition promoters IAN and DTBP enhanced ignition and reduced NO_x emissions. • Pine oil's properties enabled more complete combustion in the engine.
[73]	• Experimental study with turpentine-diesel dual fuel engine. • Measurement with gas analyzer, smoke meter, EGT indicator, and more. • Instruments range from gas analyzer to pressure pickup.	• Turpentine-Diesel dual-fuel engines showed improved performance and reduced emissions. • 60-65% diesel replacement with turpentine is feasible within 75% load.	• Increased CO and HC emissions with turpentine-diesel dual fuel engine. • Non-availability of sufficient air leads to abnormal combustion at higher loads.	• Turpentine can replace up to 75% of diesel in engines. • Improved performance and reduced smoke emissions with turpentine-diesel dual fuel. • The brake thermal efficiency of the DF engine is higher than DBL.	• The brake thermal efficiency of the DF engine at 75% load is higher.
[72]	• Experimental setup with pressure sensor, TDC sensor, and AVL exhaust gas analyzer	• Dual biofuel reduced NO_x, HC, CO, and smoke emissions compared to diesel. • Dual fuel blends showed favorable combustion, performance, and emission characteristics. • Combustion, performance, and emission parameters were compared with mineral diesel.	• The paper does not explicitly mention limitations.	• Dual biofuel blends reduce emissions and are a diesel substitute. • Dual fuel blends are a good substitute for diesel in performance. • The study explores new biofuel combinations to eliminate fossil fuel dependency.	• Dual biofuel blends reduce emissions and perform well in diesel engines.

Table 2. Summary table (continued)

Ref	Method Used	Results	Limitation	Practical Implication	Conclusion
[69]	• Bark chipping method. • Borehole method. • Steam distillation to obtain turpentine oil.	• Improved emission features, and reduced CO, HC, and smoke emissions. • Comparable performance to diesel, reduced emissions, suitable for CI engines.	• Limited data on long-term engine performance and durability. • No detailed analysis of the impact on engine components.	• Jatropha biodiesel-turpentine blends can replace diesel with improved emissions. • Offers comparable performance and combustion features in compression ignition engines. • Biodiesel is environmentally friendly, biodegradable, non-toxic, and sulfur-free.	• Jatropha biodiesel-wood turpentine blends can replace standard diesel in engines. • Reduced emissions of CO, HC, and smoke compared to diesel. • Comparable performance and combustion features with diesel.
[68]	• Performance and pollutants features examined in compression ignition engine. • Viscosity reduction by blending Jatropha Biodiesel with Mineral Turpentine oil.	• A blend of 80% Jatropha Biodiesel and 20% Mineral Turpentine resembles diesel. • Reduction in carbon monoxides and hydrocarbons, increase in oxides of nitrogen. • Specific fuel consumption is slightly higher than diesel. • The heat release rate and cylinder pressure are similar to diesel oil.	• Limited adverse fuel features of substitute biofuels. • The viscosity of vegetable oil affects combustion features. • Jatropha-Mineral Turpentine blends have slightly higher fuel consumption.	• Jatropha-Mineral Turpentine blends can be a viable alternative to diesel. • Reduced emissions of CO, hydrocarbons, and increased nitrogen oxides. • Comparable brake thermal efficiency and heat release rate to diesel.	• Jatropha-Mineral Turpentine blends are a viable alternative to diesel oil. • Reduced emissions of CO, hydrocarbons, and increased nitrogen oxides. • The brake thermal efficiency of JMT50 blend is comparable to diesel. • Specific fuel consumption is slightly higher in Jatropha-Mineral Turpentine blends.

detailed investigation and comprehensive understanding. In this chapter, the impact of turpentine-diesel oil blends on engine emissions is analysed, evaluating variations in emission composition, and examining key factors influencing these outcomes.

The study [68], conducted on the jatropha–mineral turpentine oil blends, particularly JMT20 and J100, presents valuable insights into their impact on pollutant emissions, especially HC, NO_x, and smoke opacity. The research demonstrates a comprehensive analysis of these emissions concerning various engine load conditions and blend compositions. One notable finding of the study is the significant reduction in HC emissions observed in JMT20 and J100. This decrease is attributed to the additional oxygen present in the blends, leading to improved combustion efficiency. However, it is worth noting that HC emissions tend to increase with a higher proportion of jatropha–mineral turpentine oil in the blends, indicating the complexity of the relationship between blend composition and emissions. The study also delves into NO_x emissions, revealing intriguing patterns at different load levels. Surprisingly, NO_x emissions are lower in jatropha–mineral turpentine blends compared to diesel oil at 75% load and full load. This reduction is attributed to the decreased burning temperature in the cylinder, a consequence of the shorter ID resulting from the higher cetane number of the biodiesel. The nonlinear nature of chemical rate disparity with temperature further influences NO_x emissions, emphasizing the intricate interplay of factors in emission formation and reduction. Additionally, the research addresses emission opacity, highlighting a rise in opacity with an increase in jatropha oil content in blends, particularly at higher loads. This phenomenon is linked to the suboptimal atomization of jatropha oil due to its larger particle size and higher viscosity, leading to increased emission density. These findings underscore the importance of considering fuel blend composition, combustion efficiency, and atomization properties in understanding and mitigating emission opacity.

Research [69] analyzed the pollutant emissions produced by an engine operating with blends of jatropha oil and wood turpentine (JWT) in comparison to diesel oil. The authors investigate the CO, HC, NO_x emissions, and smoke opacity resulting from the combustion of these blends. Regarding CO emissions, the study indicates that they increase with the engine load. The higher CO quantity is attributed to the richer air-fuel mixture burned in the engine, leading to oxygen deficiency and the formation of more CO. However, at 75% load, the CO emissions for certain blends are negligible. This is due to higher temperatures inside the cylinder, promoting the atomization of the blends and improved combustion. Additionally, the oxygen content in the plant oil facilitates burning at higher temperatures inside the cylinder.

Regarding HC emissions, JWT blends exhibit lower emissions compared to diesel oil. This is due to the higher oxygen available for reaction when JWT blends are added at higher engine loads. However, HC emissions increase with the percentage of wood turpentine in the blends. Carbon dioxide emissions are lower for the JWT20 blend compared to other blends because plant oil contains a higher oxygen portion, leading to lower CO_2 emissions. As for NO_x, it increases with the engine load for all JWT blends. Nevertheless, JWT blends reduce NO_x emissions at 75% and 100% loads due to lower combustion temperatures in the cylinder and a reduced stoichiometric ratio of the blend. Smoke opacity increases with the concentration of jatropha oil in the blends, especially at higher engine loads. This is due to the poorer atomization properties of the blends caused by bulky fuel particles and the higher viscosity of jatropha oil. Comparable results were observed in this study [72].

To produce an oxygenating fuel with properties like those of alcohol or esters, Garcia et al. [82] used turpentine oil obtained from residues from the paper industry or by distilling oleoresins. This study investigates pollutant emissions from an engine running on a blend of diesel oil and oxyturpentine, comparing them with emissions from pure diesel oil. The study focuses on CO, HC, and NO_x emissions during the NEDC simulation. The results reveal several key findings. At the beginning of the NEDC test, both fuels exhibited high peaks in CO emissions due to engine accelerations while the engine was still cold. As the test progresses, CO emissions decrease with rising engine and Diesel Oxidation Catalyst (DOC) temperatures, showing a consistent pattern across sub-cycles. Furthermore, the regeneration of the lean NO_x trap leads to another peak in CO emissions at the end of the NEDC. The comparison between diesel oil and the diesel + oxyturpentine blend indicates that the main difference in CO emissions occurs at the engine start, primarily due to the lower temperatures in the engine and DOC. Similarly, HC emissions are higher at the start of the NEDC due to the cold-engine conditions. After 300 seconds, the difference in HC emissions between the two fuels stabilizes, indicating that the combustion deterioration primarily affects the diesel + oxyturpentine blend during cold starts. The higher equivalence ratio and increased Exhaust Gas Recirculation (EGR) with the diesel + oxyturpentine blend led to more challenging fuel-air mixing, resulting in the elevated local formation of CO, and decreased local oxidation of hydrocarbons. The study suggests that two additional factors contribute to the increased CO and HC emissions at the beginning of the cycle: surface tension and volatility. The blend of diesel oil and oxyturpentine possesses similar viscosity to diesel, but the addition of oxyturpentine increases the fuel density, leading to higher surface tension. This phenomenon affects fuel atomization, deteriorating subsequent combustion, particularly under cold conditions. Additionally, differences in volatility between diesel oil and oxyturpentine, driven by the presence of α-pinene in oxyturpentine, further impact local temperatures and flame propagation, influencing emissions. Concerning NO_x emissions, both fuels exhibit a sharp peak during the NEDC test, primarily corresponding to the LNT regeneration and final acceleration phases. The study shows that NO_x emissions are slightly lower with the diesel + oxyturpentine blend compared to pure diesel oil throughout the NEDC. This decrease is attributed to the increase in EGR, which reduces local temperatures in the combustion chamber when diesel oil is blended with oxyturpentine. The lower cetane number of the oxyturpentine blend also contributes to reduced pressure and temperature peaks, subsequently limiting NO_x formation. Particles with diameters ranging from 5.6 to 560 nm are analyzed, revealing significant peaks during engine accelerations in both fuels. The presence of oxyturpentine reduces particle emissions, attributed to enhanced oxidation of soot particles due to oxygen atoms in the fuel molecules. Particles are categorized into nucleation mode (small particles) and accumulation mode (large particles) based on size. The diesel + oxyturpentine blend shows a notable decrease in nucleation mode particles, especially after urban driving, indicating improved combustion efficiency. Cold engine starts initially lead to high small particle emissions, reduced by oxyturpentine. As the engine temperature rises, nucleation-mode particles decrease in both fuels. Extra-urban driving results in substantial particle formation due to high fuel consumption. Particle sizes remain stable, with minor differences observed during specific driving conditions.

Another study [70] analyses the pollutant emissions resulting from the combustion of fuel blends in which turpentine oil appears to play a crucial role. The study primarily focuses on smoke opacity, particle emissions, and other exhaust gases, such as HC, CO, and NO_x. Smoke opacity was lower in blends with a higher percentage of turpentine oil compared to pure diesel oil fuel across the entire engine power range. This reduction can be attributed to the higher oxygen content in the molecular structure of turpentine oil, likely decreasing the formation of locally over-rich fuel regions responsible for primary smoke formation. Solid carbon soot particles are generated in the fuel-rich zones within the cylinder during combustion. Efficient combustion requires proper atomization, mixing, and ignition of the fuel. The physical properties of the fuel, including the cetane number, play a vital role in the ignition process. Turpentine oil blends appear to have a longer combustion duration due to increased ID, allowing carbon particles to find sufficient oxygen to transform into carbon dioxide. Thus, the chemical effects of the fuel in the flame region could explain the lower particle emissions of turpentine oil blends compared to pure diesel oil. Furthermore, emissions such as HC and CO decrease with the increasing proportion of turpentine oil in the blends, primarily because of complete combustion resulting from the oxygen content in turpentine oil. Additionally, the maximum NO_x concentration was reduced by 9% in the blend with 50% turpentine oil, accompanied by an 18% reduction in exhaust temperature.

The study [73] investigates the emissions of a dual turpentine-diesel engine under various load conditions. The results show that CO emissions gradually increase from 0% to 75% load due to a higher fumigation rate and lack of oxygen. At higher loads, flame quenching and cooled layers near the chamber walls lead to a 35% increase in CO emissions at 100% engine load. HC emissions increase from 0% to 75% engine load, then sharply rise at 100% load due to the higher fuel quantity and oxygen deficiency. NO_x emissions rise after 50% load due to increased temperatures and prolonged ID, reaching a peak at full load. Smoke emissions are significantly reduced due to pre-mixed and homogeneous charging, but visible white smoke emissions occur at high loads due to inadequate air supply and abnormal combustion.

In a study by Vallinayagam et al. [83], more efficient use of renewable plant-based fuel, specifically pine oil, was attempted through fumigation [74, 75] and its use in a single-cylinder diesel engine. Three different flow rates of pine oil, namely 0.029 g/s, 0.08 g/s, and 0.13 g/s, were used to determine diesel oil replacement capacity with this fuel, which ranges up to 36% and a maximum of 60% at low load. During the experiment, the pollutant emissions resulting from the combustion of pine oil in the diesel engine were monitored to assess the impact on the environment. The results of the experiment show that at the maximum flow rate of pine oil (0.13 g/s), HC and CO emissions are reduced by 47.8% and 67.5% at maximum load compared to diesel oil. Oxygen emissions have been observed to be lower than those from diesel oil due to better combustion of pine oil. In general, the use of pine oil in the fumigation regime resulted in a significant reduction in all emissions except NO_x emissions at full load.

Vallinayagam et al. [78] analyzed the emissions of a diesel engine fuelled with a blend of pine oil and diesel oil. Significantly, the 50% pine oil and 50% diesel blend exhibit higher NO_x emissions compared to pure diesel oil due to the increase in the peak HHR, highlighting the trade-off between NO_x emissions and smoke. The addition of IAN and DTBP reduces NO_x emissions. The improved evaporation of pine oil and its oxygen content resulted in a 41.5% reduction in smoke emissions for the 50% pine oil and 50% diesel blend compared to pure diesel oil. However, the introduction of IAN and DTBP slightly increases smoke emissions due to alterations in the combustion phases. The CO emissions are higher at lower loads for the 50% pine oil and 50% diesel blend but decrease at higher loads due to improved combustion efficiency. The addition of ignition promoters further reduces CO emissions, especially for the 50% pine oil and 50% diesel-DTBP blend, indicating enhanced combustion. Similar trends are observed in HC emissions, with the 50% pine oil and 50% diesel-DTBP blend recording a 40% reduction in CO emissions and a 34% reduction in HC emissions compared to the 50% pine oil and 50% diesel blend at full load. These findings align with previous studies, emphasizing the complex interaction between fuel composition, combustion characteristics, and emission profiles.

Fuel injection strategy in internal combustion engines plays a crucial role in reducing pollutant emissions. The manner and timing of fuel injection into the combustion chamber can significantly influence emissions of nitrogen oxides, particulates, and greenhouse gases.

Huang H. et al. in the paper [79] explore the impact of injection pressure and the mixing ratio of pine oil in blended fuels on pollutant emissions. The study reveals several important findings regarding NO_x, soot, CO, and THC emissions. In terms of NO_x emissions, the research demonstrates that increasing injection pressure results in higher NO_x emissions. This is attributed to improved fuel atomization and air/fuel mixing, leading to increased combustion temperature. Additionally, NO_x emissions rise with a higher mixing ratio of pine oil due to prolonged ID, allowing for better mixing of fuel and air, thereby increasing combustion temperature. However, when the pine oil ratio exceeds 40%, excessively delayed combustion leads to reduced NO_x emissions. Soot emissions, on the other hand, decrease significantly with higher injection pressure. The improved atomization and enhanced mixing between fuel and air reduce rich-fuel regions in the cylinder, resulting in reduced soot emissions. Moreover, increasing pine oil content in the blend leads to a sharp decrease in soot emissions due to the uniform mixing of fuel and air, preventing over-rich regions and subsequent soot formation. However, the effect weakens when the pine oil ratio surpasses 40%. CO and THC emissions follow a similar pattern, decreasing as injection pressure increases. Higher injection pressure promotes better air/fuel mixing and combustion conditions, enhancing oxidation of CO and THC. Conversely, increased pine oil content in the blend leads to higher CO and THC emissions due to prolonged ID, creating low-temperature mixing regions and incomplete combustion.

It was reported in [81] that the CO, HC, and smoke emissions have significantly decreased for experimental fuels, including blends up to B50. However, it is crucial to note that NO_x emissions have increased by 8.29% compared to regular diesel oil. These increased NO_x emissions raise concerns regarding their impact on air quality and the environment. The results indicate that experimental fuels up to B50 show promising potential for future energy production. These fuels can contribute to reducing dependency on fossil fuels and lowering pollutant emissions, given the substantial reduction in CO, HC, and smoke emissions. However, special attention needs to be given to the control and reduction of NO_x emissions to ensure a sustainable and environmentally friendly alternative in energy production.

DISCUSSIONS

Biobased fuel derived from pine resin, whether used in its pure form or blended with other components, has garnered attention from the scientific community as a promising alternative to traditional fossil fuels. Furthermore, recent research has highlighted encouraging prospects regarding emission reduction, including smoke and nitrogen oxide emissions, and has demonstrated significant improvements in engine performance parameters such as thermal efficiency and fuel consumption when pine oil is used in a mixture with diesel. This is confirmed in the work [43]. Below, in 2, are given the effects of the fuel mixtures on the performance and emissions of ICE (BSFC, BTE, EGT, HRR, NOx, CO, HC, and Smoke opacity).

However, it is important to emphasize that the performance of biobased fuel as a fuel source remains the subject of intense research across various domains, and this challenge continues to be addressed by numerous researchers globally. One of the crucial aspects influencing both emissions and diesel engine performance is fuel injection strategies and combustion chamber design. Over time, numerous researchers have engaged in projects aimed at optimizing combustion chamber geometry using a variety of fuel types and injection technologies [84]. It is worth noting that in current studies, most researchers have utilized diesel engines with traditional fuel injection strategies characterized by relatively modest pressures. However, modern common rail injection systems offer much higher pressures and, consequently, more efficient fuel atomization. Additionally, these systems allow for electronic control of fuel injection, enabling real-time optimization of injection parameters to enhance engine performance and reduce pollutant emissions.

CONCLUSION

Research and development of blends of vegetable oils and turpentine with diesel oil offer significant opportunities and challenges, and understanding the complex relationship between fuel composition, combustion characteristics, and emission profiles is crucial for the development of ecological fuels.

Impact on engine performance:

1. The use of blends of vegetable oils and turpentine with diesel oil can affect engine performance. For example, blends with jatropha oil and turpentine can achieve performance levels close to diesel oil but may experience a decrease in thermal efficiency and an increase in specific fuel consumption.
2. The higher viscosity and reduced volatility of vegetable oils can lead to diminished combustion characteristics, affecting thermal efficiency and engine performance.
3. The use of turpentine can lead to a decrease in engine volumetric efficiency, especially at high loads and with the introduction of significant quantities of turpentine into the intake.

Impact on emissions:

1. Blends of vegetable oils and turpentine can influence engine pollutant emissions. For example, some blends can reduce hydrocarbon (HC) emissions due to the

additional oxygen content, improving combustion efficiency.

2. However, HC emissions may increase with a higher proportion of blends of vegetable oils and turpentine, highlighting the complexity of the relationship between blend composition and emissions.
3. Blends with turpentine can lead to a reduction in smoke opacity and particle emissions, especially with higher percentages of turpentine.

Need for optimization and balancing:

1. To maximize engine efficiency and performance, careful optimization of mixing parameters, including blend composition, injection pressure, and other factors, is necessary.
2. It is important to balance the advantages and disadvantages of using blends of vegetable oils and turpentine, such as thermal efficiency versus emissions, to achieve an optimal fuel solution.

Benefits of alternative fuel blends:

1. The use of alternative fuel blends, such as those based on vegetable oils and turpentine, can provide promising solutions for reducing greenhouse gas emissions and air pollution, and promoting a circular and sustainable economy.

The limitations of this study stem from the insufficient information available in the literature regarding the specific testing conditions of turpentine within the internal combustion engine, as well as from the utilization of a classical injection strategy at relatively low pressures. A prospective avenue for future research would involve researchers optimizing the injection strategy using modern injection systems and fine-tuning injection parameters to achieve improved performance and reduced pollutant emissions. Turpentine exhibits potential as an additive both in terms of enhancing performance due to its high calorific value and in passive reduction of pollutant emissions, given its extraction from pine trees without harming them, thus contributing to a reduction in CO_2 emissions over the entire lifespan of the tree.

However, continuous research and development are necessary to optimize the proportions and mixing conditions to maximize the benefits and minimize the potential drawbacks of using this additive. The practical implementation of these solutions requires rigorous evaluations and adaptation to the specific requirements of each type of engine and application to ensure the long-term efficiency and reliability of propulsion systems using turpentine as an additive in diesel.

NOMENCLATURE

BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
B50	50% Pine Oil and 50% Ceiba Pentandra Methyl Ester
CA50	Crank Angles at 50%
CIE	Compression Ignition Engine
CPME	Ceiba Pentandra Methyl Ester
CPMEP	Ceiba Pentandra Methyl Ester Blend with Pine Oil
CO	Carbon Monoxide
CO_2	Carbon Dioxide
C50T50	50% Turpentine and 50% Chlorella Vulgaris
DBL	Diesel Baseline
DF	Dual Fuel
DOC	Diesel Oxidation Catalyst
DTBP	Di-Tertiary Butyl Peroxide
EGT	Exhaust Gas Temperature
EGR	Exhaust Gas Recirculation
HRR	Heat Release Rate
HC	Hydrocarbon Emissions
IAN	Iso-Amyl Nitrate
ID	Ignition Delay
JMT50	Jatropha Oil and Mineral Turpentine 50% with 50% Diesel
JMT20	Jatropha–Mineral Turpentine 20% with 80% Diesel
J100	Jatropha Oil 100%
JWT	Jatropha Oil and Wood Turpentine
LNT	Lean NO_x Trap
NEDC	New European Driving Cycle
NO_x	Nitrogen Oxides
PAH	Benzene, Naphthalene, Phenanthrene, Pyrene
P0	Pine Oil 0%, 100% diesel
P20	Pine Oil 20%, 80% diesel
P40	Pine Oil 40%, 60% diesel
P50	Pine Oil 50%, 50% diesel
RPM	Rotation per minute
TDC	Top Dead Center
THC	Total Hydrocarbon

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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